

UNIVERSIDAD POLITÉCNICA DE MADRID

Escuela Técnica Superior de Ingenieros Industriales



**A Taxonomy for the Digital,
Environmental, and Socially Just
Transition**

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Gema del Río Castro

MSc Industrial Engineer

Madrid, 2024



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Doctoral Degree in Management Engineering

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Under the supervision of:

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*Dedicate to my father, Daniel, who inspired my vocation for engineering
and encouraged me to never give up on pursuing a better world.*

Acknowledgement

This research journey has been long and daring. Midway, the pandemic struck, plunging us into one of the darkest chapters in our recent history. Then I lost my captain, without a chance to say goodbye. As if that were not enough, life gave me an ultimatum, a tempest tried to shatter my ship. Yet, I kept navigating tirelessly through the infinite blue, charting my course. When my strength was gone, when everything seemed lost, even hope, I glimpsed the shore again.

I did not choose the easy route. Naïve of me, I wanted to venture into uncharted waters, just by the joy of learning. Still, there were moments when the waves towered too high, the path felt too lonely, and even the stars at night appeared too enigmatic to guide me.

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Abstract

The convergence of digital, environmental, and social challenges demands a transformative approach to align digital and innovation landscapes with regenerative sustainability and systemic resilience perspectives. While digital transformation and innovation hold extraordinary potential to drive sustainability, their rapid and uncontrolled expansion, misaligned with sustainability values, has perpetuated technocentric approaches that fail to address global complexities. This research aims to bridge these gaps by proposing novel holistic frameworks to advance a regenerative triple transition - digital, environmental, and socially just - while recalibrating the realms of sustainability, digitalisation, and innovation with systemic regeneration and resilience as foundational values. The objectives include categorising the role of digital paradigms in addressing the UN's 2030 Agenda challenges and opportunities, developing a taxonomy and strategic objectives for sustainable and regenerative digital transformation, proposing a Sextuple Helix Innovation Model to align innovation with the triple transition, and formulating strategic recommendations to synchronize and co-evolve digital transformation, innovation, and sustainable development agendas. The methodology combined a systematic literature review, desktop research, and qualitative analysis, supported by text mining and visualisation, and expert elicitation and dialogue. The findings provided valuable insights and contributions to articulating this interplay in research and policy domains. First, the SDG gaps and opportunities are categorised, while examining the dual nature of digital paradigms in addressing them. Second, the first Taxonomy and Strategic Objectives for Sustainable and Regenerative Digital Transformation are proposed, structuring existing knowledge on the key factors of this intersection. This taxonomy aims to raise awareness and guide decision-making to align digital transformation with environmental and social priorities. It also introduces a preparedness pillar centred on readiness, resilience, and response to crises, to equip all stakeholders with the capacities and means to navigate the triple transition. Third, a Sextuple Helix Innovation Model and its enabling ecosystems (Regenerative Digital Innovation Hubs) are proposed to reorient innovation towards the regenerative triple transition. This holistic and “pluriversal” model aligns with the taxonomy and integrates six subsystems: whole-of-governance, conscious economy, ecosphere, the digital sphere, empowered whole-of-society, and open academia. The model emphasizes knowledge transfer, collaboration, co-creation, and systemic integration to drive regenerative innovation. Fourth, strategic recommendations are proposed to align and co-evolve digital, sustainable development, and innovation agendas, driving the regenerative triple transition and long-term resilience. These recommendations underscore the relevance of mindful governance, enhanced accountability mechanisms, multilevel cooperation, and targeted efforts in education and capacity-building to engage all stakeholders in building a more sustainable and inclusive future. Thus, reconciling digital, sustainability, and innovation landscapes emerges as an achievable strategic imperative to tackle emerging global challenges. Achieving this integration requires systemic frameworks that capture the underlying dynamics of this complex interplay, foster compelling narratives, and provide actionable pathways to translate insights into meaningful action. Finally, this dissertation positions the unfolding triple transition as a transformative opportunity to redefine progress and regenerate social, governance, and natural systems. In conclusion, this thesis makes a foundational contribution, paving the way for promising future research avenues aimed at realigning these critical domains toward a more sustainable, resilient, and regenerative future for all.

Resumen

La convergencia de los desafíos digitales, ambientales y sociales requiere un enfoque transformador para alinear el panorama digital y de innovación con perspectivas de sostenibilidad regenerativa y resiliencia sistémica. Aunque la transformación digital y la innovación ofrecen un potencial extraordinario para impulsar la sostenibilidad, su rápida y descontrolada expansión, desvinculada de valores sostenibles, ha perpetuado enfoques tecno-céntricos que no afrontan las complejidades globales. Esta tesis aborda estos retos proponiendo nuevos marcos holísticos para una triple transición regenerativa: digital, ambiental y socialmente justa. Asimismo, aboga por recalibrar los ámbitos de la sostenibilidad, digitalización e innovación mediante la integración de la regeneración y resiliencia sistémicas como valores fundamentales. Los objetivos incluyen categorizar el papel de los paradigmas digitales para abordar los retos y oportunidades de la Agenda 2030, desarrollar una taxonomía y objetivos para una transformación digital sostenible y regenerativa, proponer un modelo de innovación que permita alinear la innovación con la triple transición y formular recomendaciones para sincronizar y evolucionar las agendas de transformación digital, innovación y sostenibilidad. La metodología combinó una revisión sistemática de la literatura, investigación documental, análisis cualitativo, apoyado por minería y visualización de textos, así como consulta a expertos. Los resultados proporcionaron valiosas contribuciones para articular este nexo. En primer lugar, se categorizaron los retos y oportunidades del marco de ODS, explorando las capacidades de los paradigmas digitales para abordarlos. En segundo lugar, se propuso la primera Taxonomía y Objetivos Estratégicos para la Transformación Digital Sostenible y Regenerativa, estructurando el conocimiento existente sobre factores clave de esta intersección. Esta taxonomía pretende sensibilizar y apoyar la toma de decisiones para alinear la transformación digital con prioridades ambientales y sociales. Asimismo, integra un pilar de preparación centrado en la disposición, resiliencia y respuesta a crisis, para equipar a todos los actores con las capacidades y medios para navegar los retos de la triple transición. En tercer lugar, se propuso un Modelo de Innovación de Séxtuple Hélice y ecosistemas habilitadores (Centros de Innovación Digital Regenerativos) para reorientar la innovación hacia la triple transición regenerativa. Este modelo holístico y pluriversal, alineado con la taxonomía, integra seis subsistemas: gobernanza integral, economía consciente, eco-esfera, esfera digital, sociedad empoderada y academia abierta. El modelo enfatiza la transferencia de conocimiento, colaboración, co-creación e integración sistémica para impulsar la innovación regenerativa. Finalmente, se propusieron recomendaciones estratégicas para alinear y co-evolucionar las agendas de sostenibilidad, digital, e innovación, impulsando la triple transición regenerativa y la resiliencia. Estas subrayan la relevancia de una gobernanza consciente, rendición de cuentas, cooperación multinivel, así como educación y capacitación para involucrar a todos los actores para construir un futuro más sostenible e inclusivo. Reconciliar sostenibilidad, innovación y digitalización se convierte en un imperativo estratégico realizable frente a los desafíos globales emergentes. Lograrlo, requiere marcos sistémicos, como los propuestos, que capturen las dinámicas subyacentes, fomenten narrativas convincentes y trasladen las ideas en acciones significativas. Esta investigación posiciona la triple transición como una oportunidad transformadora para redefinir el progreso y regenerar los sistemas sociales, naturales y de gobernanza. En conclusión, esta tesis establece contribuciones relevantes que abren líneas de investigación prometedoras, para realinear estos dominios críticos hacia un futuro más sostenible, resiliente y regenerativo para todos.

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Abbreviations and Acronyms

AI	Artificial Intelligence
BDA	Big Data Analytics
CODES	Coalition for Digital Environmental Sustainability
DESC	Digital Economy and Society Committee
DESI	Digital Economy and Society Index
DEP	Digital Europe Programme
DIH	Digital Innovation Hub
DLT	Digital Ledger Technology
DT	Digital Transformation
EMF	Electromagnetic Fields
EO	Earth Observation
ESG	Environmental, Social, and Governance
EC	European Commission
EU	European Union
5G	Fifth Generation Connectivity
GHG	Greenhouse Gases
HE	Horizon Europe
HPC	High-Performance Computing
ICSD	International Conference on Sustainable Development
ICT	Information and Communication Technologies
ICT4S	Information and Communication Technologies for Sustainability
IoT	Internet of Things
IIoT	Industrial Internet of Things
ITU	International Telecommunication Union
LCA	Life Cycle Analysis
LDA	Latent Dirichlet Allocation
ML	Machine Learning
CML	Causal Machine Learning
OECD	Organisation for Economic Co-operation and Development
OKR	Objective and Key Result
QC	Quantum Computing
QT	Quantum Technologies
RC	Research Contribution
RCF	Report Card Framework
R&I	Research and Innovation
RQ	Research Question
RRI	Responsible Research and Innovation
RRL	Regenerative Readiness Level
SD	Sustainable Development
SCC	Smart Cities and Communities
SDG	Sustainable Development Goals
6HIM	Sextuple Helix Innovation Model
TRL	Technology Readiness Level
SRDT	Sustainable and Regenerative Digital Transformation
STI	Science, Technology, and Innovation
ToC	Theory of Change
UN	United Nations
UNEP	United Nations Environment Programme
UNDP	United Nations Development Programme
UPM	Universidad Politécnica de Madrid
WEF	World Economic Forum

1. Introduction

1.1. Background

In recent years, the world has witnessed the rise of digital transformation, which has revolutionized every aspect of life, science, society, and the economy. Likewise, the 2030 Agenda for Sustainable Development (UN, 2015a, b), the push for sustainable investment, and the regulation of socio-environmental aspects through green taxonomies have led to an unprecedented relevance of the sustainability sphere. Both digital and sustainability transformations represent a radical paradigm shift, giving rise to the phenomenon of convergence between the two, towards a triple transition that is green, digital, and socially just.

While the period from 2016 to 2019 saw a significant and unprecedented push towards articulating the UN's 2030 Agenda for Sustainable Development and integrating it into impact investment and social policies, it has taken a backseat following the pandemic and is even regressing. The period from 2020 to 2024 has been tumultuous, generating technological and social disruptions, as well as demonstrating signs of a climate and biodiversity crisis. It has also been a turning point, wherein the recovery from the pandemic crisis, driven by the imperatives imposed by global crises, has triggered a renewed push towards a more sustainable and regenerative development model for people and the planet.

In recent years, there has been a great surge in both research and policy focused on the nexus between digital and sustainable transformation aligned with the 2030 Agenda. The green, digital, and just transition aligned with the 2030 Agenda will form the core of policies and growth and recovery strategies worldwide, such as the Green Deal or the New European Industrial Strategy (European Commission, 2020a, b, c).

However, geopolitical imbalances emerged strongly in 2022 and 2023, creating a change in the landscape that hampers international cooperation, fosters distrust towards ecological advancements, and causes evident social polarization (Sachs et al., 2023). Beat by populist currents, the emergence of autocracies, the energy crisis stemming from geopolitical conflicts, raw material blockades, or the inflation crisis that has occurred, they are threatening the progress made in recent years (Sachs et al., 2023), reducing support and investment, fostering mistrust in a green future, and ultimately jeopardizing the green and social agendas promoted not long ago.

Indeed, having passed the halfway mark of the 2030 Agenda, just 6 years away from its final goal, it is evident that the pace of progress towards the SDGs is insufficient (Sachs et al., 2021; EC-Eurostat, 2021; UN, 2023a), showing that most sustainable development goals are far from being achieved (Sachs et al., 2023), and in some cases, there is even regression (UN, 2023a), particularly in environmental ones. Despite the considerable progress made from 2015 to 2019, the COVID-19 pandemic and the consequent socio-economic crisis, that still prevails, have harmed the SDGs globally (Sachs et al., 2023).

The regulatory tsunami surrounding taxonomies of environmentally sustainable activities (IPSF, 2022; EU, 2021c), impact investment, more elaborate reporting standards (EC, 2023e), commitments to climate neutrality (COP 28), or the renewed biodiversity framework following the COP15 in Montreal in 2022 (CBD, 2022), dominate the current sustainability agenda. However, they have proven to be a double-edged sword. On the one hand, while there is increasing recognition of accountability regarding ESG aspects, paradoxically, ecological whitewashing (greenwashing) is being encouraged. Behind these practices, there are also opaque agendas of corporations overwhelmed by regulatory surge and social demand.

Countering this push, the concept of sustainability is also gaining detractors and trends focused on its deceleration. On the other hand, within the scientific community, various sceptical movements have emerged regarding the advancement of green hypocrisy, with some experts even proposing the need for a "fallow period" or a "winter of sustainability" to allow for an evolution towards a regenerative economy. Likewise, the phenomenon of ecological activism is experiencing complex moments, increasingly rooted in society but also increasingly limited.

Furthermore, complex challenges persist, both in our understanding of ecological phenomena, and eco-social relationships, and in the design of frameworks for their governance. Despite being an unprecedented milestone, the 2030 Agenda presents severe design flaws and complex implementation challenges (Saito et al., 2017). The SDGs are the result of a global political commitment, combining ends and means, local and global governance, for whose achievement deep transformations and significant monitoring efforts are required (Schmidt-Traub et al., 2017), which, after a few years of progress, are not taking place.

Their voluntary non-binding nature and inherent limitations need to be addressed, especially regarding: the lack of balance and integration between dimensions (Ala-Uddin, 2019; Stevens and Kanie, 2016), to the detriment of ecological and equity goals; the complex integration and interconnections between objectives ensuring their systemic nature (Barbier and Burgess, 2017); inconsistencies between dimensions (Swain, 2018); the insufficient delineation of responsibilities and limitations related to metrics (Barbier and Burgess, 2019; Coscieme et al., 2020; Ordaz, 2019; Salvia et al., 2019); as well as, especially, the insufficient availability of quality data (Dang and Serajuddin, 2020) to monitor their fulfilment and assess their impact.

Likewise, although the agenda is an unprecedented success in achieving global consensus, the reality is that not all voices are adequately represented, and not all dimensions are equally relevant. The new regenerative approaches aim to resume the holistic idea of sustainability, offer a positive impact, and rebalance a new relationship between humanity and nature.

The international community, and the United Nations as its voice, call for accelerating transformation (UN, 2023) by addressing 6 critical points of change: human well-being and capabilities, sustainable and just economies, food systems and healthy nutrition, energy decarbonization and universal access to it, urban development, and global environmental commons. As well as five enabling levers: governance, participation, science and technology, finance, and capacity building. Innovation and digital transformation have been highlighted as crucial elements for the Agenda (UN, 2023; SNDS, 2023).

In particular, the UN (2023) includes digitalisation (especially AI), climate change, biodiversity, demographic change, and inequality, as well as changes in consumption patterns, globalization, and financing opportunities as "dynamic conditions" shaping achievements in the agenda.

However, the design of the Agenda and its implementation thus far, position digital transformation on a very secondary level, highlighting the gaps between sustainability and digital transformation agenda, even though it is one of the main facilitators for achieving sustainable development and at the same time a risk for exacerbating inequality gaps. Being immersed in the digital age, carrying serious risks and great opportunities, the integration of digitalisation into the agenda is insufficient.

Science and innovation are essential elements in the spirit of the Agenda, but they have not been adequately implemented within its framework. Additionally, innovation itself is facing its own evolution immersed in the digital age and in new paradigms, more participatory and collaborative, with more diverse actors, and more oriented towards social and environmental impact.

Innovation, as an agent of change and transformation, is fundamental to sustaining the triple transformation (Letouzé and Pentland, 2018). However, it is essential to understand how to evolve to adapt to the digital age, evolve in terms of governance and actors, and foster cooperation and knowledge exchange (Fjeld et al., 2020).

Digital transformation continues unabated, permeating and revolutionizing rapidly and causing disruptions in all areas of society, the economy, and science. Due to its extraordinary impact, it must be redirected to accelerate a profound transformation towards sustainability (D4S, 2023; UN, 2023). Despite the progress made in sustainable digitalisation and sustainability, there are still many unexplored and misunderstood aspects, both in terms of its application to the 2030 Agenda and around the socio-environmental dilemmas of various digital paradigms (e.g., Big Data, Artificial Intelligence).

Moreover, there persists a naive view of digitalisation, considering it as a magical and immaterial solution that efficiently solves and automates any problem, without considering its current capabilities, or the severe risks and impacts it can cause on society and the environment. Digitalisation is playing a leading role in one of the biggest cases of ecological whitewashing and misleading ethical narratives. From a scientific point of view, the net impacts of digital development are still unknown and uncertain, especially regarding indirect impacts, rebound effects, and cross-border repercussions (Bremer et al., 2023; Coroama et al., 2023; Becker, 2023).

Recently, Generative Artificial Intelligence (GenAI), supported by large Language Model (LLM) models, has revolutionized the business, creative, and educational worlds, exposing the severe risks it entails and sparking the debate about its ethics and sustainability (Letouzé and Pentland, 2018; Fjeld et al., 2020; European Commission, 2018a, b, c). The democratization of generative artificial intelligence has increased pressure for adequate regulation and has highlighted the importance of raising ethical and safety standards (Hurlburt, 2023; Future of Life Institute, 2023).

The growing advancements in large AI models, massive data centres, infrastructures, and devices have not reduced but rather expanded their carbon, water, and material footprints, also exacerbating the issue of electronic waste with low circularity. The digital infrastructure supporting virtualization is not immaterial but increasingly exposed to an extractive economy that pressures natural resources, ecosystems, and local communities whose impacts are being underestimated. The raw materials and energy required to power digital infrastructure are highly dependent on supply chains that threaten human rights and biodiversity, accommodated within unsustainable growth lacking good governance.

Governments worldwide have accelerated regulation to address more responsible governance of digital technology, but jurisprudential limitations, geopolitical conflicts, and decreasing international cooperation slow down their implementation.

While the environmental challenges of the digital age are inherently complex, the social challenges are even more so. These tools are being used for unprecedented scientific advances, but also for cybercrime, misinformation, cyberbullying, and social polarization (Becker, 2023). Research positions oscillate between techno-solutionist utopias of the past and the destructive dystopias of science fiction.

On the other hand, if sustainability faces a self-assessment due to concept erosion and scepticism caused by the expansion of "greenwashing," digital transformation faces abrupt growth similarly submerged in narratives of green hypocrisy and ethics (EBA, 2023; Seele and Schult, 2023).

In this turmoil, initiatives like the Digital Global Compact aim to establish responsible and multidisciplinary frameworks globally to channel dialogue, and cooperation among actors and countries, as well as "pluriversal" governance to redirect digital transformation towards sustainable development.

However, digital paradigms represent an extraordinary opportunity in the sustainability sphere. The digital age holds great promise to increase human capabilities and solve social and environmental problems previously unaddressed. Additionally, sustainability is imperative to achieve responsible digital transformation with human values.

The current model of digitalisation does not guarantee sustainable development (Chazhaeva et al., 2019; Bremer et al., 2023; Becker, 2023), with a clear gap between technology and sustainability (Akande et al., 2019). The predominant approach in the digital world is socio-economic and technocentric, based on techno-utopias and technological solutionism, oblivious to ongoing eco-social transformations.

Advancements in digitalisation for sustainability are often the result of philanthropic or governmental projects with limited social reach and impact (Letouzé, 2019; Vinuesa et al., 2020), often symbolic and difficult to scale. The study of digital paradigms for the SDGs, particularly the role of Big Data and Artificial Intelligence, has emerged as an emerging phenomenon harbouring promises and complex challenges (Letouzé, 2019; ITU, 2019; Wu et al., 2018; Vinuesa et al., 2020).

Despite the progress made, digital capacities and their impact on sustainability have not yet been sufficiently explored (ITU, 2017). It is essential to holistically integrate the potential impacts of digitalisation concerning the SDGs (Tjoa and Tjoa, 2016) and promote digital paradigms with a sustainable development perspective to achieve the 2030 Agenda (WEF, 2020a). Additionally, such a complex phenomenon demands agile, dynamic, open governance with a comprehensive perspective (Boyd and Crawford, 2011; Yu et al., 2018).

The triple transition of digital, environmental, and social realms has emerged as a promising multidisciplinary field of research transcending borders and attracting various stakeholders from governmental, corporate, and civil society spheres of science and innovation.

Addressing numerous technological and governance challenges within the realm of digitalisation itself is imperative. The rise of digital paradigms has occurred rapidly without the critical spirit, scientific dialogue, and adequate regulation. Multiple uncertainties persist concerning strategic, social, and ethical aspects. There is still no consensus or sufficient knowledge about their true impacts and value-creation mechanisms, and their capacity to surpass traditional scientific capabilities has not been empirically demonstrated yet. Despite considerable progress made, substantial barriers persist in harnessing the potential of digitalisation sustainably and creating sustainable value.

Therefore, the phenomenon of the triple transition and the nexus between digital transformation and sustainability highlights a vast space for research and political and social action in this area filled with exciting multidisciplinary debates and controversies that transcend previous conceptions of science. Research, science, and responsible political action should guide the alignment between the digital revolution and ecological revolution within planetary and social boundaries. Additionally, the need emerges to address regenerative approaches and just transitions, ensuring equitable and intergenerational development within planetary and social limits.

The academic gap is significant, with a notable disconnect between practice and science. Although the “digitalisation - sustainability” nexus has emerged as a trend, it remains an immature and highly fragmented field, demonstrating a lack of theory, terminological consensus, and weak and unfounded narratives. Despite significant growth in publications, unresolved controversies and debates persist, highlighting a significant gap between the two disciplines. The scientific gap is even more intense concerning the intersection between emerging and challenging digital paradigms like Big Data, and Artificial Intelligence and Sustainability.

There is an incipient state of development with significant research gaps in the social and environmental sphere and an extremely complex and multidimensional nature. Both sustainability and digitalisation require profound transformations, new capabilities, and cultural change management, and the extent to which they relate to and feedback to each other is still unknown.

The development of a solid terminological and theoretical framework, new methodologies, capabilities, and strategies are needed to comprehensively understand their systemic, multidisciplinary, and evaluative nature. Additionally, it is necessary to scientifically contrast their claimed virtues and demonstrate if they can truly reformulate the categorisation of reality. Practical tools are also needed for all stakeholders, including civil society, to implement sustainable, equitable, and fair digitalisation.

Aware of the challenges posed by this phenomenon, at the political level, the twin green and digital transformation is evolving towards the triple transition, where the numerous social and environmental risks it generates have taken a central stage, along with the need to fairly distribute the benefits of economic model evolution. However, it is worth noting that conventional frameworks for innovation, sustainability, or digitalisation have become outdated and do not integrate the nexus between digitalisation and sustainability. Therefore, they must be adapted to the characteristics and trends of the present and future scenarios.

Thus, there is a need to create new measurement and monitoring frameworks that accurately reflect the triple transition, involving all stakeholders and articulating agile and responsible governance to address this crossroads. Also, the global literature and community demand better metrics and evaluation frameworks to address gaps in data availability and timing, necessitating the building of new capacities. Innovative methods, tools, and responsible strategic directions are needed to merge innovation, digitalisation, and sustainability and facilitate not only digital but also conscious, sustainable, and fair transformation.

To achieve a responsible digital transformation that catalyses governance towards achieving the SDGs, it is necessary to build a collective imagination reflecting the reality of the digital age, raise awareness among all stakeholders, and reformulate institutions anchored in human and sustainability values.

1.2. Motivation and Justification

The main motivation of this thesis is to holistically explore the convergence between digitalisation, sustainability, and innovation, aiming to assess how these domains can be synergistically harnessed to drive a sustainable, regenerative, and inclusive digital transformation. This exploration also aims to evaluate how this interplay can contribute towards achieving the Sustainable Development Goals (SDGs) of the UN's 2030 Agenda (UN, 2015) and to inform future subsequent frameworks. This motivation is driven by the need to address the following key aspects:

(1) The opportunities and challenges posed by digital paradigms for achieving the SDGs toward a more sustainable, “pluriversal”¹ and regenerative development.

(2) The sustainability potential to facilitate a triple transition that is digital, environmental, and socially just, promoting regenerative approaches and resilience for society and the planet.

(3) The role of innovation and its necessary convergence with digital transformation and sustainability to address the challenges of the 21st century.

¹ The concept of pluriverse refers to the “theory of pluralism”, a state of society in which diverse perspectives are considered, allowing different social groups to preserve and develop their cultures and interests within a common civilisational framework (Merriam-Webster Dictionary, n.d.).

Thus, this research aims to formulate the conceptual context and practical tools, based on scientifically sound methodologies, for an optimal and agile implementation of the triple transition towards a sustainable future.

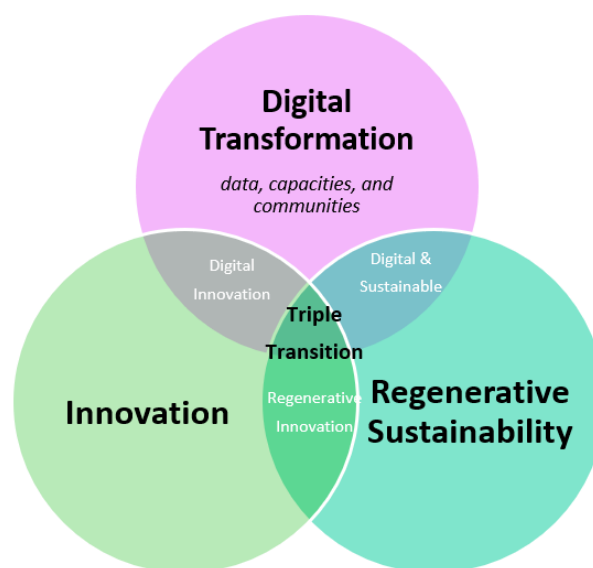


Figure 1.1. Conceptual Scheme Outlining the Dissertation Context and Rationale
(Own elaboration)

As emphasized previously, this research mission encompasses qualitatively all perspectives of the phenomenon under study, spanning across all scales from macro to micro and from global to local contexts. On one hand, it delves into the study of the SDGs and other sustainability frameworks, focusing especially on their limitations, interrelationships, and synergies with other paradigms, as well as their challenges in implementation, adoption, and agile and systemic governance.

On the other hand, it explores the transformative potential of digitalisation and digital paradigms (e.g., big data and artificial intelligence, among others) to overcome challenges and seize opportunities in their application areas. The research considers systemically potential risks, impacts, and mitigation measures, alongside relevant opportunities for regenerative and sustainable development.

The link between digital transformation, innovation, and sustainability represents a multivariable, multifaceted, and complex area of research for the scientific and policy realms. All three domains are vertiginously growing, albeit their convergence remains still immature and fragmented. There is a significant gap, between these disciplines, that needs to be addressed to progress towards their effective convergence.

Furthermore, the research addresses to what extent digital paradigms can help understand social, environmental, and governance challenges and how they can be applied responsibly, and sustainably, contributing to the achievement of the SDGs, mitigating underlying risks, and leveraging all opportunities they can offer, addressing a regenerative perspective.

Finally, it analyses, within an integrated framework, the inherent characteristics of the convergence between digital paradigms (Big Data and Artificial Intelligence), Sustainability, and Innovation, to formulate recommendations and tools that contribute to seizing opportunities, overcoming barriers, and minimizing risks inherent in their practical implementation in corporate, scientific, and governmental domains.

Thus, the research focuses on the most interesting challenges in the field while maintaining a high-level holistic approach, respecting the systemic nature of the 2030 Agenda. This dissertation also contributes to a better conceptual and terminology understanding and practical tools that may facilitate the future formulation of sustainable and regenerative digital transformation strategies. It aims to analyse the interrelationships, synergies, and trade-offs of this new goal representing the convergence of the digital and sustainable development agendas, and the sustainability paradigm itself in all its dimensions.

The current approaches lack sufficient contextual nuances. Specifically, analytical approaches barely address causality, imperative to understand the reality and implications of phenomena, as well as the potential outcome of interventions on them. Causal approaches emerge with an extraordinary potential research frontier, although they represent enormous complexity and are underdeveloped in the literature. The thesis will address them to study their potential in the realm of the convergence between digital transformation, innovation, and sustainability.

In conclusion, this research aims to deeply analyse the intricate interrelationships among digital transformation, innovation, and sustainability, while exploring the transformative potential of digital paradigms in the context of sustainable and regenerative development. It seeks to uncover and address the challenges and opportunities arising from the systemic integration and evolution of these disciplines to enable their responsible and sustainable implementation. Thus, this dissertation navigates the complexities posed by digital and innovation disruptions, aiming to provide enhanced knowledge, practical tools, and strategic recommendations towards a more sustainable articulation of digital transformation and innovation, able to create opportunities for a more resilient and regenerative future.

1.3. Research Objectives

This research provides a comprehensive and panoramic perspective on the key challenges at the intersection of digital transformation, regenerative sustainability, and innovation, underlining their significance for achieving a triple transition, which encompasses the digital, environmental, and socially just dimensions. This realm remains inadequately conceptualised and insufficiently implemented in science, practice, and existing policies. Consequently, this dissertation underscores the importance of translating research findings into actionable practice and policy insights to enable better governance of this complex interplay.

The overall mission of this research is to categorise, characterise, and articulate the key determinant factors at the intersection of digital transformation, regenerative sustainability, and innovation. It aims to propose systemic frameworks that enable the effective alignment of these realms and the articulation of their interplay facilitating the realization of a regenerative triple transition.

This dissertation also aims to demonstrate the outstanding opportunities that an effective articulation of this interplay presents. This includes generating new knowledge, addressing complex global challenges, and fostering more sustainable, inclusive, and regenerative forms of value creation that promote long-term resilience.

Simultaneously, the research seeks to categorise the inherent risks posed by digital transformation and innovation to sustainability, which need to be prevented and mitigated to ensure a genuine contribution to regenerative sustainability and resilience.

Moreover, this research intends to elucidate how digital transformation and innovation landscapes can be recalibrated and evolved to embrace regenerative sustainability. This approach aims to achieve a more coherent and synergistic alignment of these three critical fields, balancing prosperity with social and ecological values.

Therefore, to achieve this mission, the research seeks to explore and articulate the multifaceted interplay among digital transformation, innovation, and regenerative sustainability with a systemic, holistic, and "pluriversal" approach. This also entails building a common terminology, a compelling and shared narrative, and integrated frameworks to bridge the current fragmentation and divides between these realms and foster alignment and cohesion. Indeed, it seeks to synchronize and co-evolve the agendas of innovation, digitalisation, and sustainability for their synergetic contribution to the regenerative triple transition and systemic resilience.

In essence, the research ambitions to further elaborate both the conceptual understanding and the practical articulation of this interplay, to jointly advance regenerative sustainability, sustainable digital transformation, and regenerative innovation. Finally, the research aims to translate the insights gained into practical and policy pathways that contribute to the effective articulation and advancement of a regenerative triple transition towards a more equitable, sustainable, regenerative, and resilient future.

Hence, the specific objectives of this dissertation aligned with the general mission, are outlined as follows:

- **Categorise and characterise the research challenges and opportunities of the SDGs within the UN's 2030 Agenda.**

This objective involves the identification, analysis, and categorization of the challenges and opportunities related to the design, implementation, and systemic governance of the 2030 Agenda. It includes examining the interlinkages among the goals and targets, along with their connections to other sustainability paradigms, such as regeneration and resilience.

- **Examine the opportunities and risks presented by digital transformation for achieving sustainability and the SDGs.**

This objective involves identifying and evaluating the risks and opportunities that digital transformation can pose for sustainability. It also focuses on categorizing the potential contributions of digital paradigms in addressing the research gaps within the SDG framework, to advance the regenerative triple transition.

- **Characterise and categorise the key determinant factors driving a "Sustainable and Regenerative Digital Transformation" (SRDT).**

This objective involves the comprehensive examination and categorization of the opportunities and risks that digital transformation confronts in its alignment with regenerative sustainability. The main ambition is to develop a comprehensive and integrative taxonomy, complemented by strategic objectives, and a theory of change, to enable the systemic articulation of this interplay, enabling the alignment between both realms and driving progress towards the regenerative triple transition.

- **Examine and articulate the interplay between innovation, sustainability and digital transformation and propose a helix innovation model enabling ecosystems to reshape the innovation landscape in alignment with the principles of the regenerative triple transition.**

The objective aims to deepen the conceptual understanding of the interplay between innovation, digital transformation, and regenerative sustainability. Its principal ambition is to propose a systemic and pluriversal Sextuple Helix Innovation Model, along with related enabling ecosystems, which are better adapted to contemporary complexities for the effective articulation of regenerative innovation in alignment with the vision of the triple transition.

Additionally, it aims to provide strategic directions to realign current and future policies, ecosystems, and programmes, to advance regenerative innovation, the triple transition, and systemic resilience.

- **Formulation of strategic recommendations for aligning, synchronizing, and co-evolving the agendas for digital transformation, innovation, and sustainability towards their joint contribution to the regenerative triple transition.**

This objective entails the development of strategic directions to guide the alignment and integration of these three agendas and realms. Therefore, it focuses on fostering their synergistic evolution following the principles of a regenerative triple transition, while promoting long-term resilience and sustainability.

Thus, these objectives reflect the comprehensive, holistic, and multidisciplinary approach of this dissertation. They aim to advance the conceptual understanding of the complex nexus between regenerative sustainability, digital transformation, and innovation while supporting the development of pathways and strategic directions for research, policy, and practice. These efforts are intended to facilitate the alignment and evolution of the three agendas towards a regenerative triple transition, paving the way for a more sustainable, equitable, resilient, and regenerative future in the digital age.

Substantiation of the Relevance of the Proposed Objectives

The objectives of this dissertation are closely aligned with emerging trends in digital transformation, innovation, and sustainability. While digital paradigms and innovation hold outstanding potential to drive societal progress, they also present significant caveats and risks. The concept of the triple transition, encompassing the digital, green, and socially just transformations, has emerged as a promising research field with profound eco-social implications, influencing multiple sectors and disciplines.

In the context of sustainability, this concept faces rising criticism, and the ambition to achieve the 2030 Agenda is declining. This regression underscores the urgency for providing novel approaches to reinvigorate societal commitment to sustainability, and even raise the ambition toward the regeneration of societal, natural, economic, and governance systems, many of which are currently damaged. This imperative extends beyond maintaining sustainability to actively restoring and revitalizing these systems.

Simultaneously, undisciplined digital disruptions have not only endured but exacerbated their respective ecological impacts. In addition, the absence of effective and responsible governance has also intensified social and ethical dilemmas, threatening peace, democracy, and social cohesion.

Addressing these pressing challenges requires urgent action to mitigate the potential adverse social and ecological impacts of digital transformation and innovation while harnessing their exceptional opportunities for sustainable and regenerative development.

Thus, a full understanding of the interplay between these three realms, along with their strategic reorientation is essential to align them together synergically with the principles of a regenerative triple transition.

This research field intertwines three dynamic and rapidly evolving realms, digital transformation, sustainability, and innovation, all of which have experienced significant expansion and evolution over the past decade.

Through the examination and articulation of their interdependencies, this research aims to develop integrative and holistic frameworks, along with actionable insights that guide the alignment and co-evolution of these critical domains towards shaping a more regenerative, sustainable, and inclusive future.

1.4. Research Questions

This section presents the research questions (RQs) that this dissertation aims to address, which are circumscribed to four interrelated research lines focused on the triple transition (digital, environmental, and socially just), as described below.

The first research line is focused on the identification and categorization of the key research gaps within the Sustainable Development Goals under the UN's 2030 Agenda, along with the examination of the role that digital paradigms can play in addressing these challenges.

- *RQ1: What are the overarching research gaps within the SDG framework, and to what extent can digital paradigms and solutions contribute to responsibly addressing them and accelerating progress towards achieving the UN's 2030 Agenda?*

The second research line aims to identify and categorise the critical factors that influence the alignment of digital transformation with regenerative sustainability principles and values. Furthermore, it seeks to provide a comprehensive and structured framework, including a taxonomy and strategic objectives, to guide governance and decision-making, and support the advancement toward a sustainable and regenerative digital transformation (SRDT).

- *RQ2: What are the key determinant factors driving a sustainable and regenerative digital transformation, and how can they be categorised into a comprehensive taxonomy and objectives to enable decision-making in this direction?*

The third research line explores the synergistic realm of regenerative innovation, aiming to characterize its key facets and their interrelations with digital transformation and sustainability. It also seeks to propose a novel helix innovation model to effectively align this realm with sustainability and digital transformation, supporting the achievement of the triple transition.

- *RQ3: How can helix innovation models and ecosystems be reoriented to effectively support regenerative innovation and systemic resilience, and drive progress towards the triple transition?*

Finally, the fourth research direction focuses on formulating strategic recommendations to align, synchronize, and co-evolve the agendas of digital transformation, sustainability, and innovation, thereby driving the regenerative triple transition forward.

- *RQ4: What strategic recommendations can guide the alignment, synchronization, and co-evolution of digital transformation, sustainability, and innovation agendas towards the realization of a regenerative triple transition?*

1.5. Research Structure

This doctoral thesis is organized into ten chapters, each contributing to the exploration of the interplay between digital transformation, sustainability, and innovation, with a focus on advancing the regenerative triple transition. The structure unfolds coherently, encompassing all essential stages of the research.

It begins with an introduction (Chapter 1), which establishes the background and rationale for the research, defines the objectives and research question guiding the dissertation, and outlines the methodological approach and the key contributions expected. This chapter sets the foundation for the subsequent directions of the research.

Chapter 2 addresses the evolution of sustainability and its transition towards regenerative perspectives, reflecting on the controversies and limitations within current discourses.

It also provides an in-depth examination of the Sustainable Development Goals under the UN's 2030 Agenda, identifying and categorizing the gaps and opportunities, in their design and implementation. In addition, it sets the stage for exploring the potential of digital paradigms in addressing these challenges in the next Chapter.

Indeed, Chapter 3 examines the intricate interplay between digital transformation and sustainability, with a particular emphasis on categorizing the role of digital paradigms in tackling the research gaps within the SDG framework. It provides a holistic analysis of the dual nature of digital transformation concerning sustainability, examining it both as a key enabler of sustainability-focused solutions and a potential source of social and environmental risks and impacts.

Moreover, this chapter also evaluates the varied impacts of the different digital technologies on social and environmental dimensions, either positively or negatively, and underscores the relevance of reorientating this realm to embrace the triple transition, encompassing the digital, environmental, and social transitions.

Next, Chapter 4 explores the interplay between innovation, sustainability, and digital transformation, focusing on the critical role that innovation plays in advancing the regenerative triple transition. It examines the synergies among these three realms and explores the emergence of non-conventional innovation paradigms and communities, including the evolution toward regenerative innovation.

This chapter also proposes a Sextuple Helix Innovation Model (6HIM), along with its enabling ecosystems, assessing the alignment of the model with relevant research and innovation initiatives. Additionally, it outlines potential directions for reshaping innovation to responsibly contribute to the realization of a regenerative triple transition.

Chapter 5 presents one of the key contributions of this thesis: the development of a Taxonomy for Sustainable and Regenerative Digital Transformation in the pursuit of the triple transition. First, the chapter introduces the significance of the taxonomies within the digital and sustainability realms, a gap analysis of existing frameworks for assessing these two realms, and the methodological approach to developing this taxonomical framework.

Then, it provides a comprehensive substantiation of the Taxonomy structure and a thorough examination of its six pillars and respective domains. The chapter concludes by reflecting on the significance and implications of this structured framework for articulating the interplay between digital transformation and sustainability.

Building on the Taxonomy for SRDT, Chapter 6 presents the methodological approach for refining and validating this framework. The validation process is based on expert elicitation through semi-structured interviews, complemented by stakeholder dialogues and the presentation of the preliminary research findings at international conferences in the field. The feedback obtained from experts is integrated to refine the taxonomy and ensure its practical relevance and applicability.

Furthermore, this chapter includes expert input for refining the Strategic Objectives proposed in the next Chapter, along with contributions to formulating the strategic recommendations presented in the discussion.

Drawing from Chapters 5 and 6 insights, Chapter 7 introduces the proposal of Strategic Objectives and Theory of Change for SRDT and the regenerative triple transition. This chapter provides actionable pathways for mobilizing the transformation towards the vision of the triple transition. It also reflects on the need for further elaboration of these objectives with concrete metrics and agile monitoring frameworks.

Subsequently, a critical discussion is presented in Chapter 8, which synthesizes the findings and contributions of the research while contextualizing and interpreting them within the broader field. Furthermore, it also provides strategic recommendations for aligning, synchronizing, and co-evolving digital transformation, sustainability, and innovation agendas to realize the regenerative triple transition.

The conclusion (Chapter 9) summarizes the key achievements and contributions of the thesis, in response to the research questions and objectives, reflecting on their novelty, significance, and broader implications for research, policy and practice. It also identifies the research limitations and how they have been addressed.

Finally, Chapter 10 outlines potential future research avenues to further advance the field and explore the various directions opened by this dissertation.

1.6. Methodological Approach

This section provides a concise description of the methodology utilized in the dissertation, including the overall research approach, along with the specific methodological phases, and components.

The methodological framework has been carefully designed to adapt to the intertwined and complex research field, in response to emerging demands and research directions. Notably, the research context is characterised by the intersection of three intricate, multifaceted, and ever-evolving fields with blurred boundaries: regenerative sustainability, digital transformation, and innovation. Additionally, the literature in this research domain exhibits significant fragmentation, evidencing a persistent lack of consensus on theories and terminology, along with insufficient reflection on sustainability challenges across the technical, eco-social, and governance spheres.

Considering these complexities, the methodology combines inductive and deductive approaches, as well as multiple research techniques to reinforce flexibility and robustness. This approach has facilitated a gradual examination and interpretation of the studied phenomena within their context, adapting to their evolution and multifaceted nature.

Furthermore, the methodology provides a holistic and “pluriversal” perspective, covering all relevant aspects of the phenomena under study, including scientific and technological nuances, environmental and social aspects, as well as policy and practical implications. Such a comprehensive approach captures all relevant nuances, thereby enabling research contributions that advance the field.

The methodology employed in this dissertation aims to be robust, adaptive, and specifically designed to address the intricacies, multifaceted and evolving nature of the fields under study. Through a holistic approach, well-defined phases, and the appropriate combination of techniques, the research has progressed from the theoretical framework to practical validation, ensuring that the contributions are relevant and applicable to interplay amid digital transformation, regenerative sustainability, and innovation.

The detailed methodological phases and components employed are outlined in Figure 1.2, as well as in the following section. This research applied a comprehensive and robust methodology by combining diverse techniques and unfolding in five distinct phases, to profoundly examine the relationship between digital transformation, regenerative sustainability, and innovation. The methodology has been designed to trace the complex dynamics and evolution over time of this complex interplay.

Given the heterogeneity, and complexity of the frameworks under study and the immature stage of their interplay, it was essential to incorporate flexibility to capture all relevant nuances effectively, from diverse relevant sources, and ensure a thorough, comprehensive analysis.

Thus, the research approach has been structured in five distinct stages, with the appropriate iterative feedback between them, as described below.

First phase: Systematic Literature Review and Desktop Research

This initial phase focused on the in-depth exploration of the intersection between digital transformation, regenerative sustainability, and innovation. It involved a holistic examination and categorization of research challenges and controversies surrounding the UN 2030 Agenda, the digital paradigms, the innovation frameworks, and models, alongside their intersection to guide the subsequent research steps.

This has been achieved through a systematic and comprehensive review of academic and grey literature, as well as through dialogue with experts by participating in relevant international forums and working groups in the field.

In particular, this phase involved a systematic literature review (SLR) (Albert, 2019; Snyder, 2019) based on qualitative methods, to assess the intersection amid digital transformation, sustainability, and innovation fields. In this regard, relevant scientific peer-reviewed articles were sourced from databases such as Scopus, Web of Science, and Google Scholar.

Recognizing the limitations of scientific databases in capturing the rapid advancements in these evolving fields (Lai and Cole, 2022), the multifaceted nature of the research, and that many phenomena remain underexplored, relevant studies from grey literature were also included.

Furthermore, insights from relevant international forums in the field were also considered. This approach aimed to capture a rich perspective on the current state of the field, thereby allowing a broad interpretation of the developments and interconnections among the related realms.

This phase included a desktop research analysis to map relevant assessment frameworks (i.e. indices, benchmarks, reports, regulation) on digital transformation and sustainability, along with relevant documents from programmes (comitology), policies, and initiatives related to research and innovation at both European and global levels.

Concerning the review of innovation models, a bibliometric network analysis was also employed by using the “VOSviewer” open-access tool (Eck and Waltman, 2023) with data from Scopus. This allowed to map key studies and influential authors, emphasizing the relationships between the foremost works in the field.

Therefore, this approach prioritized the identification, clustering by themes and critical analysis of relevant studies capturing the ongoing debates in these fields and facilitating the generation of both a comprehensive overview, and detailed insights into the theoretical framework, along with the policy, practical, and research implications underlying these discussions.

The collected documents were initially classified based on their specific research themes, followed by a preliminary review to select the most relevant corpus for a more thorough analysis. This facilitated the prioritization of the documents, ensuring the diversity of concepts, and underscoring areas where further integration and focus were needed.

The framework selection for this research followed the methodological processes outlined by Cambridge University (2022), UNDP (2023), and Lai and Cole (2022), all of which provide significant insights for the development of robust assessment approaches.

The number of documents analysed for each research priority is summarised in Table 1.1.

Table 1.1. Number of Documents Reviewed for the SLR of the Different Research Priorities
(Own elaboration)

RESEARCH PRIORITY	NUMBER OF DOCUMENTS REVIEWED
Categorization of the SDG research gaps and the role of digital transformation in tackling them.	670 research articles and grey literature documents
Categorization of the determinant factors for a Sustainable and Regenerative Digital Transformation towards the triple transition.	335 research articles and 355 grey literature frameworks
Sextuple Helix Innovation Model for Regenerative Innovation and the Triple Transition	247 research articles

Subsequently, in the next phase, a qualitative analysis, supported by text mining and visualisation techniques, was conducted on this curated set of documents.

Second phase: Qualitative Analysis

The second phase was focused on the qualitative analysis of the previously selected relevant literature and policy frameworks. First, the identification and categorization of research gaps within the SDG context and the potential role of the digital paradigms were examined to define the subsequent research priorities and directions.

In this regard, three main research priorities were recognised: (i) the identification of the key determinant factors of a sustainable and regenerative digital transformation; (ii) the exploration of novel models and strategies for aligning innovation with digital transformation, and sustainability; (iii) and the formulation of strategic recommendations for enhancing the alignment and co-evolution of these three realms, towards their contribution to the regenerative triple transition.

Subsequently, the analysis was focused on the identification of the key factors that characterise digital transformation and regenerative sustainability from the selected literature and frameworks. This process involved qualitative analysis enhanced by advanced text mining techniques, including topic modelling, keyword extraction, clustering, and network exploration, supported by the software "RapidMiner".

In addition, visualization techniques supported by the "Voyant Tools" application (Sinclair et al., 2016; Gregory et al., 2022), a tool particularly effective in decoding complex phenomena (Fossey, 2002), helped to further interpret the findings.

Hence, the key factors defining SRDT were identified and interpreted in line with the research objectives. Furthermore, they were clustered into 6 main areas, aligned with the pillars of the UN's 2030 Agenda (UN, 2015) and the Digital Development Compass (UNDP, 2021): preparedness embedding the readiness and resilience dimension, planetary sustainability representing the environmental dimension, people reflecting the social dimension, prosperity covering the socioeconomic dimension, peace representing mindful governance, and partnerships encompassing the cooperation dimension.

The entire process was complex and laborious, involving the meticulous handling of a broad array of documents, perspectives, and insights, all of which were distilled into a cohesive and holistic taxonomy framework.

Concerning the exploration of novel innovation models, a comprehensive qualitative analysis of the selected literature, policy, and programmatic documents was conducted. This analysis was further enriched by employing text and content analysis, alongside digital visualization techniques, enabling the identification of patterns and trends within the corpus. Visualization was also facilitated by using "VoyantTools" (Sinclair et al., 2016; Gregory et al., 2022).

This approach provided deeper insights into the interconnected themes, enhancing the overall understanding of the subject matter.

The insights gained from this analysis were crucial for uncovering significant gaps and opportunities, which served as the foundation for the development of the Sextuple Helix Innovation Model, which is presented in the subsequent phase.

Third phase: Development of the Taxonomy for SRDT and the Sextuple Helix Innovation Model

This section describes the constructs developed, beginning with the development of the taxonomic framework, and following with the novel proposal of the helix innovation framework.

Concerning the Taxonomy for SRDT, the insights gained through the previously described analysis, informed the development of this framework, specifically conceived to systematically classify the key domains and thematic factors for a sustainable and regenerative digital transformation.

In this regard, the process of developing a taxonomy can be conducted either semi-automatically or manually, with each approach offering its own advantages and limitations. A manual approach provides direct control over the selection of categories and key terms, thereby allowing a more precise interpretation and flexible adaptation to the specific domain of the study.

However, it can be labour-intensive, particularly in this context, when dealing with a large volume of documents of highly heterogeneous characteristics. In contrast, automatic techniques like topic modelling (e.g. Latent Dirichlet Allocation or LDA), enable the discovery of patterns without predefined categories, thus providing scalability and more efficiency. Yet, automatic techniques can make interpretation more complex and less intuitive.

Topic modelling is an unsupervised machine learning (ML) technique widely employed to uncover hidden themes within large text corpora. Versatile algorithms such as LDA (Silge & Robinson, 2017) and LDavis (Sievert et al., 2014), organize frequently co-occurring words into coherent topics, enabling researchers to easily interpret and analyse complex textual data, thereby promoting efficient learning and dynamic modelling. Yet, they are sensitive to the hyperparameter selection, along with preprocessing and reproducibility issues.

Furthermore, clustering is another unsupervised ML method that groups similar documents using algorithms such as K-means, “Hierarchical Clustering,” and “Density-Based Spatial Clustering of Applications with Noise” (DBSCAN). The effectiveness of these techniques depends on the quality and representativeness of the selected corpus. DBSCAN and K-means are widely used in text analysis to group similar data points. In this regard, K-means is known for its simplicity, efficiency, and effectiveness in identifying well-defined, spherical clusters in large datasets, while DBSCAN excels in detecting clusters with arbitrary shapes and handling noise (Tran et al., 2023); Nanekaran et al., 2022).

Other useful and widely utilized techniques are “Keyword Extraction” with algorithms like “Term Frequency-Inverse Document Frequency” (TF-IDF), and “mBERT” (Qaiser and Ali, 2018), along with “Bag of Words” methods. In addition, many other methods can be applied for text analysis, including text classification (Naïve Bayes, SVM), sentiment analysis, word association analysis, word embedding techniques such as FastText (Grave et al., 2018), Named Entity Recognition (NER), Latent Semantic Analysis (LSA), and network exploration (Cao, 2024).

In this research, a hybrid approach was employed, combining both manual and semi-automatic methods, along with expert judgment. In this way, an iterative process was facilitated, further supported by text analysis and visualization tools, therefore ensuring both a proper interpretation and control over results.

Hence, through this process, three relevant levels were defined. This included a first level with six broad areas, referred to as pillars, considered crucial due to their significance in the research field and alignment with the 2030 Agenda, the Digital Development Compass (UNDP, 2021), and the Digital Global Compact (UN, 2024b).

The second level included 36 domains, and the third level was further divided into 273 thematic factors, forming a unique, and comprehensive taxonomy for SRDT. These three levels provided both a panoramic overview and a granular, detailed approach to support awareness and decision-making in the governance of this complex interplay.

The development of the proposed taxonomy also included an alignment assessment of the suggested domains and factors with the 17 SDGs outlined in the UN's 2030 Agenda, as recommended by Szalkowski et al. (2024). This step was crucial in reinforcing the importance of synergies and convergence between digital and sustainability agendas.

As a result, the proposed taxonomy offers a comprehensive, holistic, and “pluriversal” categorization of the phenomena of Sustainable and Regenerative Digital Transformation, supporting the pursuit of a triple transition. Following the taxonomy development, and to translate the resulting insights into actionable tools, the findings were leveraged to formulate six high-level strategic objectives aimed at advancing Sustainable and Regenerative Digital Transformation (SRDT) towards the triple transition.

Regarding the Sextuple Helix Innovation model, based on the insights from the previous two phases, the Sextuple Helix Innovation Model (6HIM) was developed and substantiated. This conceptual model builds on earlier helix frameworks by evolving the societal systems and integrating additional layers, to better address the complex interplay between innovation, sustainability, and digital transformation, aligning with the regenerative triple transition vision.

Furthermore, it was developed in alignment with the Taxonomy pillars and dimensions, the multi-capital framework (Adams et al., 2017), along with the principles of regenerative innovation and the triple transition. Thus, the proposed 6HIM model provides a conceptual framework to guide innovation in responding to contemporary challenges, emphasizing the appropriate integration of digital and sustainability disruptions with regenerative outcomes.

This phase also involved an alignment assessment to examine how existing R&I programs and communities, particularly within the digital realm, align with the principles and values of the suggested 6HIM approach. As O'Neill and Volkman (2019) argued, the alignment assessment enhances the reliability and legitimacy of evaluations, ensuring that outcomes are accurate and aligned with overarching sustainability goals.

This assessment was based on document analysis, following Bowen's (2009) study, to identify alignment and provide actionable recommendations. It was conducted through an evaluation and documentary review of five R&I initiatives selected for their relevance to this research field: the Horizon Europe Programme (EC, 2021a), three European Digital Innovation Hubs (DIHs) under the Digital Europe Programme (EC, 2024b), and the UNEP's Coalition for Digital Environmental Sustainability (CODES, 2022).

A comprehensive analysis was performed on the Comitology, Work Programme documents and other relevant sources from these initiatives. This process was supported by visualization analysis of the document corpus by using “VoyantTools,” thereby facilitating the identification of patterns and insights across the analysed materials.

Fourth phase: Refinement and Validation

This phase involved the refinement and validation of the proposed constructs through a process based on structured expert elicitation, to ensure the robustness and relevance of the results, enhance transparency and reduce potential biases and methodological limitations.

This elicitation process involved semi-structured interviews (Kvale, 2007), supported by a questionnaire, with fourteen experts in the fields of sustainability, digital transformation, and digital innovation, along with subsequent analysis and interpretation.

Additionally, this process was complemented and enriched through the participation in two international scientific conferences (i.e., ICT4S 2024, and ICSD 2023)², where two articles with the preliminary results were presented.

Further perspectives were gathered through ongoing dialogues with experts and stakeholders within relevant international forums and working groups in the field during the dissertation period. This multifaceted approach aimed to build a comprehensive and well-rounded understanding of the interplay under study, while also addressing methodological limitations. As a result, the proposed constructs were refined and validated. The elicitation process is further elaborated in Chapter 6.

Fifth phase: Discussion and Conclusion

Finally, the results were thoroughly discussed and interpreted within their research context, underlining their implications for science, policy, and practice. In addition, strategic recommendations and future research directions were proposed to advance this promising field of study further.

These strategic recommendations aim to bridge extant gaps and guide present and future agendas and ecosystems towards aligning with the principles of the regenerative triple transition, as embodied in the Taxonomy for SRDT and the 6HIM model. Therefore, the recommendations aim to ensure that both digital and R&I efforts contribute meaningfully to advancing sustainable, resilient, and regenerative systems, ultimately fostering the triple transition. Furthermore, the recommendations also provide insights into how to evolve the UN's 2030 Agenda for robustly embedding the opportunities and risks of digital transformation and regenerative innovation.

Finally, the research revealed further avenues for future research to expand the understanding of SRDT, and regenerative innovation for driving a triple transition.

An overview of the research phases and their components is presented in Table 1.2. and Table 1.3.

Table 1.2. Overview of the Research Phases and Related Activities
(Own elaboration)

RESEARCH PHASE	DESCRIPTION OF ACTIVITIES
Framework Review Systematic Literature Review (SLR) and Desktop Research	• Systematic review of pertinent scientific literature in the fields of sustainability and sustainable development, digital transformation, and innovation. The main databases utilized were Scopus, Web of Science, and Google Scholar. • Review of relevant grey literature frameworks through desktop research in relevant repositories from renowned institutions. • Mapping of measurement and impact assessment frameworks for digital transformation, sustainable development and sustainability, and innovation. • Bibliometric network analysis and visualisation of literature on n-helix innovation models. • Publication years: 1995-2023; several key publications from 2024 have also been included to update relevant aspects with new perspectives.

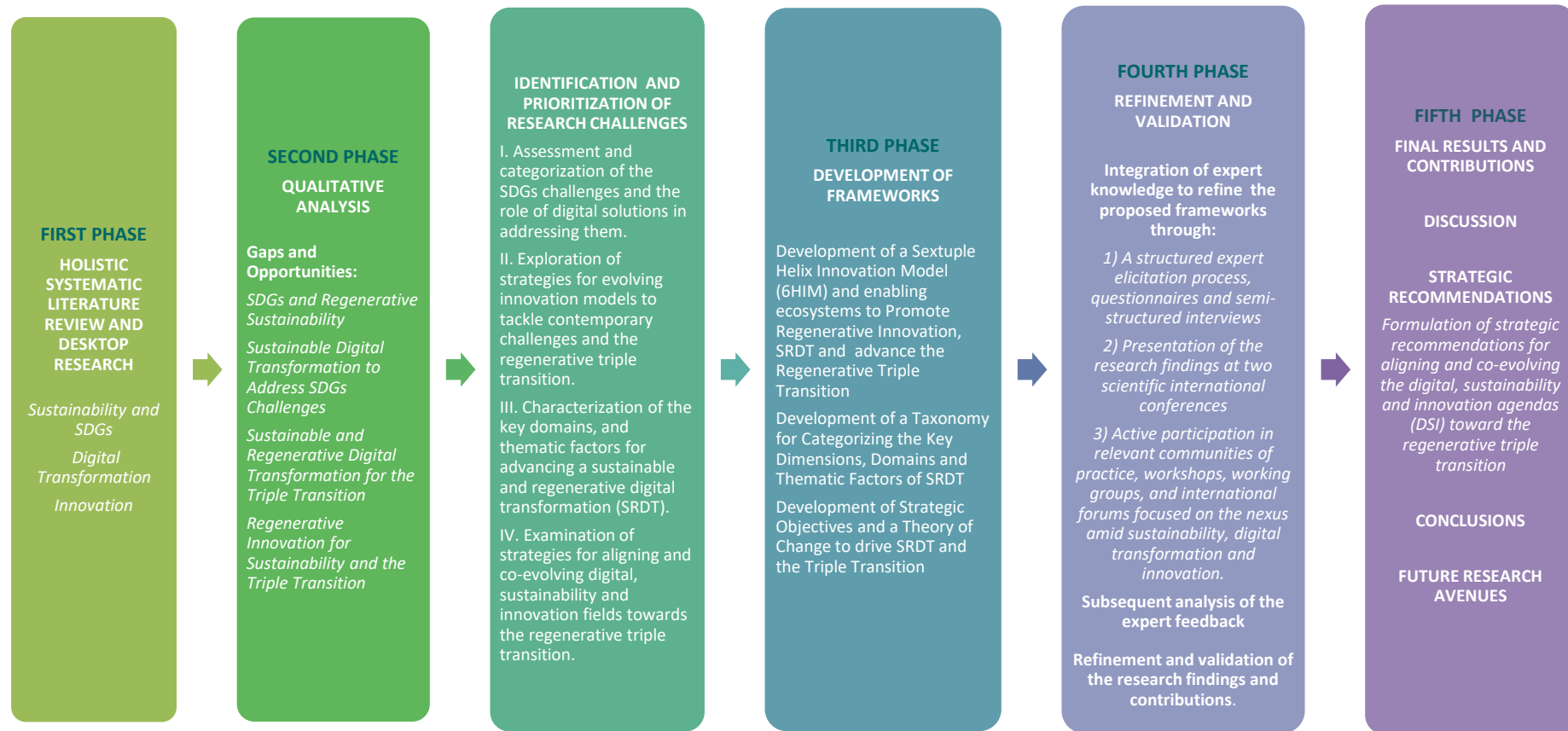
² The 9th International Conference on ICT for Sustainability (ICT4S) 2024, was held from 24th to 28th June 2024 in Stockholm, Sweden; and the 11th International Conference on Sustainable Development (ICSD) 2023, took place from 18th to 20th September 2023, in New York, United States.

	• Scale: micro (organisations, individuals), meso (sectors, cities), macro (regions, nations) • Coverage: worldwide, regional • Main Language: English
Corpus Creation	• Selection of the most relevant frameworks for creating the various corpora of the research (UN's 2030 Agenda and Digital Paradigms for the SDGs; Innovation; and Sustainable and Regenerative Digital Transformation).
Comprehensive Analysis	• Qualitative analysis of the selected documents from the literature review and desktop research outcomes. • Qualitative analysis of relevant dimensions, domains, and thematic factors, along with metrics from the selected frameworks. • Text Analysis of the corpora by combining diverse techniques: Topic Modelling (Latent Dirichlet Allocation, LDAvis); Keyword extraction (TF-IDF, mBERT); Document/Word Embedding (FastText); Network Exploration; Clustering (k-Means). • Clustering of documents based on key pillars, domains, and themes. • Analysis and visualization of document clusters and trends by using Voyant Tools.
Development of the Taxonomy for SRDT	• Rationale and theoretical framework. • Identification and categorization of the three levels (pillars, domains, and thematic factors). • Development of the Taxonomy for SRDT. • Visual representation by RawGraphs (Mauri et al., 2017). • Alignment assessment with existing frameworks (2030 Agenda, UN Digital Development Compass, Digital Global Compass).
Objective Setting and Theory of Change	• Formulation of six strategic objectives for mobilizing action towards SRDT and the triple transition. • Development of the Theory of Change for driving the transition.
Development of the Sextuple Helix Innovation Model	• Rational and theoretical framework • Development of the Sextuple Helix Innovation Model (6HIM) • Alignment Assessment of three existing initiatives against the 6HIM
Structured Expert Elicitation Process	• Questionnaire design • Identification and selection of experts • Semi-structured interviews • Subsequent analysis
Dialogue and Engagement with Stakeholders	• Presentation of a research article at the International Conference for ICT for Sustainability (ICT4S) 2024. Integration of feedback from the scientific committee, experts, and dialogue with the ICT4S community to refine the contributions to the proposed Taxonomy for SRDT. • Presentation of a research article at the International Conference of Sustainable Development (ICSD) 2023. Integration of feedback from the scientific committee experts, and dialogue with the sustainable development and digital transformation communities to refine the contributions to the 6HIM model. • Dialogue and knowledge exchange with experts and stakeholders, gaining insights from the participation in workshops, working groups, and international forums (2019-2024).
Refinement and Validation	• Integration of expert feedback from questionnaires, conferences, and forums. • Refinement of the Taxonomy for SRDT and Strategic Objectives. • Validation of the proposed taxonomy.
Formulation of Strategic Recommendations	• Analysis of findings and conclusions • Strategic recommendations for evolving the digital transformation, innovation, and sustainability agendas towards the regenerative triple transition. • Strategic recommendations for advancing SRDT and the triple transition. • Strategic recommendations for enhancing the implementation of regenerative innovation and the 6HIM. • Identification of future research directions.

Table 1.3. Overview of the Methodological Components
(Own elaboration)

METHODOLOGY COMPONENT	REFERENCES
Systematic Literature Review	Albert (2019); Snyder (2019); Vom Brocke et al. (2015); Cooper (1989)
Bibliometric Network Visualization	VOSviewer by Van Eck and Waltman (2023)
Desk Research and Framework Selection	Mohamad et al. (2023); Digital Development Compass UNDP (2021, 2023); DESI Index (EC, 2023d); Lai et al. (2022); Competitive Sustainability Index by Cambridge University CSIL (2022).
Qualitative Analysis	Saldaña (2013); Mohamad et al. (2023); Mayring (2014); Kvale (2007)
Taxonomy Development	Nickerson et al. (2013); Hermman et al. (2023); Saidani et al. (2019); Mohamad et al. (2023).
Text Mining	LDA (Silge and Robinson, 2017); LDAvis (Sievert et al., 2014) FastText Word Embedding: Khomsah et al. (2022); Agustiniingsih et al. (2022); Galea et al. (2018); Grave et al. (2018); Gupta et al. (2019) TF-IDF and mBERT: Qaiser and Ali (2018) LSA: Goulart (2018); Wang and Zheng (2013) Network exploration: Cao (2024); Čeněk et al. (2019); Townend (2017); Lee (2014b) Clustering (K-means): Tran et al. (2023); Nanehkaran et al. (2022)
Visualisation	VoyantTools by Sinclair et al. (2016); Gregory et al. (2022); RawGraphs (Mauri et al., 2017); RapidMiner (n.d.)
Helix Model Development	Carayannis et al. (2012)
Alignment Assessment and Content Analysis	MSCI SDG Alignment Methodology (2024); OECD Alignment Assessment Methodology (n.d.); O'Neill and Volkman (2019); Bowel (2009)
Objective Setting	Thinyan et al. (2022); Zhou et al. (2018); John Doerr (1999)
Theory of Change	Bommasani et al. (2023); UNDP (2021); DGRA Index (World Bank, 2022); Motion Project (2022)
Expert Elicitation Process	Hemming et al. (2018); Hadjigeorgiou et al. (2022); Bojke et al. (2021); Kvale (2007);
Participatory Research	Digitainable Project by Bonn Alliance (2019-2022)

Figure 1.2. Methodology Scheme of the Dissertation
(Own elaboration)



1.7. Overview of the Research Contributions

This section introduces an overview of the principal research contributions developed within the frame of this doctoral thesis and their relationship with the proposed research questions (see Table 1.4). These contributions provide a comprehensive understanding and structured frameworks to address the complex interplay between digital transformation, sustainability, and innovation, with a focus on advancing the regenerative triple transition (digital, environmental, and socially just). Furthermore, they aim to bridge existing knowledge gaps, while providing actionable insights and strategic directions to guide this promising transformation, as a foundation for advancing research, policy, and practice in the pursuit of a regenerative and inclusive future.

Table 1.4. Overview of the Research Contributions

(Own elaboration)

RESEARCH CONTRIBUTION	RESEARCH QUESTION	CHAPTER
RC1: Categorization of the research gaps and opportunities within the SDG framework, along with the role of digital paradigms in addressing these challenges.	RQ1: What are the overarching research gaps within the SDG framework, and to what extent can digital paradigms and solutions contribute to responsibly addressing them and accelerating progress towards achieving the UN's 2030 Agenda?	<i>Chapters 2 and 3</i>
RC2: Proposal of a Taxonomy for a Sustainable and Regenerative Digital Transformation (SRDT).	RQ2: What are the key determinant factors driving a sustainable and regenerative digital transformation, and how can they be categorised into a comprehensive taxonomy and objectives to enable decision-making in this direction?	<i>Chapters 5, 6 and 7</i>
RC3: Proposal of Strategic Objectives and a Theory of Change for driving SRDT in the pursuit of the Triple Transition.		
RC4: Proposal of Sextuple Helix Innovation Model and enabling ecosystems to promote regenerative innovation and support the triple transition.	RQ3: How can helix innovation models and ecosystems be reoriented to effectively support regenerative innovation and systemic resilience, and drive progress towards the triple transition?	<i>Chapter 4</i>
RC5: Proposal of Strategic Recommendations for aligning, synchronizing, and co-evolving the agendas of digital transformation, sustainability, and innovation towards the regenerative triple transition.	RQ4: What strategic recommendations can guide the alignment, synchronization, and co-evolution of digital transformation, sustainability, and innovation agendas towards the realization of a regenerative triple transition?	<i>Chapter 8</i>

The next chapter explores the evolution and conceptual foundations of sustainability and examines the Sustainable Development Goals (SDGs) under the UN's 2030 Agenda, identifying their challenges and opportunities.

2. The Evolution of Sustainability towards Regeneration

2.1. An Introduction to Sustainability: Significance and Controversies

This section introduces the concept of sustainability, tracing its origins and historical development, analysing its significance, addressing its caveats and controversies, and concluding with the emergence of regenerative sustainability.

2.1.1. Origins and Historical Development of the Sustainability Concept

In contemporary discourse, sustainability has transcended mere environmental concern to become a moral and economic imperative (Fullerton, 2015). This shift is driven by the recognition of the intricate interplay between nature, society, and businesses, as evidenced by research by Kiron and Unruh (2018), Marcus et al. (2010), and Bolis et al. (2021). Increasingly, the valuation of any organization is contingent upon its ability to navigate and positively impact these interconnected realms.

Success, therefore, is no longer solely gauged by economic metrics, as underscored by thought leaders such as Fullerton (2015) and initiatives like the UN Global Compact and Accenture (2019). Today, a comprehensive understanding of sustainability is essential for businesses to thrive amidst evolving societal expectations, regulatory frameworks, and environmental challenges.

Paradoxically, despite growing awareness and discourse around sustainability, the reality paints a starkly different picture, where the world finds itself far from being a sustainable place. This dissonance between acknowledgement and action stems from numerous factors. While sustainability has gained traction as a principle, its implementation often falls short due to the complexities of global governance, competing priorities, and short-term thinking prevalent in many sectors. The Global Resources Outlook 2024 report by UNEP (2024a) underlined the escalating consumption of natural resources by the global economy, exacerbating the triple planetary crisis of climate change, biodiversity loss, and pollution, with a disproportionate impact on human well-being and inequality.

Indeed, unsustainable behaviours remain or worsen (Kopnina, 2020; Osburg and Lohrmann, 2017), leading to growing threats (Priyadarshini and Abhilash, 2018; Yingchun et al., 2018). Progress to date has not prevented the damage to the environment (Leal-Filho et al., 2018; Sabau, 2020). According to the World Economic Forum (WEF, 2024b), environmental-related threats outrank the rest of global risks.

The Anthropocene trajectory has placed intense pressure on earth systems, due to the supremacy of economic growth at the expense of environmental and social degradation (Kopnina, 2020; Steffen et al., 2015), causing supply problems, along with economic and ecological damage (Kopnina, 2020; Osten et al., 2017). A conspicuous stagnation of sustainable development is revealed, a divide between intention and poor adoption, known as the “sustainability gap” (Dyllick and Muff, 2016; Seele, 2016a).

Numerous experts argue that the concept of sustainable development (SD) is an oxymoron (Spaiser et al., 2017), a powerful but idealistic umbrella (Shahadu, 2016) made of multiple competing interests, demanding sound management and methodologies. The boundaries of the sustainability conception have been built without a systemic perspective (Lozano, 2015). Decades of fragmented research and divergent theories have contributed to a feeble status, full of misconstructions. Even when sustainability science has impacted the research landscape, by shedding light and bridging gaps amid disciplines, it remains in its infancy (Elsevier, 2015), as a “niche field” (Messerli et al., 2019).

Sustainability problems remain unanswered (Köhler et al., 2019), being considered wicked (Capasso et al., 2019) and deserving innovative approaches, particularly in the social sphere (Kirschke and Newig, 2017). Significant efforts have been devoted to defining sustainability, supported by a vast literature.

However, the concept is controversial (Köhler et al., 2019) and it has been so often misused, that the actual meaning is weakened. Even when it could allow different views, the current lack of consensus undermines its realization (Waas et al., 2011). Attaining sustainability will require interactive efforts among disciplines, which have not yet been embraced, since research remains silo-based (Bergman et al., 2018). Thus, an integrated and more consistent approach is urgently needed (McMichael et al., 2003).

Foremost concepts of sustainability and SD were formed at the beginning of the XX century onwards (De Oliveira Neto, 2018), even though early notions are much older (Waas et al., 2011). The SD concept became popular and gained momentum with the publication of the mythic “Brundtland report,” from the World Commission on Environment and Development (WCED, 1987). Yet even nowadays it remains poorly understood (Mensah, 2019; Shi et al., 2019), challenging policymakers and scientists (Ramcilovic-Suominen and Pülzl, 2018).

From then on, sustainability has inspired intense and controversial debates, evolving together with a sound body of theories and myriads of definitions. Two relevant milestones were put forth by Freeman (1984), author of the “theory of the stakeholders” and (Elkington, 1997) who proposed the renowned “triple bottom line”. Another iconic milestone was the “Earth Charter” (2000), a transformative framework towards a sustainable, just and peaceful society. Rockström et al. (2009) coined the “planetary boundaries” frame, where sustainability is conceived as the ability to stay within 9 ecological carrying-capacity thresholds.

During the 1980s ecological sustainability was the focus (Osburg, 2017). This narrow emphasis on ecology caused counterproductive conflicts with the dominant social and economic realms, jeopardizing sustainability as a whole (Bergman et al., 2018). In the 1990s, the perspective evolved, pursuing reconciliation amid environmental, economic, and social dimensions based on the ‘triple bottom line’, coined by Elkington (1997). Currently, the climate crisis outranked the rest of the ecological concerns. Recently, new dimensions have been added, namely the cultural aspects and a 4th pillar of good governance (Shi et al., 2019).

Daly et al. (1995) put forth a novel classification: weak, intermediate, and strong sustainability based on diverse types of capital. In weak sustainability, economic, natural, and social capitals are substitutes. In intermediate sustainability, natural capital could be partially substituted. Strong sustainability is featured by an economic vision able to preserve natural and social capital (De Oliveira Neto, 2018). Neumayer (2010) enhanced this definition based on indicators such as: “genuine savings, sustainable economic welfare indexes, ecological footprints”. Shi et al. (2019) argued that strong sustainability should be the preferred concept.

However, it remains unaddressed in the literature, lacking specific actions (Osburg, 2017). Chang (2017) remarks on the relevance of Corporate Social Responsibility (CSR) while Hazen et al. (2016) examined theories such as social capital, institutions, agency, and actor-network.

Lastly, the UN 2030 Agenda adopted in 2015, constitutes the most ambitious, goal-based, and universal blueprint for sustainability ever in the history of humanity. Nonetheless, sustainability is currently undergoing a “winter” of self-reflection and realignment to adapt to the new expectations of the future.

Defining sustainability is overly complex, due to its holistic character, normative dimension, scale dependence and multiple facets. Hence, a universal concept remains “elusive” and controversial (Bergman et al., 2018; Köhler et al., 2019; Waas et al., 2011; White, 2013). Sustainability entails both means and ends, it is a process and a destination, a sort of philosophy with diverse communities (Johnston et al., 2007) stemming from multiple fields (Zamora-Polo et al., 2019).

Boundaries are not clear, going beyond theory and predisposed to interpretation (Köhler et al., 2019). Therefore, it cannot be fully empirically proven without context-based interpretation (Waas et al., 2011).

Caradonna and Ingram (2015), Glavic and Lukman (2007), Pater and Cristea (2016) and Waas et al. (2011), provided reviews about the evolution of the concept and terminology, which has been classified into functional definitions associated with "sustainable development" and systemic approaches (Pater and Cristea, 2016). Köhler et al. (2019) took stock of research trends and future avenues in the field of sustainability transitions.

Despite lacking a universally agreed definition, most scholars concur on the fundamental principles in which sustainability is founded, namely: normativity, equity, integration, and dynamism (Waas et al., 2011). Sustainability brings a notion of durability and futurity, harmonic co-existence of nature and humanity, preservation, equality and fairness, respect, and protection of what is valuable, equitable and efficient resource allocation and environmentalism (Basiago, 1995; Costanza and Patten, 1995).

Resilience (Roostaie et al., 2019) and trust (Osburg, 2017; Wenzel, 2017) are also highlighted in recent studies together with de-growth (Caradonna and Ingram, 2015) and circularity (Antikainen and Bocken, 2019; Schroeder et al., 2019; Weissbrod and Bocken, 2017).

The most agreed concept relies on the balanced articulation of three pillars: social, environmental, and economic. Munasinghe (2004) suggested that sustainability can be regarded as the process of improving human progress while maintaining the resilience of the economic, social, and environmental systems.

While environmental sustainability is linked to the ecosystem's capacity to preserve its purposes in the long term, economic sustainability is perceived as a "normative concept" related to the capacity to efficiently and responsibly optimise the use of available resources to maximize profitability over time (Osburg, 2017). In addition, social sustainability entails society's willingness to endure community well-being, equity, and intergenerational justice, interrelated with trust and ethical behaviour (Osburg, 2017).

Boyer (2016) underscored that the social domain remains overlooked and suggested applying a context-based systemic approach to sort out wicked problems associated with sustainability. Osten et al. (2017) stated that even in common-pool resource systems characterized by social dilemmas and conflicting interests, sustainability is possible. Wenzel (2017) set forth the "System Capacity Horizon (SCH)" meaning that sustainability is an evolving concept, a role model for success spiral, defining a "target function of life" constrained by system boundaries (ecological, social, or financial).

Emerging schools of thought claim for an urgent major transformation to overcome inertia, de-growth progress (Caradonna and Ingram, 2015) and shift towards a "conscious capitalism" (Mackey and Sisodia, 2013). Martinuzzi and Schönherr (2019) analyse corporate sustainability from the early philanthropic focus to the future data-driven, systemic, goal and impact-based frameworks embedded within the organisations' purpose.

Indeed, sustainability should be regarded from a holistic, systemic, inter-disciplinary and forward-looking perspective (Ben-Eli, 2018) keeping a balance between the development and preservation of nature and communities (Kates et al., 2001). Scholz et al. (2018) conceive a systemic perspective based on: "transdisciplinary inquiry, systemic limits, inter-intragenerational justice".

Conventional theories and fragmented constructs are not sufficient to trigger the desirable changes towards reconciling progress, people, and the planet. Therefore, novel holistic models are required to embed added-value sustainability in the very heart and purpose of every organisation (Bocken et al., 2014; Patala et al., 2016) and human beings.

2.1.2. Unravelling the Caveats of the Sustainability Concept

Vogt and Weber (2019) critiqued the widespread misunderstanding of the sustainability concept, warning against the pitfalls of "green hypocrisy." They propose a rehabilitation of sustainability based on seven dimensions, stressing the interconnectedness of ecological, social, and economic factors. Their call for interdisciplinary analyses and systemic thinking aims to foster a more holistic understanding of sustainability.

Contrastingly, the World Economic Forum (WEF, 2024b) while emphasising digital-related risks, fails to adequately connect them to environmental concerns. This disconnect is concerning given the proliferation of misinformation about climate change in cyberspace, underscoring the need for a more integrated approach to risk assessment.

Wiek et al. (2012) shed light on the hurdles faced by sustainability scientists and emphasize the importance of collaboration, transformative change, and academia's role in bridging the gap between science and society.

Samuel et al. (2022) cautioned against the ambiguity surrounding sustainability, warning against equating it solely with Environmental, Social, and Governance (ESG) measures. They pointed out the inadequacy of current conceptual frameworks and the challenge of addressing indirect impacts from global supply chains.

Gonzalez-Marquez and Toledo (2020) argued that the global socio-environmental crisis necessitates the emergence of sustainability science as a consolidated research field. They illustrated how sustainability science has followed Kuhn's model of scientific revolutions but highlighted a general insufficiency in problem-solving power within the field. Early signs of a paradigm crisis are identified through empirical data, emphasizing the need for a critical revision of these sustainability foundational premises to drive radical qualitative leaps in addressing urgent contemporary challenges.

2.1.3. The Emergence of Regenerative Sustainability

Integrating novel perspectives on regenerative approaches can foster a visionary shift towards long-term sustainability. Indeed, regenerative sustainability emphasizes the need to reconnect and maintain human society and nature in harmony, by promoting net-positive impacts across ecological, health, and social dimensions. This paradigm integrates concepts like "triple net-zero" (net-zero energy, water, and waste), health-focused and wellness design, and social equity, forming a flexible and evolving framework. It also relies on continuous feedback loops and cohesive management practices, thereby enabling ongoing learning and adaptation to enhance the health and resilience of ecosystems and communities.

The term "regenerative" was originally coined by R. Rodale to describe the ongoing organic renewal of soil life in the context of land use, particularly in organic farming practices (Lyle, 1994). This concept implies the continuous replenishment of complex soil life without relying on agrochemicals, highlighting the inherent self-renewal capacity present in natural systems. This notion of self-renewal extends beyond agriculture to encompass all systems that support life, emphasizing the transition from linear to cyclical flows in design and resource management.

Despite its modern application, the concept of regenerative systems precedes the industrial age and has persisted throughout human history. Lyle (1994) explored regenerative systems as fundamental to achieving sustainable development objectives. He underscored the importance of self-renewing processes where end products serve as raw materials, offering a practical guide to implementing regenerative principles across various domains such as energy, water, agriculture, and building design.

Lyle (1994) also advocated for interdisciplinary collaboration to integrate these systems effectively, emphasizing their essential role in advancing sustainable development.

Certainly, the concept of regeneration has been more commonly used in the urban sphere and, initially, in agriculture and permaculture, although they are currently expanding across all disciplines. In this sense, it is closely related to nature-based solutions, biomimicry, and ecosystem services, as well as other more spiritual or philosophical concepts, such as the rights of nature, the central concept of ecology, or the Gaia hypothesis.

Furthermore, regeneration is related to the debate about the limits to growth (Meadows et al., 1972). For instance, Sachs (2022) reflected on the emergence of initiatives like “Regeneration 2030”, which advocates for more holistic, ethical, and sustainable business practices aligned with the UN’s 2030 Agenda. In addition, Sachs called for a transformation in economics and science toward a more holistic approach recognising the interplay between economy, ethics, sustainability and the common good.

Similarly, Mang and Reed (2012) underlined the urgent need for radical changes to ensure Earth’s continued suitability for human habitation calls for a shift in worldviews from mechanistic to ecological perspectives. Fullerton (2015) asserted that global challenges, such as climate change, inequality, and financial crises, have sparked a re-evaluation of traditional capitalism, which is unsustainable and exacerbates social and environmental problems.

Yet, there is a growing movement of innovators seeking to reimagine capitalism to benefit society and the planet. Their goal is to create a regenerative form of capitalism that promotes long-term social and economic vitality for global civilization. In this regard, it is questioned whether perpetual economic growth is truly sustainable given finite resources and examines the role of modern finance in driving unsustainable outcomes. Regenerative capitalism seeks inspiration from living systems, which are sustainable and regenerative over time. It draws on holistic approaches from various fields, including urban planning, economics, and technology, aiming to transform capitalism into a network of balanced, vibrant, and regenerative economies.

While some may view this framework as idealistic, others argue that it does not go far enough. Nevertheless, it serves as a bridge between the prevailing capitalist system and the emerging paradigm of regeneration. Unlike traditional models, this approach prioritizes fostering healthy human networks as its central objective, rather than merely addressing social and environmental issues through reductionist, problem-solving methods. Instead of viewing sustainability as the end goal, it considers it as an inherent outcome of promoting systemic health. Certainly, true wealth transcends mere financial assets and encompasses a holistic perspective that considers various forms of capital, including social, cultural, living, and experiential wealth.

Another perspective is provided by Gibbons (2020), who argued that, over time, sustainability paradigms have progressed from addressing immediate human needs to enhancing human well-being and ecological system viability. Regenerative sustainability represents the next evolutionary step, transcending these goals by striving for thriving living systems where overall health and well-being continually improve.

In contrast to earlier paradigms, regenerative sustainability is grounded in a holistic worldview that integrates insights from science, practice, diverse forms of knowledge, and both inner and outer dimensions of sustainability. It aims to harmonize human consciousness and actions with principles of living systems. Embracing regenerative sustainability offers holistic approaches rooted in the functioning of thriving living systems, addressing the underlying causes of sustainability challenges, while fostering inspiration and motivation.

Nevertheless, advancing regenerative sustainability requires fundamental shifts supported by increased awareness, education, theoretical and practical development, leadership, community empowerment, and spiritual integration.

Therefore, regenerative sustainability emerges as the next evolution of sustainability paradigms, surpassing conventional and contemporary approaches by adopting a holistic worldview. It integrates diverse disciplines, novel science advancements, and ancient wisdom to manifest thriving living systems at all scales. Regenerative sustainability views humans and nature as interconnected systems, aiming for alignment with principles of wholeness and change. This paradigm shift emphasizes the dynamic nature of communities and the need for continual regeneration and hinges on key capacities such as adaptation, self-organization, and holistic decision-making.

Rather than problem-solving, regenerative sustainability sees living systems as evolving along a continuum of health and complexity. Acknowledging the influence of inner and outer dimensions, regenerative sustainability integrates both aspects for transformational change. Practices like regenerative development operationalize these principles, paving the way for transformative change towards thriving living systems.

Cole et al. (2013) argued that regenerative design emphasizes the interconnectedness of socio-cultural and ecological systems, demanding a conscious consideration of the future implications of design decisions. This study initiated a discussion on how socio-cultural and ecological systems co-evolve and connect to regenerative design concepts to enhance the theoretical underpinnings of regenerative design in the built environment.

Moreover, the concept of regeneration is strongly associated with the “handprints” and “net-positive” notions. Norris et al. (2021) presented the “Sustainability and Health Initiative for Net-Positive Enterprise” (SHINE) project and introduced the concept of “handprints” as a measure of transformative positive changes relative to business-as-usual (BAU) practices. Indeed, handprints represent voluntary efforts by organizations not only to reduce their own ecological footprints but also to influence and diminish the footprints of others, creating a ripple effect of positive change.

The “SHINE handprint” framework utilized dynamic life cycle assessment (LCA)-based modelling to quantify handprints, measured in units related to footprint impact. This framework follows a systematic process of defining scope, conducting inventory analysis, assessing impacts, and interpreting results, aligning with traditional LCA methodologies. However, it diverges by incorporating both the baseline business-as-usual (BAU) footprint and the positive actions taken by the actor within the system boundary.

Cole (2015) examined regenerative sustainability as a net-positive approach grounded in procedural sustainability and constructivist social theory. This perspective emphasized iterative processes and socially constructed pathways toward sustainability. While it shares similarities with regenerative development and design, often rooted in systems thinking and ecological principles, it differs in its more philosophical perspective.

The origins of regenerative sustainability and regenerative design in social and ecological domains respectively highlight the importance of understanding their relationship for the co-evolution of human and natural systems.

The discourse on regenerative business models seeks to distinguish them from concepts like sustainability and circular business models, emphasizing a focus on social-ecological systems and planetary health. In this regard, Konietzko et al. (2023) examined the discourse surrounding regeneration within organizational studies, seeking to elucidate its distinguishing characteristics.

Through literature reviews and focus groups with international and Indigenous participants, the study identified key features of regenerative business models. The regenerative models prioritized planetary health and societal well-being, delivering value across multiple stakeholder levels through activities like regenerative leadership and partnerships with nature. This study also underscored the need for robust policy frameworks and further research to integrate intrinsic value considerations and avoid greenwashing in adopting regenerative and net positive impact narratives.

While sharing design approaches with sustainability and circularity, regenerative models diverge in goals and systemic perspectives. The prevailing perspective on sustainable business models emphasized socio-technical systems at various levels of organization and society, focused on mitigating negative impacts on the environment and affected communities. Circular business models align closely with this view, aiming to enhance resource efficiency and circularity to minimize environmental impact by reducing material and energy throughput.

In contrast, regenerative business models adopt a social-ecological systems perspective, emphasizing the interdependence of natural ecosystems and human societies while prioritizing health and well-being. Inspired by the Gaia hypothesis (Lovelock, 1988), these models conceptualize the planet as a self-regulating organism, paralleling social-ecological systems to biological entities composed of interconnected components. They aim not only to reduce negative impacts but to redefine the relationship between humans and nature, incorporating individual purpose, leadership, spirituality, and Indigenous wisdom (Berkes et al., 2000).

Furthermore, regenerative businesses can pursue net-positive impact by optimizing multi-capital and impact accounting, aiming to ensure that their positive ecological handprint outweighs their footprint (Muñoz and Branzi, 2021; Polman and Winston, 2021). They prioritize equity, fairness, and the rights of nature and animals, co-creating products and services that promote human and environmental health (Perey and Benn, 2015). Drawing from Indigenous wisdom and nature-inspired design, they enhance resilience and climate adaptation while channelling financial returns to enhance natural capital (Buono, 2020; Gardner et al., 2022).

However, the concept of regenerative business models remains ambiguous, with diverse interpretations and overlaps with sustainable and circular models (Morsetto, 2020; Tedesco et al., 2022). Regenerative, sustainable, and circular models converge on design efforts aimed at different spheres: regenerative and circular focus on the biosphere, sustainable and circular on the techno-sphere, and sustainable and regenerative on the human-sphere (Konietzko et al., 2023).

Indeed, the current global challenges, particularly, the anthropogenic impacts like climate change, exert unprecedented pressure on ecosystems, pushing beyond planetary boundaries with uncertain consequences for the Earth's regenerative capacity. This underscores the urgent need for effective intervention to shift away from the current unsustainable approach.

Despite these overlaps, regenerative business models represent a paradigm shift towards prioritizing planetary health and societal well-being, challenging the prevailing linear economic models, and emphasizing the need for regeneration in the face of environmental degradation (Dasgupta, 2021; Robinson and Cole, 2015).

Regenerative sustainability advocates for a balanced, less anthropocentric relationship between humans and nature, drawing on ancestral values often overlooked in modern society. It envisions an equal-to-equal partnership between humans and nature, in contrast to the prevailing consumerist culture. While sustainability itself is complex, with goals like climate neutrality posing significant challenges, transitioning to a regenerative society is even more daunting.

Despite the sustainability holistic approach, implementation often remains anthropocentric, prioritizing socioeconomic concerns over environmental ones. True regeneration necessitates overcoming these tensions and equally valuing ecological and social considerations.

According to Gerhards and Greenwood (2021), governance instruments aimed at promoting sustainability have evolved, incorporating voluntary measures that blend sustainability guidance with marketable public information like certifications and ratings. While these instruments traditionally relied on standardized criteria, recent literature highlights the importance of context-sensitive and systems-based, or “regenerative” approaches.

This study focused on the “One Planet Living” framework in the UK and evaluated these contrasting approaches by applying the concept of legitimacy, commonly used in product certification, to this broader range of governance instruments. Standardized approaches have shown success in uptake but often at the expense of other legitimacy aspects like program effectiveness and informational quality. Therefore, there is a growing need to evaluate established instruments from a regenerative perspective and develop more scalable and effective regenerative approaches.

Mang and Reed (2012) underlined that, in the built environment sector, which significantly impacts global resources and systems, design practitioners play a crucial role in facilitating the transition towards regenerative sustainability. This can be achieved through the development, application, and evolution of comprehensive methodologies explicitly shaped by a regenerative sustainability paradigm. To successfully transition to a regenerative practice, practitioners must not only adopt new techniques but also embrace a new role and mindset, learning to work developmentally.

Cole (2012) argued that the concept of regeneration, implying renewal and transformation, has historically been applied to build environments after devastation or decline, marking a commitment to rebuilding with new aspirations. Recently, regeneration has gained traction in reframing green building practices with broader connotations, focusing on the co-evolution of human and natural systems.

This growing prominence of regenerative design stems not only from dissatisfaction with existing assessment methods like LEED but also from a convergence of historical threads and the integration of long-standing architectural principles into a coherent framework. Central to regenerative design is the shift in prevailing paradigms, challenging existing worldviews and offering a holistic approach to sustainable development.

Regarding the alignment of regenerative sustainability and the SDGs, a few studies have explored this complex connection. According to Gibbons (2020), the novel alignment brought by regenerative sustainability elevates sustainable development goals to regenerative development goals, with specific indicators and strategies co-created through transformative processes tailored to each location.

Ibrahim and Ahmed (2022) examined the transition from traditional sustainability to regenerative practices as a response to escalating ecosystem degradation and climate change challenges. While traditional sustainability encompasses social, environmental, and economic aspects, it falls short of adequately addressing these global issues.

Regeneration is defined by Ibrahim and Ahmed (2022), as an intentional healing and rejuvenating process that restores the balance and harmony between human systems and nature, aiming to create long-term social and natural capital through cooperative interactions between natural ecosystems and people. This study proposed nine regenerative development goals (RDGs) aligned with the SDGs to ensure complementarity.

The challenge extends beyond semantics, as it involves addressing fundamental issues such as existing structures, the lack of holistic system integration, and the prevailing anthropocentric and economically driven perspectives (Ibrahim and Ahmed, 2022). Further research is suggested to develop educational programmes and assessment tools for evaluating built environments based on the RDGs and SDGs.

However, the proposed RDGs do not significantly differentiate themselves from the existing SDGs. They lean more towards conceptual aspirations rather than practical realization, a vague concept without consensus or clear implementation strategies.

Renaming efforts are not sufficient to address sustainability challenges. Achieving true progress requires a paradigm shift towards comprehensive sustainability, recognizing the intricate interconnections between social, environmental, and economic factors. This shift demands dismantling unsustainable practices and cultivating new models that prioritize regenerative approaches and equitable outcomes for both humans and the planet. Thus, a deep transformation in values, systems, and behaviours is urgently needed, transcending superficial changes in terminology.

Sonetti et al., (2019) discussed the evolution of sustainability concepts, emphasizing a transition towards a regenerative paradigm that goes beyond meeting current needs to restoring environments and communities. They also advocated for a novel definition of sustainability that embraces humanistic and ecological values, emphasizing the importance of social and behavioural change in addressing global environmental challenges. According to these scholars, the SDGs play a key role in promoting this shift by promoting proactive global social goals and a more interconnected relationship between human development and environmental health (sustainable well-being).

Nevertheless, challenges remain regarding current practices and regenerative approaches. For instance, extant approaches focus on renewable energy and carbon remediation, while regenerative strategies prioritize ecosystem restoration and holistic urban design. Sonetti et al., (2019) also underlined the importance of education, particularly bottom-up approaches, in driving regenerative behaviours and fostering eco-literacy.

Figure 2.1. visually illustrates the evolution from the conventional concept of sustainability to the novel vision of regeneration, based on holistic thinking, regenerative design, and the harmonious co-existence of societal and natural systems.

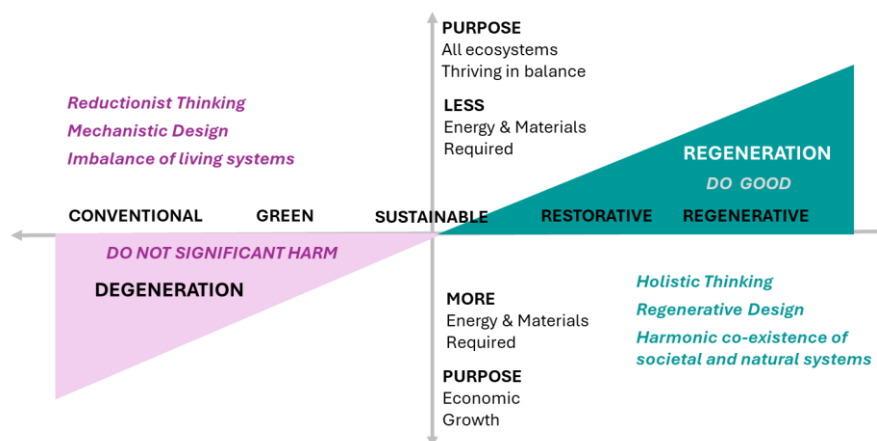


Figure 2.1. Evolution from Sustainability to Regeneration
Own elaboration, based on Fullerton (2015)

Concerning the implementation of regenerative practices in the realm of digital transformation, it is still incipient with little empirical evidence.

In this regard, Sonetti et al., (2018) explored the integration of technologies such as artificial intelligence to enhance the relationship between buildings and their inhabitants, aiming for socially just, ecologically regenerative, and economically viable cities. Through the Human Observation Meta-Environment (HOME) project, researchers tested an ICT architecture in a sentient room to observe human behaviour data. AI methods like Natural Language Analysis and Computer Vision were used to analyse user comfort, aligning with regenerative design principles. The study underlined the importance of incorporating user needs in designing spaces and smart systems, with interdisciplinary insights from a workshop on potential impacts. Overall, this study contributed to understanding how ICT data can inform human-centric regenerative design processes.

Similarly, Hyun Woo et al. (2020) developed evaluation indexes for sustainable urban regeneration plans, focusing on integrating smart technologies. They found that most plans lack sufficient consideration of smart technology-related information and policies. While implementation receives high scores, action strategies are often overlooked, with energy and transportation sectors particularly neglected. This study also emphasized the importance of multi-faceted policies and long-term perspectives for sustainable urban regeneration through smart technology initiatives.

The heart of the matter lies in the lack of awareness, adoption, and insufficient drive for transformation. Resistance to change, rooted in entrenched economic and anthropocentric views, obstructs sustainable development. While regeneration is crucial, it is just one aspect of the broader sustainability paradigm, which already integrates social, environmental, economic, and governance dimensions.

Debating terminology distracts from real challenges since sustainability inherently means doing good and safeguarding the planet and people. Prioritizing action over semantics is essential to address urgent issues. Redirecting efforts towards concrete actions advances sustainability and promotes well-being for both people and the planet.

A compelling argument countering the belief that regeneration represents a departure from sustainability is also presented. Rather, sustainability encompasses fostering positive change for both humanity and the planet, including concepts like regeneration and the circular economy under the umbrella of strong sustainability.

In the rapidly evolving society, novel trends are always emerging, from conscious capitalism to regenerative development, these concepts all stem from the core principles of sustainability. Regeneration reaffirms the commitment to creating positive change, emphasizing the interconnectedness between nature and humanity, and striving for a more balanced and harmonious relationship between them.

2.2. The Rationale of the Sustainable Development Goals

2.2.1. Background of the United Nations 2030 Agenda

In 2015, two historical global agreements came into life, bringing unprecedented consensus, for making true a sustainable inclusive development within the planetary and social justice boundaries: the COP21 Paris Agreement (UNFCCC, 2015) together with the adoption of the resolution “Transforming our World: the 2030 Agenda for Sustainable Development” (UN, 2015a). Both represent a strategic compass and outstanding opportunity, not exempt from challenges, for building up an inclusive and sustainable future by the 2030 horizon.

The 2030 Agenda consists of 17 goals, 169 targets, and 231 indicators, supported by 5 pillars: planet, people, peace, prosperity, and partnerships. It represents a promising blueprint for curbing the excruciating “anthropogenic effects on the planet” (Osburg and Lohrmann, 2017), pursuing global governance and transnational policy coherence (Dalby et al., 2019; Kanie and Biermann, 2017).

Building on the Millennium Development Goals (Sachs, 2012) and a result of a broad participatory process (Saito et al., 2017), the Agenda aspires to be action-oriented, indivisible, multidisciplinary, inclusive and universally applicable, by integrating the three pillars of sustainability: economic, social and environmental (Biermann et al., 2017; Cheong, 2017; European Union, 2019a; Kanie and Biermann, 2017; Osburg and Lohrmann, 2017). It fosters goal-based and non-binding governance, relying on a flexible compliance nature (Biermann et al., 2017), which will require unique global cooperation (Dalby et al., 2019). The SDGs are carriers conveying interventions and policy constructions, advocating for priorities and values, and mobilizing action towards them (Ala-Uddin, 2019; Fukuda-Parr and McNeill, 2019).

Furthermore, the Agenda aims to comprise relevant trends, such as the fourth industrial revolution, the impulse for a circular economy and responsible use of resources, the equality and gender dimension or the need for enhancing trust. It offers a novel perspective to transform global needs into solutions to societal challenges (WBCSD, 2019a), evolving towards a strong sustainability that preserves natural and social capitals within the planetary boundaries (Holden et al., 2014).

The SDGs, theoretically, represent a new future for net-value impact-oriented sustainability for any organisation (Martinuzzi and Schönherr, 2019). Overall, the 2030 Agenda is an exceptional and ambitious attempt to reconcile progress and sustainability by building a “sustainable world leaving no one behind”.

Facing such an enormous challenge will require cross-scale collaboration from all stakeholders and countries (Dalby et al., 2019; Florini and Pauli, 2018; Vazquez-Brust et al., 2020), as well as policy integration and coherence (Saito, et al., 2017; Valencia et al., 2019). Nevertheless, at the midpoint and with only six years ahead for 2030, numerous critical voices are rising against the current scheme, underscoring multiple limitations and drawbacks, which justify further dialogue to improve this blueprint for humanity.

The SDGs will not be attained unless urgent measures are taken and sustainable transitions are triggered (Walsh et al., 2020). A disruptive transformation of the global economic and social systems is needed to achieve both the Agenda and the COP-21 agreement (Horan, 2019; Stevens and Kanie, 2016; UN, 2019d).

As follows, the relevance of articulating the 2030 Agenda as a systemic network of goals is explored.

2.2.2. The SDGs as a Systemic Network of Interlinked Goals

A critical aspect of the 2030 Agenda lies in its interconnected nature. Indeed, the SDG goals and targets are closely intertwined and can be viewed as a systemic network, as widely acknowledged in the literature (Barbier and Burgues, 2017; Cutter, 2015; Dalby et al., 2019; Griggs et al., 2017; Griggs et al., 2014; Hall et al., 2018; Le Blanc et al., 2017; Le Blanc, 2015; Liu et al., 2018; Liu et al., 2015; Mensah, 2019; Miola et al., 2019; Niestroy, 2016; Nilsson et al., 2018; Nilsson et al., 2016; Schmidt et al., 2017; Stafford-Smith et al., 2017; UN, 2018a; Weitz et al., 2019; Weitz et al., 2018; Zhou and Moinuddin, 2017).

However, the synergies and trade-offs among these goals remain poorly understood and are rarely reflected in policy, underlining the need for further research to deliver a genuinely systemic approach. Research on SDG interactions represents a rapidly growing field facing multiple challenges, controversies, and open debates.

Indeed, assessing these interlinkages is currently hampered by limitations of existing methodologies to address causal relationships and contextual dependencies, combined with data scarcity and inconsistencies. This underscores the need for more robust, hybrid approaches that combine qualitative and quantitative methodologies, as well as emerging fields such as Causal Machine Learning (CML).

As of 2024, the literature on the interlinkages among SDGs presents a fragmented and heterogeneous research landscape, characterized by diverging findings and contradictory perspectives.

This dissertation asserts that research on SDG interlinkages can be classified into three distinct generations. First-generation studies largely relied on qualitative methods, including expert judgment and literature reviews, supplemented by basic quantitative methods like statistical correlations and network analysis. Although these studies provided a foundational understanding of SDG interrelationships, they suffered strong limitations, concerning subjective biases, potentially spurious conclusions, and lacking the analytical rigor needed to manage complex, multidimensional data.

Second-generation studies began to address these limitations by adopting more advanced, hybrid approaches, integrating qualitative insights and quantitative analyses. These studies mainly focused on developing SDG interlinkage networks by linking pairs of indicators, using a combination of statistical techniques and expert views to map out potential synergies and trade-offs. Yet, the reliance on expert interpretation in identifying these links introduced biases and continued to fall short of establishing causality, which is considered a critical component for informing policies (Bennich et al., 2023).

The field is currently transitioning into third-generation studies, which incorporate advanced analytics, such as Causal Machine Learning (CML), together with expert judgment to address the shortcomings of earlier methodologies. While traditional ML primarily focuses on prediction, CML aims to model causal relationships, making it particularly useful for assessing complex dynamics, like the SDG interlinkages. CML holds promise by offering tools to model causality and contextual nuances.

Notably, the ability of CML to model “what-if” scenarios may provide valuable insights for decision-makers, enabling them to predict the outcomes of potential policies and adjust strategies accordingly. Yet, the ethical implications of AI cannot be overlooked, by ensuring fairness and transparency in the application of CML. Nevertheless, CML in this domain remains in its infancy.

Causal analysis has become a focal point of recent advancements, where two main approaches are emerging: causal discovery and causal inference. Causal discovery involves identifying causal relationships among variables, which is essential for understanding the underlying dynamics that drive SDG interactions. In contrast, causal inference is focused on estimating the impact of specific interventions within this network of relationships. Both methods are critical for policy development, as they can provide insights into how targeted actions may influence multiple SDG indicators simultaneously.

However, the application of causal discovery and inference in this domain faces multiple challenges, requiring further development and integration with qualitative insights for meaningful results.

Currently, methodologies for capturing causal interrelations between SDG goals and targets face significant limitations. For instance, the Granger Causality Test (GCT) is widely used in the literature, but it assumes linear relationships, requires long-time series data, and only addresses predictive causality, rendering it unsuitable for many SDG dynamics.

Similarly, techniques like Partial Distance Correlation (PDC) and LASSO struggle with non-linearity and are less effective in complex systems. Bayesian Networks, while powerful for modelling causal relationships, rely on prior knowledge, introducing potential biases.

Other approaches, such as DEMATEL are resource-intensive and depend on subjective expert input, which can limit objectivity. Also, the Aggregated Causal Analysis (ACA) is useful for handling complex causal relationships but struggles with data limitations.

Additionally, widely used statistical methods like Pearson Correlation and Spearman Correlation only measure correlations between variables and fail to address causality, making them inadequate for understanding the deeper interlinkages between SDGs.

Furthermore, data scarcity hinders the potential of quantitative methodologies, including CML. Certainly, a significant barrier to assessing the SDG interlinkages relies on the lack of quality data on the SDGs. Many SDG indicators lack comprehensive and up-to-date data, limiting the ability of analytical methodologies to capture interrelationships accurately.

The time series data available for SDG indicators is insufficient, leading to challenges in validating findings and conducting longitudinal studies that can reveal trends and causal pathways. For example, time delays and inconsistent data across regions make it difficult to track progress on specific SDG targets.

To mitigate these data limitations, researchers are exploring alternative data sources such as geospatial data, IoT data, and synthetic data, which can provide new insights in areas with limited traditional data collection.

However, these alternative data sources face challenges related to acceptance and standardization. Leveraging these sources could enhance the robustness and relevance of SDG analyses, supporting more accurate and comprehensive assessments of SDG interlinkages (Bennich et al., 2023).

Studies on the Synergies, Trade-Offs, and Spillovers

The literature provides a myriad of studies, employing diverse methodologies, approaches, and contextual perspectives, most of them presenting severe limitations and contradictory findings. An overview of pioneering and significant studies underlining relevant aspects in this area is provided as follows.

The complex analysis of interlinkages among SDGs can be approached using either a sectoral perspective (e.g., Griggs et al., 2017) or a comprehensive one, serving as a tool for prioritizing actions (e.g., Weitz et al., 2018). Meanwhile, other researchers have focused on examining the links among specific goals, such as Coopman et al. (2016), Fuso-Nerini et al. (2018), Saraswat et al. (2017), Schmidt et al. (2017), Singh et al. (2018), and Velis et al. (2017).

Certainly, manifold strategies exist for analysing the SDG interlinkages, both qualitative and quantitative, with five primary methodologies standing out: linguistic, literature-based, expert judgment, quantitative, and modelling or simulation approaches (Miola et al., 2019). Yet, many existing studies combine multiple approaches within hybrid methodologies. Indeed, it is recommended to integrate both qualitative and quantitative perspectives to overcome the limitations of individual methodologies when analysed in isolation.

A relevant approach to addressing the interlinkages was the conceptual framework proposed by Nilsson et al. (2018). This framework employed a defined typology and characterization method for mapping interactions among SDGs, providing a structured way to understand their complexities.

Also, the creation of robust models to explore these interactions has been addressed by several experts, including Collste et al. (2017), Khalili et al. (2017), and Shahrier et al. (2017).

Concerning the challenges, a major gap in this area lies in understanding trade-offs. As Allen et al. (2019b) argued, uncertainties persist in understanding these trade-offs.

While the literature reveals diverse scopes, scales, and findings, there is broad consensus among scholars regarding the persistent trade-offs and the lack of sufficient progress in achieving environmental goals.

Many studies have found that certain economic and social goals (e.g., economic growth and social equality) are often prioritized at the expense of environmental sustainability targets. Indeed, goals related to economic development (SDG8) frequently conflict with those focusing on climate action and ecosystem preservation (SDG 13, 14, and 15).

In this regard, Scherer et al. (2018) analysed the interactions between SDG1 (poverty), SDG10 (inequality), and environmental goals (SDG13, SDG15, SDG6) across 166 countries, concluding that promoting social goals usually resulted in increased environmental impacts. Similarly, Barbier and Burgess (2019) examined the trade-offs between net gains in SDG1 and other goals, underlining that progress in poverty reduction often comes at the cost of environmental goals (SDG11–15).

Pothen and Welsch (2019) further argued that advances in economic growth have led to an increased material footprint, exacerbating environmental stress. Pradhan et al. (2017) concluded that SDG12 is the Goal presenting more negative interactions, with ten goals (SDG 1-7, SDG 9-10, SDG17), which could hamper sustainable consumption and production. This tension underscores the need for policies that prioritize environmental sustainability within the broader context of sustainable development (Weitz, 2018).

While existing studies fail to provide definitive evidence due to contradictions, contextual differences, and a lack of robustness in applied methodologies, most scholars suggested that synergies often outweigh trade-offs. However, the significance of these interactions varies considerably depending on the specific context, which underlines the relevance of tailored approaches to SDG implementation.

Griggs et al. (2017) demonstrated positive synergies among goals such as SDG2 (Zero Hunger), SDG3 (Good Health and Well-being), SDG7 (Affordable and Clean Energy), and SDG14 (Life Below Water) through expert analysis.

Similarly, Mainali et al. (2018) applied network analysis and the Advanced Sustainability Analysis (ASA) framework in South Asia and Sub-Saharan Africa, identifying synergies and trade-offs particularly involving SDG1 (No Poverty), SDG2, SDG6 (Clean Water and Sanitation), and SDG7. Studies by Fuso-Nerini et al. (2018) and Fader et al. (2018) explored the water-energy-food nexus, emphasizing the intricate interdependencies among these critical areas.

Conversely, trade-offs between Climate Action (SDG13) and other goals have been underscored by Von Stechow et al. (2016), who highlighted the critical role of curbing energy demand to achieve broader sustainability. Similarly, McCollum et al. (2018) identified significant knowledge gaps in the interlinkages of SDG7 (Energy) with other goals, revealing dependencies shaped by time, geography, governance, technology, and directionality. Hall et al. (2018) identified SDG17 (Partnerships) and SDG13 as key enablers for achieving other goals while asserting the importance of integrated water management (SDG6) and the interdependencies influencing health (SDG3).

Trade-offs within the land-food nexus have also been explored. Obersteiner et al. (2016) analysed the impacts of environmental conservation initiatives on food prices, advocating for Sustainable Consumption and Production (SDG12) as central to mitigating trade-offs and achieving systemic balance. Their findings reinforce the need for a systemic approach in formulating strategies to effectively implement the SDGs.

Kroll et al. (2019) analysed the evolution of synergies and trade-offs among goals, underscoring the role of innovation in creating a “virtuous cycle of progress”. They concluded that positive synergies were found for SDGs 1, 3, 7, 8, and 9, while pervasive trade-offs remained for SDGs 11, 13, 14, 16, and 17. Mantlana and Maoela (2019) examined the interlinkages of SDG9 with social inclusion (SDGs 2 and 11) and environmental issues (SDGs 6, 13, and 15), concluding that both significant synergies and trade-offs existed, particularly among SDGs 6, 13, and 15, which they argued should be acknowledged in policy frameworks.

Dolley et al. (2020) emphasized overlooked trade-offs related to food security and poverty within peri-urban dynamics, attributing these issues to non-representative aggregate data and top-down approaches. Scharlemann et al. (2020) contended that current assessments failed to focus on environmental-human interactions, which influence most SDGs and should therefore be given greater consideration.

Therefore, these findings emphasized the fragmentation of the research landscape and the complexity of establishing a universal methodology or unified vision regarding synergies and trade-offs among SDGs. They also underscored the critical need for cross-fertilization and interdisciplinary collaboration to enhance understanding of these interlinkages.

Another significant aspect of assessing SDG interlinkages is the consideration of transboundary spillovers, which remain underexplored. For instance, advancements in economic growth and infrastructure development often result in unintended environmental degradation in neighbouring regions, underscoring the need for comprehensive frameworks that account for transboundary and cross-sectoral impacts.

McCollum et al. (2018), Sachs et al. (2019a), and Schmidt-Traub et al. (2019) criticized the pervasive and largely ignored nature of spillovers across countries in both research and policy frameworks. Dawes (2019) argued that the SDG network lacks self-consistency, suggesting that indirect trade-offs could hinder the achievement of certain goals. However, Dawes also noted that strategically targeted and allocated network effects, even when unevenly distributed, could be leveraged to advance progress toward achieving the goals.

The introduction of tools such as the Spillover Index in the SDG Index represents a relevant step towards addressing these challenges, reflecting a growing awareness of the far-reaching consequences of spillover effects and their implications for policymaking.

Methodological challenges

Considering the methodologies, the literature reveals significant gaps, underscoring a fragmented landscape where diverse authors often reach contradictory conclusions, depending on the focus, methodology and context of their studies. Consequently, there is a pressing need for a deeper understanding, greater coherence, more robust methodologies, and the development of more effective assessment tools.

Furthermore, the literature emphasized that a “whole-of-government” approach should be adopted to reflect the interlinkages among SDGs while avoiding negative transboundary effects (Miola et al., 2019; UN, 2018a). In this context, Karnib et al. (2017a) suggested a science-based qualitative nexus approach to analyse both direct and indirect relationships, while also recognizing the importance of quantitative methods combined with bottom-up perspectives (Karnib et al., 2017b).

Considering the constraints of existing methodologies in fully capturing the intricacies and complexities of interlinkages, and particularly in identifying causal relationships, the integration of multiple methods becomes indispensable.

Certainly, fusing quantitative and qualitative approaches is essential to better understand SDG interlinkages, enabling the harnessing of synergies while minimizing trade-offs and spillovers (Obersteiner et al., 2016). Furthermore, cross-sector and transnational cooperation should be reinforced to address potential trade-offs and spillovers more effectively (Breuer et al., 2019; Miola et al., 2019; Schneider et al., 2019; Weitz et al., 2019). According to Nilsson et al. (2016), incentivizing cross-cutting relationships across sectors and goals also plays a pivotal role in the operationalisation of the 2030 Agenda.

In this context, Van Soest et al. (2019) advocated for the integration of methods such as expert surveys, interdisciplinary integrated assessment models, and text mining to enhance outcomes while addressing underrepresented social and human issues. They also emphasized the importance of improving the representation of geographies and sectors. Similarly, Requejo-Castro et al. (2020) explored interlinkages related to SDG6 through Bayesian Networks, analysing data from 179 countries.

Their findings emphasized the robustness of this analytical approach and underscored the importance of adopting a multi-sectoral perspective.

Experts such as Sachs et al. (2019a) called for the development of more robust measurement methodologies, supported by advanced digital technologies, to improve the understanding of interlinkages among goals and targets. Such advancements would enable the translation of these insights into more coherent and effective policies for sustainable development (Breuer et al., 2019; Obersteiner et al., 2016; Schneider et al., 2019).

However, complexities and uncertainties persist, particularly regarding the different scales of implementation and the need for context-specific actions (Allen et al., 2018; Georgeson and Maslin, 2018; Griggs et al., 2013; McCollum et al., 2018). These challenges demand further research and policy efforts to address the integration of goals effectively (Barbier and Burgess, 2019; McCollum et al., 2018; Miola et al., 2019; Zimm et al., 2018).

Open Debates

The potential extrapolation of results between studies remains a subject of open debate. While some researchers argued that identified synergies and trade-offs in one context can provide valuable guidance for policymaking, other scholars cautioned that contextual dependencies often limit the generalizability of findings across regions.

Indeed, local variations in social, environmental, and economic conditions frequently mean that successful interventions in one area may not yield comparable results elsewhere. This underscores the importance that policymakers adopt flexible and context-specific strategies to ensure positive outcomes (Weitz, 2018).

In this regard, Bennich et al. (2023) emphasized that while synergies and trade-offs are often context-specific and study findings are inherently complex, a general understanding of significant interconnections among goals and targets can be invaluable for designing policies and managing sustainable development more effectively.

Another point of debate is the suitability of quantitative linear methods in assessing SDG interlinkages. While linear methods are often easier to implement and interpret, some researchers argued that they fail to capture the complex, non-linear dynamics present in sustainable development.

Non-linear methods, while more complex, can provide a more nuanced view of SDG interactions, particularly where feedback loops and compound effects play significant roles.

Recent studies predominantly advocated for hybrid approaches that integrate multiple methodologies, including statistical techniques, network analysis, and causal inference. These approaches are seen as the most promising for understanding SDG interdependencies, as they balance the strengths of both linear and non-linear methods. Hybrid models that incorporate qualitative insights alongside quantitative rigour can address the challenges associated with causality and contextual sensitivity, offering more comprehensive and actionable findings (Bennich et al., 2023).

Implications for Governance

Achieving the 2030 Agenda requires whole-of-government and multi-sectoral approaches, with a shift from isolated interventions to integrated policy strategies. These strategies are essential to harness synergies, mitigate negative trade-offs, and address spillover effects, ensuring that progress in one SDG area does not hinder others. To effectively navigate the complex network of SDG interlinkages, policymakers should adopt policies and interventions that account for both synergies and trade-offs. These policies should focus on minimizing adverse impacts on environmental goals, avoiding siloed approaches, and promoting cross-sectoral collaboration. For example, fostering economic growth (SDG 8) should not undermine climate action (SDG 13), which is crucial for long-term sustainability.

Therefore, policies should aim to optimize positive synergies and limit negative interactions, tailoring interventions to the specific needs and context of each region. This approach requires robust, multi-dimensional methodologies that combine both qualitative and quantitative data. In that sense, causal discovery and inference are highly necessary.

Moreover, scholars underscored the critical importance of collaboration between science and policy, as well as between research and practice, in fostering a more integrated decision-making process. Such collaboration is particularly essential for evaluating the impact of interventions.

In conclusion, the study of SDG interlinkages underscores the complexity of sustainable development and the urgent need for innovative methodologies, improved data, and well-designed policies that address synergies, trade-offs, and spillovers. Accomplishing the 2030 Agenda depends on the ability of society to recognize and act on the interconnected nature of the SDGs, particularly when it comes to the environmental goals currently in conflict with socioeconomic priorities. Researchers and policymakers should develop equitable and sustainable strategies to assess these interlinkages and translate insights into policies that balance economic, social, and environmental priorities.

2.2.3. Design Caveats of the SDGs

The 2030 Agenda resulted from a complex policy process instead of a science-based dialogue, leading to a diluted ambition when setting the final targets (Fukuda-Parr and McNeill, 2019). Thus, the rationale of the SDG framework is weak, and the language remains complex and multi-layer (Ala-Uddin, 2019).

Moreover, related provisions are feeble (Biermann et al., 2017), containing caveats and inconsistencies (Spaiser et al., 2017; Swain, 2018), which erode its credibility and jeopardize its achievement (Georgeson and Maslin, 2018; Saito et al., 2017).

Even when, experts agree on the pertinence of the 17 SDGs at the macro level, when downscaling to the target level, shortcomings are revealed.

Indeed, only 29% of the targets are well-developed (ICSU, 2015), most are narrow, not representative, and difficult to measure hindering progress or demanding additional regulatory efforts. Moreover, a clear implementation approach is missing (Horton, 2015).

Despite the pretended holistic ambition, goals, and targets are not well-connected, remaining inspired by a silo-based philosophy (Bergman et al., 2018) dominated by the economic dimension (Ala-Uddin, 2019; Pogge and Sengupta, 2015; Stevens and Kanie, 2016), and weakening the realization of the Goals.

The new compass for sustainability is neither critical with the status quo nor transformative enough (Stevens and Kanie, 2016). It should be ethically rooted, ambitious, and disruptive and not just rewording old-fashioned models of progress (Dalby et al., 2019; Moore, 2015). Additionally, social, human, and environmental values are insufficiently considered since economic growth overweighs the discourse. Inclusivity is quite feeble (Dalby et al., 2019; Stevens and Kanie, 2016; Ulbrich et al., 2019; Weber, 2017), favouring commercial and political interests and omitting relevant issues such as political freedom or democracy (Ala-Uddin, 2019).

Foundations for balancing inter-generational, and intra-generational equity or social justice are also lacking (Spijkers, 2018; Tehama et al., 2019; Vasconcellos Oliveira, 2018). The current Agenda scheme overlooks the ecological and relational dimensions of inclusiveness (Gupta and Vegelin, 2016).

Furthermore, it has been criticized for being reductionist (Priyadarshini and Abhilash, 2018), failing to disrupt harmful structures (Hawkes and Buse, 2019) along with for numerous contradictions (Dalby et al., 2019), since it supports conflicting elements leading to a difficult implementation with uncertain impacts (Crespo-Cuaresma et al., 2018; Vasconcellos Oliveira, 2018).

A narrative of change is missing (Costanza et al., 2016; Ostrom, 2014). Priorities of all the stakeholders are not reflected, showing a low balance between local and global scales. Roles and responsibilities are diffused without obligations (Spangenberg, 2017). Some authors argue that it seems more like a wish list rather than a consistent set of smart goals (Diaz-Sarachaga et al., 2018; Pogge and Sengupta, 2015). Indeed, the Agenda seems disconnected from recognized methodologies and trends in the sustainability sphere (Lempert, 2017). A critical view is needed to impede conventional narratives which exacerbate inequalities (Ala-Uddin, 2019).

Saner et al. (2019) suggest revisiting the 2030 Agenda to make the most of prior advances and existing international agreements and include overlooked issues. Spijkers (2016) claims a more prominent impulse to sustainability, allowing cross-fertilization among disciplines and alignment with international frames. Stevens and Kanie (2016) plea for transforming the idea of development towards systemic approaches. Indeed, as of 2024, there are critical voices advocating for the urgent enhancement of the 2030 Agenda, with some even suggesting the inclusion of novel Sustainable Development Goals (e.g. Luers, 2020).

Given their relevance in pursuing a truly sustainable and inclusive future, as follows the controversies regarding the imbalances behind the SDGs Agenda are exposed.

2.2.4. Imbalances among Dimensions and Underrepresented Aspects

As aforementioned, even when the 2030 Agenda aims at being universal and integrative, numerous scholars denounce that economic development remains the main cornerstone, attesting to imbalances and notable financial inertia (Ala-Uddin, 2019; Lempert, 2017; Priyadarshini and Abhilash, 2018; Stevens and Kanie, 2016; Swain, 2018; Weber, 2017).

International agreements on the mentioned domains are feebly considered (Saner et al., 2019), and relevant elements are omitted (Dalby et al., 2019). Risks are not appropriately reflected, nor are resilience and accountability.

Environmental and social aspects are poorly covered (Allen et al., 2016), proving strong limitations in terms of inequality, ecosystems, poverty, consumption and production, and governance. An absence of ecology and human rights (Pogge and Sengupta, 2015), as well as insufficient representation of cultural values, are evidenced. Despite its relevance, migration appears as a missing goal (Dalby et al., 2019). The health goal does not cover transboundary problems such as global pandemics or climate impacts on well-being (Dalby et al., 2019). Additionally, the education-related goal is ambiguous (Kopnina, 2020; Walid and Luetz et al., 2018) and related indicators could hinder advancement (Dalby et al., 2019).

Certainly, it is generally agreed that the environment is the weakest dimension, whereas economic-focused goals (i.e. SDG8 and SDG9) are oversized at the expense of the ecological-based (i.e. SDG12, SDG14, SDG15, SDG6), which indeed are the lagging ones. Particularly, the SDG12 presents a narrow scope, predominantly focused on efficiency and poor ambition, being unable to reflect the relevance of sustainable consumption and production (Gasper et al., 2019) and neglecting guidance on transformation (Bengtsson et al., 2018).

Indeed, environmental targets were diluted during the 2030 Agenda negotiation, discarding truly transformative goals or strong implementation means (Elder and Olsen, 2019), then resulting in feeble and inconsistent (Spaiser et al., 2017). The role of ecosystem services should be better embedded (Macellari et al., 2018; Spijkers, 2016), together with the integration of natural capital as a foundation of the development cycle (Lempert, 2017; Martinez-Harms et al., 2018; Vasseur et al., 2017).

Furthermore, the contribution of soil science is not well considered (Bouma et al., 2019) and the water-energy-food-climate nexus is absent. Giannetti et al. (2020) compare the SDGs with the model of capitals and the “five sectors sustainability model” (5SenSu) attesting an unbalanced distribution, where the environmental capital is reduced, thus claiming a good balance.

Lobos-Alva and Hoff (2017) advised integrating the planetary boundaries, coined by Rockström et al. (2009), within national strategies, identifying vulnerable and highly productive contexts for supporting transformation, conceived from a systemic vision (Bengtsson et al., 2018).

Uncertainties exist about the true potential of the 2030 Agenda to tackle sustainability challenges (Leal-Filho et al., 2019a) in comparison with previous tools such as the “Earth Chapter” (Earth Chapter, 2000), considered more advanced, balanced, and integrated.

An imbalanced and economic-driven Agenda would not be able to reduce inequality (Pogge and Sengupta, 2015). On the contrary, it could aggravate the current unsustainability landscape (Kopnina, 2016). Besides, many SDGs deserve better and further attention (Salvia et al., 2019). The imbalance is strongly derived from the lack of integration since economic and social progress could hinder environmental goals (Scherer et al., 2018). Ethical approaches considering all relevant dimensions are needed to move beyond the status quo (Kopnina, 2016).

Therefore, interactions should be understood and acknowledged, and all dimensions should be better balanced (Bergman et al., 2018) and seamlessly integrated (Cutter, 2015) reflecting the vision of strong sustainability.

Additionally, two crucial domains for sustainable development, namely digital transformation and science and innovation, are not adequately translated and represented within the 2030 Agenda's goals and implementation means. These significant aspects are further discussed in Chapters 3 and 4.

The following section discusses the huge challenges which must be tackled for wisely implementing and governing such an ambitious, multifaceted, and integrative agenda.

2.3. Implementation and Governance of the SDGs

2.3.1. Overview of the Pervasive Implementation Challenges

Implementing the SDGs poses serious defies, regarding planning, monitoring, assessment, and financing (Dalby et al., 2019; Georgeson and Maslin, 2018) together with related policy challenges (Kanie and Biermann, 2017; Stevens and Kanie, 2016). The Goals are born universal but need to be translated locally, into national plans, which depend on variable priorities across geographies (Allen et al., 2016; Salvia et al., 2019; Stafford-Smith et al., 2018).

Translating the SDGs into local contexts requires a clear, long-term vision supported by policy targets (Galli et al., 2018) along with investments. Indeed, the present allocated level of investment is not sufficient to address the Agenda, revealing a financing gap (Lagoarde-Segot, 2020) and the urgency to mobilize further resources (Barua, 2019).

Therefore, such implementation remains a burdensome task, full of complex challenges (Caiado et al., 2018). Nevertheless, it also represents an opportunity to navigate SD challenges (Leal-Filho et al., 2019a), and align local and global needs supported by science-based systemic frameworks (Stafford-Smith et al., 2018).

Enhancing the means of implementation and governance to overcome hurdles and accelerate progress is the subject of intense research and debate (Bartram et al., 2018; EU, 2019b; Griggs et al., 2017; Priyadarshini and Abhilash, 2018; Yingchun et al., 2018). Science and policy can significantly contribute by acknowledging interconnections, evidence-based procedures, and well-designed indicators, (Schmalzbauer and Visbeck, 2016). Success in achieving the 2030 Agenda will rely on the level of local commitment and enactment, integration of all SD dimensions and alignment with extant initiatives (Biermann et al., 2017).

2.3.2. Localization, Integration, and Multilevel Governance as Priorities

Localization emerges as a relevant issue in the literature. Jones and Comfort (2019) discuss localization challenges in the UK, concluding that a lack of consistent policies, limited awareness, and funding gaps persist. Engström et al. (2019) studied cross-scale water, land, climate, and energy interactions in Sweden.

Terama et al. (2019) examined the relationship between urban sustainability and the SDGs with a Nordic perspective, claiming that is disconnected from local practice, demanding better integration and multidisciplinary approaches. Allen et al. (2019a) explored nesting national models in Australia and claimed coherent policies and investments while acknowledging potential risks. Fukuda-Parr and Muchhala (2020) analysed the role of developing countries, particularly the “agency of the South”, in shaping global norms.

Schmieg et al. (2018) argued that individual ethical norms at the micro-level could decelerate unsustainability at the meso-level, while norms at the macro-level, such as the SDGs, may accelerate innovations. Kabisch et al. (2019) underlined the relevance of local contexts in achieving urban transformations. Schmidt-Traub et al. (2019) suggest involving civil organisations and cities as key players towards the localization of the SDGs while enhancing integration into regulatory frameworks.

At the midpoint of the 2030 Agenda, over three hundred Voluntary National Reviews (VNRs) are already available (UN, 2019h). As of 2023, 188 out of 193 UN member states have presented at least one VNR. However, for numerous countries, VNRs have not comprehensively properly reported the assessment of SDGs (Allen et al., 2019a). According to the UN, newer VNRs are embracing a more proactive and inclusive approach to follow-up and review processes.

These evolving practices prioritize evidence-based reporting derived from disaggregated data, indicating a growing dedication to comprehensive analysis and assessment. So far, VNRs have primarily focused on readiness and progress, rather than providing comparisons between policies or contexts, which remain underreported (Elder and Bartalini, 2019).

There is a need for quantitative assessment of SDG performance across countries, but it is currently lacking (Allen et al., 2016; Engström et al., 2019; Huan et al., 2019; Lafortune and Schmidt-Traub, 2019; Salvia et al., 2019). Dickens et al. (2019) advocate for benchmarks and national indicators to avoid diminishing significance. Nation-states shoulder the responsibility for advancing the SDGs, but there are disparities in commitment and action.

While some, like Nordic countries and the EU, show dedicated support, others, especially in the developing world, face challenges due to limited resources (Sachs et al., 2023).

Challenges persist in global governance: voluntary actions limit accountability, developed countries are not held accountable for impacts or financing, trade rules do not align with SDGs, and coordination between levels of government is lacking. Mechanisms like VNRs and NDCs fall short. Stronger multilateral cooperation is needed to align efforts with SDGs.

Besides, complexities regarding different scales should be soundly considered by reconciling all specificities from the global to the local domains. Relevant methodological hurdles and data gaps and lags remain (Dang and Serajuddin, 2020; Guo, 2020; Jacob, 2017), hampering effectiveness assessment. Hence, further research is needed concerning measurement efforts (Elder and Bartalini, 2019).

Regarding integration in governance, it should be based on science-based foundations, policy coherence, together with science-policy interfaces, as central issues for the 2030 Agenda (European Union, 2019b; Georgeson and Maslin, 2018; Karlsson-Vinkhuyzen et al., 2018; Miola et al., 2019; OECD, 2019a; OECD, 2019c; Tosun and Leininger, 2017; UN, 2018b; Valencia et al., 2019). Indeed, target 17.14 is specifically focused on policy coherence.

However, current governance fragmentation could hinder the SDGs achievement (Monkelbaan, 2019). As widely acknowledged, the 2030 Agenda needs to move beyond monitoring and focusing on achieving a better balance among dimensions, leading to a systemic, holistic system approach (Bartram et al., 2018; Coopman et al., 2016; Cutter, 2015; Liu et al., 2015; Miola et al., 2019; Zhou and Moinuddin, 2017; Stafford-Smith et al., 2017).

Allen et al. (2018) reviewed the SDGs implementation in twenty-six countries, concluding that, despite progress, critical gaps prevail regarding interactions, showing a prevalence of silo-based approaches, counterproductive for unleashing the transformative power of the 2030 Agenda.

Dalby et al. (2019), Stevens and Kanie (2016) and Obersteiner et al. (2016) argued that the SDGs require an unprecedented integration effort to shift beyond siloes. Bartram et al. (2018) critique the means of implementation of SDG6 (water) providing policy recommendations to enhance this goal. Van der Hel and Biermann (2017) compare six international science-based initiatives, related to SDGs governance, analysing how they achieve the necessary “salience, credibility and legitimacy” to be soundly integrated within policy. Tosun and Leininger (2017) explained that domestic policies strongly influence the implementation strategies, leading to divergent interpretations of interlinkages and integration.

Indeed, “whole-of-government” and “whole-of-society” visions are needed to foster ownership and trigger governance transformations (OECD, 2019b; UN, 2018a). The SDGs should integrate both social and ecological well-being at all levels, but current integration and vertical diffusion remain poorly developed (Kanie et al., 2014). Indeed, Integration should consider three dimensions: horizontal, vertical, and engagement of stakeholders (UN, 2018a; Valencia et al., 2019), including governance frameworks across geographies and scales to better deal with transboundary issues (Amos and Lydgate, 2019; OECD, 2019c; Schmidt et al., 2017).

The 2030 Agenda is indivisible, therefore unsuitable prioritization practices (i.e. “cherry picking”) could danger the holistic vision (Allen et al., 2018; Georgeson and Maslin, 2018; Zhou and Moinuddin, 2017). Manifest overlaps and uneven support are evidenced, together with poor coordination or accountability (ECOSOC, 2017). Certainly, accountability is feebly considered (Zimm et al., 2018), since proper tools are lacking, and the 2030 Agenda mainly refers to monitoring instead.

Bowen et al. (2017) identified three governance challenges: raising collective action, equitably managing trade-offs, and providing mechanisms to secure accountability. Grainger-Brown and Malekpour (2019) conclude that existing implementation methods lack transformative power and strategic acumen.

Monkelbaan (2019) suggested an “Integrative Sustainability Governance framework” standing upon power, knowledge and norms pillars and considering resilience, systemic discussions, and behaviour issues. Sullivan et al. (2018), and Caiado et al. (2018) called for innovative tools and analytical frameworks to overcome challenges. Kanie et al. (2019) plead for action coherence and compliance, spurring transformative shifts both on the science and policy sides while adapting extant instruments and policies. Similarly, Reynolds et al. (2018) explored the role of system thinking towards pursuing SDG17 (means of implementation), concluding that capacity-building and action-learning platforms are required.

Knowledge gaps persist, particularly amid social and ecological systems at the local level, limiting the effectiveness of governance (Mastrángelo et al., 2019). Indeed, knowledge management is a relevant, yet overlooked, element which could support implementation (Barrantes-Briceño and Almada-Santos, 2019), enhancing policy and practice. Certainly, the literature reflects the need for a paradigm shift based on multi-level governance and full stakeholders’ engagement (Dalby et al., 2019; European Union, 2019b; Martens, 2019; Messerli et al., 2019; UN, 2019d).

Caiado et al. (2018), Giannetti et al. (2018) and Horan (2019) underscore the potential offered by partnerships and the need to reinforce bottom-up approaches. However, this transformation is not straightforward, since multiple uncertainties remain regarding human-environment complexities, unknown cause-effect relations, conflicting views from different stakeholders and context-based specificities (Messerli et al., 2019). Thus, agents of change, actionable strategies and enhanced gears are needed to achieve the Goals (OECD, 2019c; UN, 2019d).

Sachs et al. (2019b) and the “The World in 2050 Initiative” (IIASA, 2019) concurred that six shifts are required to spur progress, by tackling education and inequalities, health and well-being, low-carbon sustainable energy and industry, sustainable land use and food systems, smart cities and harnessing the digital revolution.

Chapman and Shigetomi (2018) recognized the relevance of the lifestyle factor. Fostering public involvement is crucial (European Union, 2019b; Li et al., 2018), but policy reforms are not sufficient, production and consumption patterns and power structures should be also transformed prioritizing human rights and planetary boundaries (Bengtsson et al., 2018; Martens, 2018). A narrative of change and disruptive transformation of the idea of development is unavoidable (Bengtsson et al., 2018; Stevens and Kanie, 2016; UN, 2019d) by decoupling economic growth from environmental degradation shifting to circular economies (Schroeder et al., 2019).

Policy and financial enabling frameworks are key critical leverage points (Dalby et al., 2019; Lagoarde-Segot, 2020; UN, 2019g) yet poorly developed. Geopolitical stability and good governance must be enhanced (IMF, 2019), together with incentives, and investment labels (UN, 2019d), fostering international cooperation (UN, 2019g) and promoting debt and tax reforms (ECOSOC, 2019b).

In conclusion, multiple limitations exist to overcoming implementation challenges by achieving a truly whole-of-government integrative and context-savvy approach, being able to engage all the stakeholders, and avoiding counterproductive prioritization. Better coordination and accountability mechanisms guided by analytical frameworks, science-based approaches, sound policy enablers and a shift towards sustainable patterns are open issues yet to be decoded.

2.3.3. Monitoring Progress and Assessing Impact towards The SDGs

The SDGs realization strongly depends on monitoring and evaluation (Lu et al., 2015; OECD, 2019b; UN, 2018a; Schmidt-Traub et al., 2017), which indeed, relies on ensuring robust accountability (Bebbington and Unerman, 2018; Wackernagel et al., 2017). Measuring progress is imperative for the implementation (Dalby et al., 2019; Persson et al., 2016; Reyers et al., 2017; Yonehara et al., 2017).

However, the current data vacuum, non-consistent indicators, limitations regarding data processing, interoperability, and interpretation, together with the absence of sound methodologies and coordinated efforts to compare progress across geographies (Crespo-Cuaresma et al., 2018) are hindering follow-up (Lior et al., 2018; Lu et al., 2015).

Extant analytical and modelling tools are not able to cover the 169 targets, evidencing knowledge gaps and the need to reduce complexity and enhance accountability (Zimm et al., 2018).

A taxonomy and systematic approaches for quantifying progress are absent (Xu et al., 2020). Besides, the emphasis on using institutional indicators is jeopardizing the understanding of effectiveness and overlooking interactions (Benson et al., 2019). Defining the measurement purpose in line with materiality assessment, together with proper integration within governance, are essential factors (Schönherr et al., 2019).

Early preliminary attempts to assess the SDGs framework have been undertaken, although the 2030 Agenda remains a voluntary effort, lacking mandatory reporting mechanisms. Monitoring efforts to date are mainly devoted to single indicators (Barbier and Burgess, 2019).

An additional difficulty comes from the complex nature and interpretation of the SDGs, requiring further refinement and clarification of their underlying objectives (Dang and Serajuddin, 2020).

Therefore, monitoring and evaluation should go beyond indicators and outcomes, by considering contextual issues (Fukuda-Parr and McNeill, 2019; Renn et al., 2020). Thus, ensuring that progress is relevant, equitable and truly sustainable (Schwandt et al., 2016). Indicators are not able to explain failures, wicked issues, or complex dynamics, thus, a system approach is needed (Renn et al., 2020).

Localization is critical to overcome mismatches between theory-driven indicators and local conditions. The compatibility between accountability regimes and integrated policy approaches is controversial. Therefore, accountability should be reflected by using a context-based approach and shared governance among all actors, avoiding strong regimes (Karlsson-Vinkhuyzen et al., 2018).

The definition of essential variables with a systemic perspective is crucial, enabling both sustainable transformation and interaction at the policy level (Reyers et al., 2017). Tracking the spatial-temporal dynamics of progress at the global and local levels seems imperative (Xu et al., 2020). Even though, concepts such as sustainable value creation (Arnold, 2018; Dressler and Bucher, 2018), inclusivity or resilience, are especially difficult to assess (Bamberger et al., 2016; Yonehara et al., 2017).

An inclusive approach is crucial to improve measurement, along with a proper narrative and understanding of priorities (Bidarbakhnia, 2020). Multi-sectoral action and prevention-driven policies are required (Lozano et al., 2018).

In summary, suitable context-based and systemic methodologies, accountability compatible with policy integration, data availability and granularity, along with capacity building are critical elements to consider for evaluating progress, thus far untapped, requiring further efforts.

2.3.4. The Role of Indicators and Data Availability and Quality

The SDGs indicators were adopted in 2017, after a tough process led by the United Nations Statistics Division, wanting a scientific debate, but was eventually influenced by political struggles and competing interests (Kapto, 2019), hence resulting in relevant shortcomings (Brussel et al., 2019). Indeed, indicators are still being reviewed as of 2024.

According to the UN Statistical Division, as of March 2024, there exist 231 SDG indicators in total. The updated tier classification contains 157 Tier I indicators (those with well-built methodology and available data), 66 Tier II indicators (lacking data coverage), and eight indicators that have multiple tiers (different components of the indicator are classified into different tiers). After years of efforts on statistical enhancements from 2015 to 2024, no Tier-III indicator remains (those featured by both limited data and methodologies) (UNSTATS, 2024).

The Inter-Agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs) will conduct a Comprehensive Review of the global indicator framework in 2024, in line with UN GA Resolution 71/313. The aim is to enhance the framework for monitoring the 2030 agenda while avoiding additional burdens on national statistical work. Changes are intended to be limited in scope and focus on implementation for SDG achievement. New indicators must have an agreed methodology and available data for at least 40% of countries and populations across relevant regions.

However, this cautious approach contradicts calls from SD experts to include further and better metrics, particularly concerning emerging and non-represented aspects like digital transformation and STI.

Concerning indicators, significant challenges persist. Many SDG indicators continue to suffer from data gaps and delays, and despite improvements in methodology, certain metrics may still exhibit contradictions (Bissio, 2019; Dawes, 2019; Hickel, 2019).

Nevertheless, measuring SD is highly complex due to the underlying limitations of interpretation, its multidimensional nature, and tensions among dimensions, particularly regarding public goods. Monitoring requires a broad analysis of the goals' essence. Therefore, indicators should be selected based on their ability to reflect the respective SDG value and not only on data availability. Further effort in enhancing Tier II and III indicators is highly necessary (Fukuda-Parr and McNeill, 2019).

A relevant body of literature on SDGs indicators can be found, concluding that extant metrics suffer relevant limitations (Annan-Diab and Molinari, 2017; Barbier and Burgess, 2019; Dlouhá and Pospíšilová, 2018; Galli et al., 2018; Hák et al., 2016; Lehtonen et al., 2016; Salvia et al., 2019; Storey et al., 2017; UN, 2019c; World Bank, 2019).

The current framework has been criticized for being narrow, inflexible, and unfeasible; hence undermining the purpose of monitoring what matters instead of doing what can be measured with official statistics (Georgeson and Maslin, 2018).

SDG indicators are considered reductionist based on their conception and use (Ordaz, 2019), and assessment based on present metrics could be confusing (Janoušková et al., 2018). Mapping indicators could be useful to devise solutions while avoiding threats (Kraak et al., 2018).

Measurement challenges are linked to interpretation, demanding a refinement of the goal formulation and subtle purposes, and cost-effective solutions to bridge the data vacuum (Dang and Serajuddin, 2020). Certainly, relevant data gaps and lags remain (Jacob, 2017), as well as underreported transboundary impacts such as migration (UN SDSN, 2019).

Thus far, data is available for half of the indicators (Dang and Serajuddin, 2020) and only fifty of the 169 SDG targets are ready for progress assessment (Martens, 2018).

Most uncertainties and challenging measures are linked to SDG12 (Dalberg, 2017) and those goals related to ecosystems and climate (i.e. SDG13, 14, 15), (OECD, 2019c). Indeed, data gaps affect 77% of environmental-related goals (UNEP, 2019). Satisfactory progress has been made only on 23% of the environment-focused indicators owing to a combination of policy, reporting and funding. Most of them suffer negative trends, therefore further data and actions are needed to accelerate progress (UNEP, 2019).

Furthermore, Lozano et al. (2018) and Hall et al. (2019) underscored uncertainties and data limitations concerning the health-related goal (SDG3), which could yield inaccurate aggregation, estimation, and modelling.

Trade-offs and spillovers across boundaries have been ignored by most metrics, therefore they should be considered (Schmidt-Traub et al., 2019; Sachs et al., 2017). Better data collection, analysis and interpretation are looked for (Lozano et al., 2018), not only to measure progress but also to make corrections and projections (UN SDSN, 2019).

Regarding SDG11 on sustainable cities, inconsistencies are uncovered concerning other frameworks, revealing the need for comprehensive approaches to benchmarking and assessing policies (Giles-Corti et al., 2019). Ulbrich et al. (2019) explore how inequalities could affect the representativeness of the SDG indicators, particularly on the goal devoted to cities (SDG11).

Dickens et al. (2019) suggested defining tangible targets at the national level, along with indicators and benchmarks to avoid reducing the significance of prescribed global indicators, while allowing comparative evaluation. Without representative and integrated measures, persistent bias would remain.

Most experts claim that a critical review of current indicators, alongside the formulation of alternative metrics and benchmarks going beyond the “obsolete” GDP indicator (Costanza et al., 2104; Hák, et al., 2016; Mair et al., 2018; Merry, 2019; Rubio-Mozos et al., 2019; Saito et al., 2017; Schmidt-Traub et al., 2017; Suciú and Năsulea, 2019). GDP indicators (i.e. SDG8) contradict the principles of sustainability efforts since strongly clash with those goals devoted to ecology and equality (Coscieme et al., 2020).

Current frames underachieve on sustainability, yielding cascade effects on poverty and inequality (Wackernagel et al., 2017). Vanham et al. (2019) analyse environmental footprints that overlap with indicators and explore their potential to assess progress towards the SDGs and the “water-energy-food-ecosystem” nexus.

Fioramonti et al. (2019), Ivanov and Peleah (2018) and Suciú and Năsulea. (2019) pleaded for alternative indicators for wellbeing, to reinforce the sustainability narrative by connecting a new economic paradigm compatible with the goals (i.e. Happy Planet Index, Sustainable Human Development Index).

For instance, the “Inclusive Wealth Index” (UNEP, 2018) is a simple index, comprising the natural, human, and manufactured capital which could complement the GDP, even though it represents a weak sustainability concept.

Composited multi-dimensional indexes going beyond national implementation could help to overcome some limitations (Diaz-Sarachaga et al., 2018; Campagnolo et al., 2018; Lozano et al., 2018), and offering a holistic approach (Lior et al., 2018).

Lemke and Bastini (2020) suggested a “Multilevel Sustainable Development Index (MLSDI)” able to overcome the limitations of existing indices, which hardly reflect all the dimensions of sustainability and are unable to compare agents at distinct levels due to methodological caveats.

In the corporate realm, harmonized indicators and methodologies for reporting are critical, avoiding narrow approaches (Global Reporting Initiative and UN Global Compact, 2018). Nevertheless, novel metrics and composited indexes suffer limitations and should be enhanced, including potential contrasting effects (Bondarchik et al., 2016).

Hence, crafting novel science-based metrics, together with context-friendly measures, leveraging new data sources, better aggregation, and integration, are urgently needed in order to ensure that, despite the challenges, all targets can be measured, all countries can monitor progress, and transboundary issues can be considered.

2.3.5. Adoption and Progress as of 2024

Thus far, limited progress has been evidenced, although is slow-paced and unevenly distributed across contexts and actors (Sachs et al., 2019a; UN, 2019a; UN, 2019b). Hurdles to wide-ranging achievement persist (Bryan et al., 2019). The world is off-target, since no country has yet achieved the goals (Dalby et al., 2019; OECD, 2019c) and even top-performing countries face challenges (Sachs et al., 2019a).

The cascading global crises from 2020 to 2024 have significantly impacted the advancement of the 2030 Agenda (UN, 2023a), exacerbating geopolitical tensions and hindering SDG achievement. Decreasing commitments to cooperation amid these tensions have diverted financial and human resources away from sustainable development efforts. Furthermore, the COVID-19 pandemic dealt a severe blow to most SDGs, with its aftermath still felt in many nations as of 2024, echoing throughout the 2030 Agenda.

Despite concerted efforts and recovery initiatives, emerging geopolitical conflicts and macroeconomic shifts have introduced further challenges, impeding progress towards SDG attainment.

The first SDG Summit held in 2019 (UN, 2019f) pleaded for a decade of urgent action. Meanwhile, the second SDG Summit in 2023, which marked the mid-point of the 2030 Agenda, convened political leaders and stakeholders to assess thoroughly the SDGs' status to respond to the interlocking global crises. Besides, aimed to provide high-level political guidance on transformative and accelerated actions required to meet the SDGs by 2030 (UN, 2023b).

This Summit also emphasized the importance of digital transformation, committing to bridging digital disparities and maximizing its benefits globally. It highlighted the need for increased participation in the digital economy, especially in developing countries, through improved infrastructure and partnerships. Additionally, it underscored efforts to bridge gaps in science, technology, and innovation, focusing on environmentally friendly technologies and integrating scientific evidence into policymaking.

Besides, the significance of effectively utilizing Artificial Intelligence and strengthening data systems to track SDG progress was recognized.

Regarding the monitoring of the SDGs, key cornerstones for tracking stock on progress are, inter-alia: the annual report from the United Nations "Progress Report towards the SDGs" providing a perspective of the status of the goal (2016-2023); the annual versions of the SDG Index and Dashboards (UN SDSN, 2019-2023) which classify countries according to their performance. Yet, this index has been criticized for its limited consistency and low performance on sustainability (Wackernagel et al., 2017); and the SDG Atlas (World Bank, 2018a, 2023).

Other relevant documents are the OECD's report "Measuring Distance to the SDG Targets" (OECD, 2019c and 2022) concerning the OECD countries. Besides, within the European context, the Eurostat Monitoring Report describes progress within the European Union (2019a, 2023).

As the halfway mark toward achieving the SDGs by 2030 is reached, the Sustainable Development Goals Report 2023 (UN, 2023a) painted a concerning picture. Only 15% of the 169 targets are on track for achievement, with 48% off track and 37% stagnating or regressing. Progress on most SDGs is unsatisfactory, with many indicators moving slowly or even regressing below the 2015 baseline (UN, 2023a, b). Escalating humanitarian needs and the impacts of climate change worsen global inequalities. Weakened international solidarity and trust hinder collective efforts to address these crises.

However, nearly two-thirds of the goals are still attainable, with progress in reducing extreme poverty leading to significant quality of life improvements. The report calls for heightened global efforts, emphasizing the potential for achievement through political determination and the effective use of technology, resources, and knowledge. It also highlights the compounding effects of the COVID-19 pandemic, sluggish economy, climate change, biodiversity loss, pollution, and the conflict in Ukraine, particularly affecting developing countries.

Climate finance falls short of commitments, risking exacerbated inequalities and global fragmentation. An urgent Rescue Plan for the People and Planet is proposed, emphasizing deep reforms, long-term financing, debt restructuring, and contingency financing through the SDG Stimulus. Immediate action is needed to salvage the SDGs and drive substantial progress forward.

The Global Sustainable Development Report 2023 (UN, 2023a) urged urgent and concerted efforts to achieve the SDGs by 2030. It called for transformative actions and global collaboration based on scientific evidence and political leadership, emphasizing the necessity of purposeful and positive transformations for sustainable development.

Sachs et al. (2023) reported in the 2023 edition of the SDG Index, that global progress has stagnated, particularly in environmental targets. Environmental crises, including breaches of planetary boundaries, pose unprecedented risks to biodiversity, water resources, and climate stability. Social challenges exacerbate these risks, threatening social cohesion and governance stability.

According to Sachs et al. (2023), The years 2022 and 2023 have marked record-high temperatures, with the world significantly off track to achieve climate targets set by the Paris Agreement and SDG 13. Global warming has already surpassed 1.2°C, increasing at a rate of over 0.3°C per decade. This trajectory indicates a high likelihood of exceeding the critical 1.5°C threshold, possibly within the next decade. Projections from the UNEP Emissions Gap Report (2022a) suggest that current policies are leading to a catastrophic 2.8°C warming by 2100. Even with the implementation of existing Nationally Determined Contribution targets, warming is expected to reach around 2.4°C by the end of the century.

Despite net-zero pledges from many countries, the most optimistic scenarios based on these pledges would still result in approximately 1.8°C warming by 2100. These alarming statistics highlight the urgent need for more ambitious and effective climate action to mitigate the severe impacts of climate change.

Therefore, urgent adoption and implementation of the SDG Stimulus, alongside comprehensive reform of the global financial architecture, are imperative. Investing in statistical capacity, science, and data literacy is highlighted as essential. UN Member States should commit to accelerating SDG progress to 2030, and to setting even more ambitious SDG targets by 2050, incorporating the recent “Kunming-Montreal Biodiversity Framework and the High Seas Treaty”.

Sachs et al. (2023) recommended six key transformations for national pathways to achieving the SDGs by 2030: universal quality education and innovation-based economy; universal health access and coverage; zero-carbon energy systems; sustainable ecosystems, agriculture, and climate resilience; sustainable cities; universal digital access and services. UN Member States are urged to accelerate SDG progress to 2030 and set ambitious targets for 2050, incorporating recent biodiversity and high seas agreements.

However, societal polarization and geopolitical conflicts hinder the global cooperation necessary for achieving the SDGs. Achieving the SDGs relies on five pillars of good governance: Long-term SDG pathways for public policy; SDG financing at scale and timing; Global cooperation to reduce conflict; Innovation for social inclusion and environmental sustainability; and Regular reporting on SDG progress.

The European Commission (EU, 2023) has made significant strides in advancing the SDGs, with initiatives like the European Green Deal and the Climate Law. A “whole-of-government approach” to implementing the SDGs has been proposed within policy documents shaping the EU’s strategy since 2016. In terms of investment, the Recovery and Resilience Facility funded by Next Generation funds, presents a crucial opportunity aligned with the green and digital transition.

The EU plans to present its first Voluntary Review at the UN’s High-Level Political Forum in 2024. Eurostat’s seventh edition monitoring report on the SDGs for 2023 uses approximately one hundred indicators, aligning with global SDG indicators. It analyses the short-term impacts of ongoing crises and spillover effects of EU consumption on a global scale. Considerable progress is noted on SDGs 5, 8, and 1, followed by SDGs 3, 4, 9, 10, and 16. Moderate progress is observed on SDGs 11, 12, and 14, with slower progress on SDGs 2, 6, 7, 15, 13, and 17.

The OECD (2022) underlined that many countries have made significant strides in implementing SDGs, notably in gender equality, emissions reduction, and youth employment. OECD countries meet ten out of 112 and nearing achievement on eighteen more, mainly concerning basic needs and policy implementation.

Challenges persist in ensuring inclusivity, restoring trust in institutions, and addressing environmental pressures, with decreasing trust in institutions over time and ongoing environmental threats. Data gaps pose challenges in assessing SDG progress, with incomplete reporting frameworks and uneven coverage.

Assessing dynamic performance is hindered by insufficient time-series data, particularly for goals like climate action and gender equality. Capturing interlinkages between goals and ensuring gender focus in relevant indicators are areas needing improvement. Globally coordinated monitoring efforts are essential, facilitated by instruments like the System of Environmental-Economic Accounting (SEEA).

Streamlining targets and indicators should occur within national dialogues informed by international frameworks, emphasizing the need for clearer differentiation between policy instruments and outcomes to effectively track SDG progress.

Accountability and sovereignty imply that this streamlining and selection of targets and indicators should take place in the context of a national dialogue informed by international frameworks (Stiglitz et al., 2018).

The GSDR 2023 report (UN, 2023a) outlined a comprehensive framework for accelerating progress, emphasizing the need for shared transformation strategies encompassing national plans, local initiatives, fiscal measures, data investments, partnerships, and accountability measures. Capacity-building at individual, institutional, and network levels is advocated to facilitate innovation and digital transformation, conflict management, and crisis response. The integration of science, policy, and society is highlighted as crucial for fostering a future where both people and nature thrive.

Additionally, the report underscored the importance of transformative actions in achieving the SDGs, drawing on historical examples like the Green Revolution. The stylized model, the S-curve, illustrates successful transformation phases: emergence, acceleration, and stabilization. Ambitious public policies are deemed essential for driving innovation and ensuring a timely transition to sustainable practices, despite challenges such as technology lock-ins and political opposition.

Moreover, the GSDR 2023 report discussed interlinkages between the SDGs, emphasizing the complex relationships between goals and the need for integrated policy solutions. International spillovers are highlighted as significant factors affecting SDG implementation, necessitating innovative methods for tracking, and addressing these impacts.

Therefore, according to recent reports, social inclusion and environmental-related goals are alarmingly worsening, showing a worrisome biodiversity loss, exacerbation of the climate crisis, unsustainable pollution of oceans, consumption and rising footprints (Sachs et al., 2023; UN, 2023a; Asian Development Bank, 2019; Sachs et al., 2019a; UNEP, 2019). Projected extreme poverty and hunger indicators are unbearable and access to health services remains deficient. Inequalities and conflicts are rising, and humanitarian crises are enduring, placing human rights in danger in many contexts, and threatening social cohesion and progress (UN High-Level Political Forum, 2019).

Climate action is perceived as an urgent priority (Dalby et al., 2019), followed by responsible consumption and production (Globescan and SustainAbility, 2019).

Also, transboundary issues, such as migration, and ignored spillovers are hindering progress in vital goals (Sachs et al., 2017; Sachs et al., 2019a; Schmidt-Traub et al., 2019; UN, 2019b).

Moreover, some megatrends might be threatening the Goals: the unsustainable growth model, weakened multilateralism overlooking transboundary responsibilities, strong structural and financial barriers such as debt crisis, unfair trade, and democracy loss worldwide.

Existing reports show different, occasionally contradictory, conclusions depending on the approach used, evidencing a fragmented knowledge regarding progress, extremely context dependent. Methodologies and tools are unsatisfactory and often inconsistent, lacking an agreed systematized measure of progress (Xu et al., 2020). Thus, novel approaches to tackling the context, offering strategic directions, and fostering commitment and collaboration are required (Asian Development Bank, 2019).

Sabau (2020) argued that the present lack of progress relies on a narrow understanding of sustainability values and claims to reorient governance towards a “tetra-valuation” approach across key actors, based on: “exchange, labour, use and function value”. Moyer and Hedden (2020) proposed an integrated assessment model (International Futures) to evaluate progress toward the target nine indicators related to human development.

Biermann et al. (2017) underlined the relevance of aligning the SDGs with extant initiatives, integrating all SD dimensions. Lozano et al. (2018) highlight the need for multi-sectoral common action and prevention-driven policy action.

Current policies and frames have yielded limited progress, therefore deep and urgent transformations are required to accelerate progress (Moyer and Hedden, 2020; UN, 2023a). Political leadership and engagement from all stakeholders are urgently needed to increase funds and spur action to catalyse change (UN, 2019d; UN, 2023a).

Thus far, the SDGs have not showcased transformative effects on global governance, but they have influenced policy dialogues to gather unprecedented support and international funding for sustainable development.

In addition, accountability is deficient, and collaboration also faces challenges, resulting in merely incremental progress. Considering the holistic ambition of the 2030 Agenda, it becomes evident that the central issue lies in the interpretation of the goals.

Recent geopolitical tensions and economic setbacks have raised proposals to discard this framework, risk invalidating the progress made in aligning international objectives and actors. In this regard, Fuso Nerini et al. (2024) not only advocated keeping the SDGs as central in present and future policy agendas but also explored the importance of extending them to 2050 to ensure progress in global development amidst growing challenges.

They proposed adapting the SDG framework by setting interim targets for 2030 and 2040, focusing on key priorities such as climate action, poverty alleviation, and clean energy, along with reinforcing inclusive governance, regional cooperation, and reforming the global financial architecture.

Moreover, they pointed out the key role of emerging technologies, such as artificial intelligence (AI), in both potentially advancing and hindering SDG progress.

Therefore, poor progress to date results in several hurdles which need to be tackled, in terms of institutional coordination and capacity, adoption and ownership, flawed assessment standards, together with unsuitable indicators, methodologies and data gaps.

New metrics, specific tools and tailored guidelines for accountability and reporting, by harnessing technology and new data sources, are required to cover the SDGs singularities.

2.3.6. Roles, Responsibilities, and Collaboration among Actors

Achieving the SDGs will require close-knit collaboration, cooperation, and coordination efforts, as well as shared responsibility from all stakeholders, to move beyond intentions into actions (Frey and Sabbatino, 2018; Kurz, 2020). In this regard, ensuring policy coherence, improving legitimacy (Donoher, 2017) and active engagement of businesses, governments and civil society is crucial (Galli et al., 2018; Lucas et al., 2016; Messerli et al., 2019; Schönherr et al., 2017; UN, 2019d).

However, the roles within the 2030 Agenda, have not been properly discussed nor soundly established (Spangenberg, 2017). Responsibilities should be defined to mediate trade-offs and spillovers, as well as to unravel the potential contribution from all actors. Given the ambition of the SDGs, promoting collaboration and activating narratives of change, are essential factors for overcoming hurdles and inertia, towards accelerating progress (Dalby et al., 2019; UN, 2019d).

Business Realm

The private sector plays a decisive role in the implementation and financing of the 2030 Agenda (Cordova and Celone, 2019; Frey and Sabbatino, 2018; Kolk et al., 2017; Priyadarshini and Abhilash, 2018; Van der Waal and Thijssens, 2020; Van Zanten and Van Tulder, 2018). Companies are expected to lead the transformation, by motivating market sustainability, crafting sustainable approaches (CSIL, 2017), building purpose-driven culture, and inspiring their supply chains (Deloitte, 2017; UN Global Compact and Accenture, 2019). Mainstreaming the SDGs is not straightforward (Elder and Bartalini, 2019), since open issues and lack of understanding about added value and actionable strategies remain (Betti et al., 2018; Van Zanten and Van Tulder, 2018). Unsuitable means of implementation, together with institutional or cultural factors could hinder adoption and progress (Rosati and Faria, 2019).

Van der Waal and Thijssens (2020) study the motivations that could guide companies to get actively involved in the 2030 Agenda, to create shared value for the “common good”, concluding that business involvement is limited and “evasive”, apparently encouraged by “legitimacy” and institutional factors.

Indeed, businesses are gradually committed to the 2030 Agenda, and progress is being made, supported by tools like the SDG Compass (WBCSD, 2015), CEO Guide (WBCSD, 2017), Good Life Goals (WBCSD, 2019c), SDG Matrix (UN Global Compact and KPMG, 2017) or the Blueprint for Business (UN Global Compact, 2017). Yet, companies are not taking appropriate accountability actions, nor sufficiently aligning materiality with the SDGs (KPMG, 2018; Schönherr et al., 2017; WBCSD, 2019b). SDG adoption is moving ahead, with SDG13 (climate) on top and other ecological goals on bottom. Nevertheless, corporate involvement persists limited and obscure in terms of governance, as well as highly dependent on the type of SDG (Vazquez-Brust et al., 2020).

A controversial discussion relies on how to prioritize actions based on principles (UN Global Compact and Accenture, 2019), while avoiding “cherry-picking” counterproductive decisions (CSIL, 2017), which would threaten the holistic mission of the 2030 Agenda. It seems that companies are prioritizing some SDGs focused on climate, well-being, or growth at the expense of ecosystems or food security (KPMG, 2018). Another notorious aspect to avoid is the use of the SDGs as a “greenwashing” marketing instrument to induce behaviour change in consumers or stakeholders, which could yield a loss of trust (Pimonenko et al., 2020).

Rendtorff (2019) analyses the SDG's role as a governance tool and driver for business ethics and CSR, triggering the transformation of the economic model. Martinuzzi and Schönherr (2019) claim for impact-oriented, collaborative, data-intensive, universal systemic framework to guide companies in better measuring their impacts.

Cordova and Celone (2019) underlined the relevant role of industrial innovation as a driver of the SDGs. Govindan et al. (2020) study the particular barriers to the SDGs concerning the novel “industrial sharing economy” paradigm. Van Tulder (2018) advises purpose-driven businesses to tackle wicked problems, guided by principles to understand and integrate the Goals.

Redman (2018) claimed to address communication, tactical and strategic issues. Vildåsen (2018) perceived the SDGs as a platform for debating social and environmental concerns with stakeholders, facilitating collaboration. Rubio-Mozos et al. (2019) underscored the role of purpose-driven SMEs and entrepreneurs, claiming for a new systemic “engagement ecosystem” shifting to a sustainable growth model aligned with the 2030 Agenda.

A framework for SDG business reporting has been designed by leveraging the Global Reporting Initiative (GRI) standards, the Global Compact and the Responsible Investment principles (Global Reporting Initiative and UN Global Compact, 2018) although it presents limitations. Szennay et al. (2019) analyse the relationship between the SDGs and GRI indicators confirming a strong link but also business coverage gaps.

Muff et al. (2017) suggested a framework to translate goals into business opportunities, nurturing the SDG Compass which presents an ambiguous and low-ambitious scope. Current tools are not appropriate, evidencing a lack of proper indicators (Lopez, 2020), open-source rankings or standards based on impact. Hence better guides and standards are urgently required (Topple et al., 2017).

In essence, embedding the SDG into the corporate strategy and reporting, while avoiding counterproductive prioritization is essential. This relies on fostering collaboration with stakeholders and building novel guidelines and tools towards raising ownership. Regardless of the utmost relevance of business for achieving a sustainable future, little is known about how companies can integrate the goals into corporate governance and business models (Dahlmann et al., 2019) demanding further and interdisciplinary research (Dalby et al., 2019).

Academic Realm

The relevance of science, research and education communities for catalysing the SDGs has been broadly acknowledged (Colglazier, 2015; ECOSOC, 2019a; Leal-Filho et al., 2019b; Kopnina, 2020; Messerli et al., 2019; Priyadarshini and Abhilash, 2018; Saito et al., 2017; Schmalzbauer and Visbeck, 2016; Stafford-Smith et al., 2018; UN, 2019d).

Undeniably, science is crucial to providing significant indicators and monitoring systems to understand interactions and complexities (Schmalzbauer and Visbeck, 2017; UN, 2019d). Nonetheless, a profound understanding of its contribution, along with proper indicators, roadmaps and reporting processes are required (Colglazier, 2015).

Education is a multiplier for sustainability, therefore, new transformational educative models (Zamora-Polo et al., 2019) and governance frameworks (Kickbusch and Hanefeld, 2017) which activate sustainability are required, although it remains a challenge (Giangrande et al., 2019). The current education role within the 2030 Agenda is questioned, for being unable to recognize extant paradoxes, promoting an economic-based notion of development, and lacking ecology ethics (Kopnina, 2020).

Despite progress, a lack of capacity persists in most academic institutions regarding sustainable practices. Gaps in research and practice particularly in terms of demographic diversity could hinder education for sustainability (Rashid, 2019).

Moreover, science and research communities should yet agree on a common ground about ethical and epistemic values around sustainability (Schneider et al., 2019).

Public Sector and Governments

Given the enabling character of public institutions, they play a leading role in driving the Agenda governance (UN, 2018a; UN, 2019b; UN, 2019e), particularly towards supporting SDG16. A holistic approach comprising all the dimensions of sustainability and related interlinks, together with the reinforcement of synergies, alignment and collaboration across scales is required to break down silos (Cutter, 2015; Dalby et al., 2019). New integrative systemic models and tools are needed to guide policymaking (Collste et al., 2017; Liu et al., 2015).

Civil Society

Little attention has been paid to the role of civil society (Martens, 2019) and individuals, which is also linked to localization, despite their immense potential contribution to the SDGs (Li et al., 2018). Indeed, consumption represents 60% of the global wealth (UNCTAD, 2019), thus, citizens are relevant agents in pursuing a more sustainable society (Micheletti et al., 2014). The historic global demonstrations for climate action in 2019, have shown the potential behind mobilizing civil society towards sustainability purposes. However, spaces for civil society participation are limited, therefore constraining the respective influence on sustainable policy and the SDGs implementation, revealing a “democracy-influence paradox” (Sénit, 2019).

Citizen science also constitutes a relevant data source which could be integrated into the SDGs reporting system (Fritz et al., 2019). Public awareness, citizen engagement, ownership and people-centric indicators are critical and must be enhanced (EESC, 2018; Guan et al., 2019; Lucci, 2015; Rubio-Mozos et al., 2019; Thinyane, 2018; UN, 2019d) and bottom-up governance should be better leveraged (Martens, 2019). Knowledge about behaviour formation towards the goals is limited (Guan et al., 2019). Hence, further research and policy development is desirable to fully explore the meaningful contribution of civil society to change patterns and accelerating change.

Multi-Stakeholder Partnerships

These alliances are fundamental drivers of SD, helping to rally different actors while bridging market failures, “free rider” issues or governance gaps (Nelson, 2017; Van Zanten and Van Tulder, 2018). Thus, cross-sectoral, public-private and collaborative partnerships are considered crucial elements for successfully achieving and funding the 2030 Agenda in line with the UN Addis-Abeba Action Agenda (UN, 2015c; Dalby et al., 2019; Florini and Pauli, 2018; Horan, 2019; Kolk et al., 2017; OECD, 2019c; UN, 2019d; ECOSOC, 2019b; UN SDSN, 2019).

Certainly, the 17.16 and 17.17 targets focus on effective public-private and civil society partnerships. Particularly, data partnerships are essential for the responsible use of digital technologies (Data4SDGS, 2019; Data-Pop Alliance, 2017; UN SDSN, 2019; WEF, 2019a).

Rasche et al. (2019) argue that enhanced legitimacy and accountability are needed to evolve the use of data for development through partnerships. Sussha (2020) discusses that data collaborations are promising although little is known about how to successfully implement such partnerships.

However, articulating partnerships and bringing together different stakeholders is not forthright. Strong complexities, implementation and governance hurdles, unclear impacts (Berrone et al., 2019; UN DESA, 2019) or limited effectiveness persist (Beisheim and Ellersiek, 2017; Melo, 2018; Nelson, 2017).

Horan (2019) reveals two main caveats regarding the identification and implementation of transformative and efficient partnerships, and suggests enhancing: “compensation, collaboration, capacity, coordination and incentives”. Success strongly depends upon stable political and economic structures not always available. Aligning actors, and providing incentives and instruments are also challenges.

The added value brought by partnerships has yet to be clarified and they need to be scaled up to leverage their transformative power (UN Global Compact and Accenture, 2018). Further research based on facts and contextual understanding is needed for leapfrogging and scaling the partnerships for the SDGs.

Pluriversal approaches

In addition to multi-stakeholder partnerships, it is necessary to promote pluriversal approaches that represent all perspectives. Advancing the triple transition demands that actors from the digital, environmental, and social sectors engage in close cooperation, reflecting the respective transitions into the 2030 Agenda.

In conclusion, clarifying the roles, and responsibilities and unlocking the engagement, ownership, and collaboration of all the actors, at all levels of society in the same direction, is essential to accelerate transformation and progress for pursuing the goals.



Figure 2.2. Scheme of the Key Stakeholders for Achieving the 2030 Agenda
(Own elaboration)

2.4. Categorization of the SDG Research Gaps and Opportunities

In this research, the rationale behind the Sustainable Development Goals has been examined, uncovering their main research gaps which deserve future attention, summarized as follows.

As discussed in the literature review, recent research has been dominated by discussions on the systemic nature of the 2030 Agenda and the interlinkages between its goals and targets, which continue to pose significant challenges for both research and policy development (i.e. Allen et al., 2019b; Barbier and Burgues, 2017; Griggs et al., 2017; Liu et al., 2018; Liu et al., 2015; Nilsson et al., 2018; Saito et al., 2017; Schmidt et al., 2017; Stafford-Smith et al., 2017; Weitz et al., 2018).

Despite the rapidly expanding body of literature on this critical topic, the interlinkages remain poorly understood and insufficiently integrated into policy.

This caveat is especially significant about trade-offs (Allen et al., 2019b; Barbier and Burges, 2019; Dolley et al., 2020; Kroll et al., 2019; Obersteiner et al., 2016; Pradhan et al., 2017; Scherer et al., 2018; Von Stechow et al., 2016), and transboundary spillovers (McCollum et al., 2018; Sachs et al., 2019a; Schmidt-Traub et al., 2019).

Thus, the current state of research remains highly fragmented and filled with contradictory findings, which hinders a comprehensive understanding of the systemic network of goals.

Notably, as Dawes (2019) argued, current knowledge of the SDG network and its structure cannot be considered consistent. Existing studies are uneven, highly context-dependent, and often challenging to generalize, with frequent contradictions.

A consensus acknowledges this flawed understanding, resulting in poorly defined prioritization that threatens to undermine the holistic nature and effective implementation of the 2030 Agenda. Moreover, multiple complexities (Allen et al., 2018; Griggs et al., 2013; McCollum et al., 2018; Georgeson and Maslin, 2018), combined with a dearth of suitable tools and effective science-policy interfaces persist, and continue to pose significant challenges (Allen et al., 2018; McCollum et al., 2018).

There is a clear need for further research to address this significant gap, through novel science-based methodologies (Sachs et al., 2019a; Van Soest et al., 2019). These methodologies must handle complexities across various contexts, scales, and disciplines, by integrating qualitative and quantitative approaches (Karnib et al., 2017a; Karnib et al., 2017b; Obersteiner et al., 2016).

Moreover, strengthening science-policy interfaces (McCollum et al., 2018; Obersteiner et al., 2016; Zimm et al., 2018), along with enhancing transnational cooperation (Breuer et al., 2019; Georgeson and Maslin, 2018; Nilsson et al., 2016; Schneider et al., 2019; Weitz et al., 2019) are crucial for acknowledging interactions and then informing policy prioritization.

Drawing on the research insights gained through the examination of the challenges and opportunities of digital transformation for sustainability, it is evident that innovative technologies (Breuer et al., 2019; Kroll et al., 2019; Schneider et al., 2019), especially digital solutions and capabilities, have the potential to supercharge and accelerate scientific discovery, as well as to improve governance in addressing the complexities and caveats of SDG interlinkages.

Secondly, an emerging strand of literature denounced the design shortcomings and significant imbalances within the current SDG framework, including included diluted ambition (Fukuda-Parr and McNeill, 2019), extreme complexity (Ala-Uddin, 2019), inconsistencies (Spaiser et al., 2017; Swain, 2018), and contradictions (Crespo-Cuaresma et al., 2018; Dalby et al., 2019; Vasconcellos Oliveira, 2018).

Additionally, the framework is criticized for omitting or underrepresenting ecological and human-centric issues (Allen et al., 2016; Dalby et al., 2019; Gasper et al., 2019; Giannetti et al., 2020; Gupta and Vegelin, 2016; Martinez-Harms et al., 2018; Spijkers, 2018; Stevens and Kanie, 2016; Vasconcellos Oliveira, 2018; Weber, 2017) and for its unevenness and lack of integration across dimensions, with an overly strong financial focus (Ala-Uddin, 2019; Lempert, 2017; Priyadarshini and Abhilash, 2018; Pogge and Sengupta, 2015; Scherer et al., 2018; Stevens and Kanie, 2016; Swain, 2018; Weber, 2017).

Furthermore, critics pointed to its absent alignment with widely recognized frameworks in sustainable development (Lempert, 2017; Saner et al., 2019), and its feeble transformative narrative (Costanza et al., 2016; Leal-Filho et al., 2019a).

Prior studies evidenced a weak enactment approach (Diaz-Sarachaga et al., 2018; Horton, 2015), unresolved tensions across scales and dimensions, and significant controversies regarding the representativeness of the targets.

Addressing these flaws is imperative, as they may erode the credibility and implementation of the 2030 Agenda (Georgeson and Maslin, 2018; Leal-Filho et al., 2019a; Saito et al., 2017). Consequently, there is an ongoing debate, characterized by divergent views on the suitability of the current Agenda framework.

This debate could benefit from a multidisciplinary science-policy dialogue (Messerli et al., 2019) and the application of novel analytical capacities (McCollum et al., 2018).

Additionally, emerging sustainability trends, such as conscious capitalism (Mackey and Sisodia, 2013), "net-positive" or "handprinting" (Kühnen et al., 2019), and the multi-capital value creation models (Ruijs et al., 2018), have the potential to enrich this debate, yet they remain largely overlooked in current literature.

In light of this analysis, a critical reassessment of the 2030 Agenda is highly recommended (Ala-Uddin, 2019; Salvia et al., 2019; Saner et al., 2019; Stevens and Kanie, 2016). This reassessment should aim to address the unveiled shortcomings and balance the different sustainability dimensions (Bergman et al., 2018), thereby embedding a genuinely holistic approach to sustainable development.

Moreover, a relevant body of literature is devoted to persistent implementation and governance challenges, (i.e. Bartram et al., 2018; Caiado et al., 2018; Dalby et al., 2019; Georgeson and Maslin, 2018; Griggs et al., 2017; Priyadarshini and Abhilash, 2018; Yingchun et al., 2018).

Most implementation hurdles are closely tied to discerning the localization, along with integration aspects (Allen et al., 2019a; Allen et al., 2016; Fukuda-Parr and Muchhala, 2020; Kabisch et al., 2019; Salvia et al., 2019; Schmidt-Traub et al., 2019; Stafford-Smith et al., 2018).

A closer examination of recent studies uncovered fragmented governance (Monkelbaan, 2019), numerous integration challenges, and a lack of comparative analyses across different contexts (Allen et al., 2016; Dickens et al., 2019; Elder and Bartalini, 2019; Engström et al., 2019; Huan et al., 2019; Lafortune and Schmidt-Traub, 2019; Salvia et al., 2019).

This multidisciplinary Agenda presents complex issues that are not yet fully understood (Allen et al., 2018; Caiado et al., 2018; McCollum et al., 2018; Messerli et al., 2019), and reveals tensions across scales and dimensions, potentially leading to inappropriate prioritizations (Allen et al., 2018; Georgeson and Maslin, 2018; Zhou and Moinuddin, 2017).

Furthermore, policy gaps persist due to missing whole-of-government approaches and the inadequate integration of contextual issues (Messerli et al., 2019). In this context, developing and understanding coordination mechanisms for addressing transboundary challenges remains an area that requires further advancement (Amos and Lydgate, 2019; Schmidt et al., 2017).

Despite their importance, only a handful of studies examined the funding gap (Barua, 2019; Dalby et al., 2019; Lagoarde-Segot, 2020). Additionally, the roles of capacity-building, awareness-raising (Bowen et al., 2017), knowledge management (Mastrángelo et al., 2019; Barrantes-Briceño and Almada-Santos, 2019), and transformative narratives have been insufficiently explored (Bengtsson et al., 2018; Kanie et al., 2019; Stevens and Kanie, 2016). Therefore, these topics merit further research and deeper consideration.

Other aspects such as the multi-level governance (Dalby et al., 2019; Martens, 2019; Messerli et al., 2019; Sachs et al., 2019a), the integration beyond silos allowing cross-fertilization (Allen et al., 2018; Dalby et al., 2019; Obersteiner et al., 2016; Stevens and Kanie, 2016; Spijkers, 2016), and the alignment among various governance levels, disciplines, and stakeholders present significant opportunities for overcoming current challenges (Biermann et al., 2017; Leal-Filho et al., 2019a). However, thus far these aspects have received limited attention.

Therefore, there is a clear need for further assessment and the development of novel analytical tools (Caiado et al., 2018; Sullivan et al., 2018) to address governance uncertainties and contextual nuances. This advancement is crucial for developing science-based systemic approaches (Bartram et al., 2018; Liu et al., 2015; Stafford-Smith et al., 2018) and creating interfaces that can effectively inform policy (Georgeson and Maslin, 2018; Karlsson-Vinkhuyzen et al., 2018; Schmalzbauer and Visbeck, 2016).

Based on the uncovered gaps, there is a clear opportunity to harness digital capabilities to address these challenges. Moreover, the development of policy and financial enabling frameworks is crucial, serving as key leverage points. These frameworks should be guided by science and innovative, holistic approaches to effectively tackle the complexities of sustainable development.

Prior research has emphasized the significance of measuring progress through monitoring and evaluating the SDGs (Dalby et al., 2019; Lu et al., 2015; Persson et al., 2016; Reyers et al., 2017; Schmidt-Traub et al., 2017; Yonehara et al., 2017). Nonetheless, significant research challenges persist, particularly regarding accountability (Bebbington and Unerman, 2018; Bowen et al., 2017; Wackernagel et al., 2017; Zimm et al., 2018), the absence of appropriate taxonomies (Xu et al., 2020), and the lack of robust methodologies and analytical tools (Crespo-Cuaresma et al., 2018). These gaps continue to hinder the needed comprehensive assessment (Lior et al., 2018; Lu et al., 2015).

Additionally, little attention has been paid to exploring the conflict between accountability and integration (Karlsson-Vinkhuyzen et al., 2018), and the dynamics across various scales (Xu et al., 2020), which merits further investigation to cope with context-specificities. A context-based assessment that goes beyond mere indicators is urgently needed (Barbier and Burgess, 2019; Fukuda-Parr and McNeill, 2019; Renn et al., 2020; Reyers et al., 2017; Schönherr et al., 2019; Schwandt et al., 2016). Such an assessment should be capable of capturing both the qualitative and quantitative nuances of sustainability and reflecting the complexities inherent in the SDGs (Dang and Serajuddin, 2020).

Another relevant gap is related to the limitations of current metrics. As argued by Brussel et al. (2019), many studies focusing on indicators reveal notable shortcomings and inconsistencies, often resulting from a lack of solid scientific foundations and dialogue. Consequently, there is a consensus on the inadequacy of existing metrics and a pressing need to develop new, more appropriate ones (Annan-Diab and Molinari, 2017; Barbier and Burgess, 2019; Dlouhá and Pospíšilová, 2018; Galli et al., 2018; Georgeson and Maslin, 2018; Hák et al., 2016; Janoušková et al., 2018; Lehtonen et al., 2016; Ordaz, 2019; Salvia et al., 2019; Storey et al., 2017).

Several scholars advocate for a critical review of current metrics that moves beyond GDP-based indicators (Campagnolo et al., 2018; Coscieme et al., 2020; Costanza et al., 2014; Hak et al., 2016; Mair et al., 2018; Merry, 2019; Rubio-Mozos et al., 2019; Saito et al., 2017; Schmidt-Traub et al., 2017; Suciu and Năsulea, 2019). Besides, an open debate on alternative indices is ongoing (Diaz-Sarachaga et al., 2018; Fioramonti et al., 2019; Lozano et al., 2018; Suciu and Năsulea, 2019).

Moreover, severe limitations regarding data availability (Dang and Serajuddin, 2020; Jacob, 2017; Lozano et al., 2018; Martens, 2018), interoperability, and analytics (Dawes, 2019; Hickel, 2019) continue to hinder progress. As Dang and Serajuddin (2020) argued, these difficulties stem not only from the indicators themselves but also from the way the goals are formulated, which suggests a need for their refinement to facilitate their interpretation.

Thus, this analysis underscores the need for further research efforts on the road to enhance accountability, assessment approaches, and indicators, particularly for the less developed indicators that currently lack robust methodology or data (Fukuda-Parr and McNeill, 2019). Additionally, there is a critical need to address the, so far overlooked, transboundary spillovers (Sachs et al., 2017; Schmidt-Traub et al., 2019).

Given the exceptional prospects that digital transformation may offer in this realm, this research contends that a comprehensive exploration of the digital paradigms (e.g., Big Data Analytics and AI) to provide novel data sources, proxies, and analytics, would be highly valuable in overcoming the limitations of current indicators.

Regarding headway on the SDGs, early literature unveils truncated adoption, off-target trajectories, and uneven advancements across different contexts (Dalby et al., 2019; Sachs et al., 2019a), alongside fragmented knowledge. This situation may stem from a confluence of insufficiently addressed implementation challenges (Bryan et al., 2019), policy gaps (Moyer and Hedden, 2020), limited capacity, and geopolitical megatrends.

As Sabau (2020) suggested, limited progress could also be the result of a narrow interpretation of sustainability values. Additionally, some authors highlight that ignoring transboundary issues and spillovers is a major obstacle to advancement (Sachs et al., 2019a; Sachs et al., 2017; Schmidt-Traub et al., 2019).

Additionally, current reporting systems have faced criticism due to struggles with data quality, inconsistency (Wackernagel et al., 2017), and contradictory findings. These concerns indicate the need for better alignment of the SDGs with existing frameworks (Biermann et al., 2017), the development of new benchmarks, along with the adoption of a multidisciplinary perspective (Lozano et al., 2018).

Accelerating progress is urgently needed (Moyer and Hedden, 2020; Sachs et al., 2019a). These points underscore the need for data-driven, systemic, and context-sensitive approaches to track progress dynamics and encourage adoption. This, in turn, presents an opportunity for digital paradigms, where digital capabilities could play a highly supportive role.

Furthermore, recent studies emphasized the relevance of encouraging engagement and ownership among all actors (Galli et al., 2018; Lucas et al., 2016; Messerli et al., 2019; Schönherr et al., 2017), along with promoting global collaboration to deliver the Agenda goals (Dalby et al., 2019; Frey and Sabbatino, 2018; Kurz, 2020).

However, research reveals several drawbacks in this regard, potentially linked to unclear roles and responsibilities (Spangenberg, 2017) within a non-binding Agenda (Biermann et al., 2017), along with the persistence of siloed approaches and inertias (Bergman et al., 2018; Cutter, 2015; Dalby et al., 2019).

Besides, the added value and means of implementation of the SDGs for the different actors (i.e. businesses, academia, civil society, and public sector) have not been clearly articulated. Thus, a profound and systematic analysis is required to discern these relevant concerns.

Concerning this, a growing body of literature examined the role of business in pursuing the 2030 Agenda, underlining both their significant potential (Cordova and Celone, 2019; Frey and Sabbatino, 2018; Schönherr et al., 2017), and their considerable drawbacks in terms of involvement (Vazquez-Brust et al., 2020), and yet-uncertain added value (Van Zanten and Van Tulder, 2018).

Several studies have noted the lack of effective reporting tools and guidelines (Dahlmann et al., 2019; Dalby et al., 2019; Lopez, 2020; Topple et al., 2017) and the uneven alignment between corporate strategies, policy priorities, and scientific perspectives. These deficiencies can lead to cosmetic approaches, superficial engagement, or counterproductive "cherry-picking" practices (Pimonenko et al., 2020), ultimately undermining the holistic, purpose-driven vision of the 2030 Agenda.

Therefore, establishing a mutual understanding of the sustainability meaning is crucial, as argued by Schneider et al. (2019). Additionally, exploring emerging corporate trends and purpose-driven models, along with the regenerative paradigm, could further enrich this discussion.

When it comes to the role of civil society, despite its relevance, both grassroots movements and society participation have been assessed to a very limited extent (Li et al., 2018; Martens, 2019; Sénit, 2019). Little is known about behaviour formation and strategies for raising public awareness and involvement in support of the Goals (Guan et al., 2019; Lucci, 2015; Rubio-Mozos et al., 2019). Further research in this area could be useful for accelerating progress toward the Goals. Furthermore, relevant factors such as cultural influence (Rosati and Faria, 2019), barriers to adoption, education (Kopnina, 2020), and capacity building remain poorly explored.

Concerning a very relevant pillar of the agenda, the partnerships, the literature underscored the outstanding potential of the collaboration mechanisms and multi-stakeholder alliances to unite diverse actors and break down siloes (Amos and Lydgate, 2019; Dalby et al., 2019; Florini and Pauli, 2018; Horan, 2019; Kolk et al., 2017; Vazquez-Brust et al., 2020). Indeed, as Vildåsen (2018) argued, the 2030 Agenda can serve as a platform for dialogue across stakeholders. Nevertheless, collaboration issues remain underexplored, revealing complexities and governance obstacles that merit further examination (Berrone et al. 2019; Beisheim and Ellersiek, 2017; Melo, 2018; Nelson, 2017).

The insights derived from the literature evidence that in-depth research is required to profoundly understand these reported challenges. Given the outstanding capacities of digital ecosystems to spur collaboration (Pappas et al., 2018), this research suggests that a novel approach based on leveraging digital tools and capabilities could significantly enrich this domain by strengthening collaboration, driving transformative narratives, and influencing behaviours to accelerate progress toward the Goals.

In addition, the review has uncovered a critical challenge for this dissertation: the role of technological innovation in knowledge creation, diffusion, and transfer. Certainly, the essential role of technological innovation diffusion and knowledge transfer for accelerating transformations toward the SDGs has been explored in only a limited number of recent studies.

The current research points to significant opportunities (Centobelli et al., 2020; Colglazier, 2015; Cordova and Celone, 2019; Walsh et al., 2020), but also highlights uncertainties and trade-offs, particularly concerning ecological conservation and social welfare (Aldieri et al., 2019). Notably, major knowledge gaps persist in the literature (Barrantes-Briceño and Almada-Santos, 2019; Mastrángelo et al., 2019).

Moreover, technology and innovation are often narrowly addressed within the current Agenda framework, as noted by Walsh et al. (2020). Key aspects, such as the diffusion of spillovers (Aldieri et al., 2019), knowledge flows, social impacts (Corsi et al., 2020), and environmental concerns (Capasso et al., 2019), remain underexplored. Other aspects such as responsible research and innovation (RRI) (Thapa et al., 2019; Van der Leeuw, 2018; Lehoux et al., 2018), systemic complexities (Labanca et al., 2020), and inclusive or grassroots innovation, are also poorly considered. These gaps underscore the need for additional research, together with the full integration of these factors into policy frameworks.

Most studies acknowledged that policy heralds as an essential mediator in overcoming potential market or structural failures, impacts, and externalities (Aldieri et al., 2020; Capasso et al., 2019; Sinha et al., 2020; Walsh et al., 2020), while promoting the diffusion of eco-innovation and knowledge-sharing (Berawi, 2017). However, given the limitations of current policy agendas, several authors argued that they need to be reoriented to foster eco-aware, responsible, and inclusive technology-driven transformations toward sustainable development (Centobelli et al., 2020; Vatananan-Thesenvitz et al., 2019; Walsh et al., 2020).

In contrast, others suggest that neither technology nor policy alone can drive sustainability transformations (Köhler et al., 2019) since additional factors such as strategic planning, enabling mechanisms, regulations, and competencies are required (Rogge and Reichardt, 2016; Edmondson et al., 2018; Walsh et al., 2020).

In this context, digital technologies have emerged as essential tools for shaping knowledge creation (Fukuda-Parr and McNeill, 2019) and driving sustainable transformations (Pappas et al., 2018). Nonetheless, the literature offers a limited exploration of this potential opportunity.

In light of the insights gained, this research argues that technology and innovation, particularly within the digital realm, are crucial enablers for advancing the SDGs, provided they are utilized ethically and in an environmentally sustainable manner. Further research is essential to discern present challenges and unlock the full potential of technology and innovation in service of the 2030 Agenda.

Despite the challenges unveiled, this dissertation emphasizes the remarkable opportunities available to address such caveats and accelerate progress toward the 2030 Agenda, as illustrated in Figure 2.3.

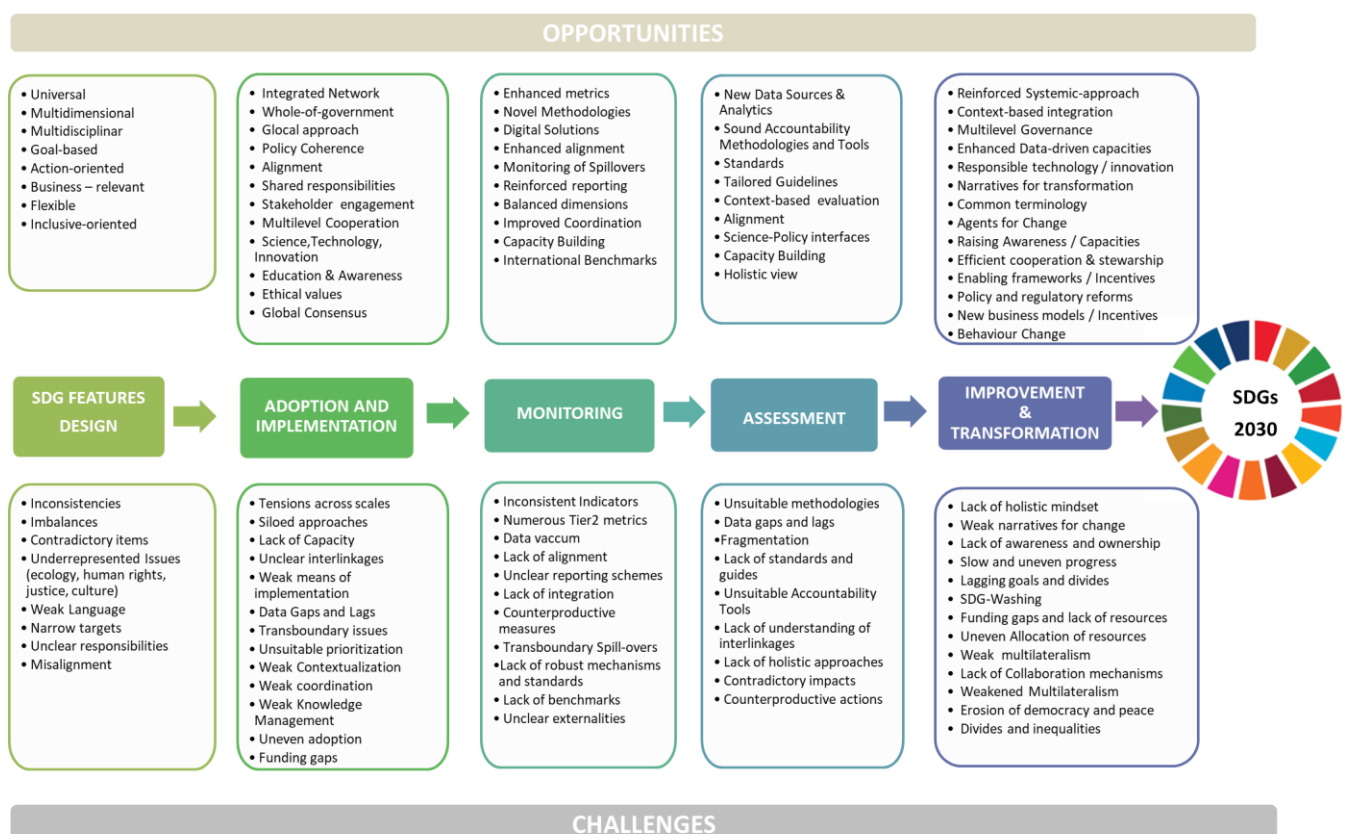


Figure 2.3. Categorization of the Opportunities and Challenges for the SDGs Realization
(Own elaboration)

In this context, some potential solutions lie in harnessing the digital revolution opportunities and fostering innovation for both environmental and social benefit. Furthermore, the evolution of the 2030 Agenda towards meeting the novel demands of the regenerative triple transition (digital, ecological, and socially just), emerges as a crucial pathway forward.

This research identifies seven key clusters of research gaps within the SDGs, each requiring further exploration and offering significant potential to benefit from digital technologies and innovations. A detailed outline of these gaps is presented in Table 2.1. Additionally, these gaps are further examined in the next chapter.

Table 2.1. Clusters of Research Gaps in the SDG Framework

(Own elaboration)

Research Gap and Related Phase of Governance
RG1. Systemic Nature and Understanding of Interlinkages (<i>Design that also affects the implementation</i>)
RG2. Design Shortcomings and Imbalances (<i>Design that also affects the implementation</i>)
RG3. Whole-of-Governance Hurdles (<i>Implementation and Governance in general</i>)
RG4. Monitoring and Evaluation Challenges (<i>Implementation and Governance in general</i>)
RG5. Truncated Adoption and Uneven Progress (<i>Implementation and Governance in general</i>)
RG6. Unclear Roles, Responsibilities, and Limited Cooperation (<i>Design, implementation, and governance</i>)
RG7. Untapped Innovation, Technological Development, and Knowledge Management (<i>Design, implementation, and governance</i>)

2.5. Concluding Reflections on the Evolution of Sustainability and the SDGs

In this dissertation, the evolution of the sustainability notion towards the emergence of regenerative perspectives has been examined, along with the categorization of the design and implementation gaps within the 2030 Agenda, which require further exploration and concerted efforts from all stakeholders.

Indeed, the concept of sustainability has evolved from an ecological focus to encompass a moral and economic imperative for societal progress. This encompasses frameworks like “stakeholder theory,” and the “triple bottom line,” to contemporary approaches, including circular economy principles, resilience building, and regenerative practices.

Despite growing awareness, this concept remains complex, and controversial, showing a substantial “sustainability gap,” where intentions often fail to translate into meaningful action, hindered by fragmented governance, financial inertia, and short-term thinking. Future progress in sustainability calls for integrating robust, cross-disciplinary frameworks that address interconnected risks, consider long-term ecological and social impacts, and foster inclusive, purpose-driven practices with regenerative value across all sectors. In this regard, this dissertation emphasizes the reorientation of sustainability towards regeneration, as a critical pathway to address global challenges.

The United Nations’ 2030 Agenda endorsed in 2015, proposed 17 Sustainable Development Goals (SDGs) across five pillars (planet, people, peace, prosperity, and partnerships), intended to catalyse a shift by a comprehensive and universal framework for sustainable development.

However, this blueprint is non-binding, requiring unprecedented cross-scale cooperation, policy coherence, and systemic transformation to realize its goals. At the midpoint of the 2030 Agenda, progress remains uneven and lagging, calling for bold actions and transformative changes. Despite these challenges, the SDG framework has achieved relevant advances, including raising global awareness of sustainability issues and mobilizing unprecedented international cooperation and policies across multiple sectors, which provide a solid foundation to accelerate progress in the coming years.

Regarding the general structure of the 2030 Agenda, it embodies a network of interconnected goals, where synergies and trade-offs among targets reveal complexities yet to be fully understood. Challenges persist in analysing these interlinkages, with varied methodologies, from qualitative expert judgments to quantitative modelling, and hybrid strategies. The fragmented literature reflects contradictory findings, uncovering significant knowledge gaps, particularly concerning causality and context-specific interactions. Overall, this evolving field calls for context-sensitive approaches, using both qualitative and quantitative techniques, alongside integrating causal inference and expert interpretation, to guide SDG-based policies more effectively.

Building on these insights, this dissertation identifies this research gap as the most critical within the SDG context and provides a sound overview of existing methodologies and potential future directions to address it more effectively.

The SDGs were shaped by complex political processes rather than scientific dialogue, leading to design caveats, diluted ambitions, complex language, lack of coherence (Fukuda-Parr & McNeill, 2019), and predominancy of the economic dimension, at the expense of social equity and ecological protection (Ala-Uddin, 2019; Stevens & Kanie, 2016).

While the macro-level goals are broadly supported, the targets are considered narrow, unrepresentative, and challenging to measure. Furthermore, they have been criticised for lacking actionable implementation and clear accountability (Spangenberg, 2017) and being unable to address the root causes of inequality (Dalby et al., 2019). Therefore, the 2030 Agenda needs to be revisited to integrate established international agreements and emerging sustainability trends, shifting toward truly systemic, and interdisciplinary approaches (Saner et al., 2019). In this sense, this dissertation aims to address this research gap, by exploring strategic recommendations for renovating the 2030 Agenda towards a refined and regenerative approach.

Considering the design caveats, the 2030 Agenda remains heavily focused on economic growth, while key ecological and social aspects concerning inequality, ecosystem protection, and human rights, receive limited coverage (Ala-Uddin, 2019; Swain, 2018). Particularly, the environmental goals have been diminished limiting their transformative potential (Elder and Olsen, 2019), and the educational objectives are ambiguous and lack precise indicators (Kopnina, 2020). Yet, innovations with a regenerative lens bring a unique opportunity to provide solutions to address these challenges.

To address these design imbalances, a more comprehensive, integrative, systemic approach that equally emphasizes ecological, social, and economic dimensions is essential, supported by ethical frameworks and guided by strong sustainability principles (Bergman et al., 2018). Moreover, critical areas like digital transformation, alongside science and innovation, lack an appropriate representation despite their relevance for sustainable development. Considering their significance, these research gaps are considered a priority in this dissertation, thus they are explored in Chapters 3 and 4.

Concerning implementation, the SDGs also face numerous challenges and policy barriers at every stage, from planning and financing to monitoring and impact assessment. The efficient implementation of the SDGs relies on localization, integration, and multilevel governance. While the SDGs were designed as universal goals, they must be adapted to national contexts with varying local priorities, which complicate the alignment (Allen et al., 2016; Stafford-Smith et al., 2018). Nonetheless, this presents an opportunity to address the challenges through “glocal” strategies, connecting local realities with global goals (Jones & Comfort, 2019; Terama et al., 2019).

Improving governance structures, evidenced-based policies, and robust and flexible implementation methodologies, based on reliable indicators and data, is critical for an effective implementation of the SDGs (Schmalzbauer & Visbeck, 2016). However, fragmented governance hinders progress, and the 2030 Agenda lacks mandatory reporting mechanisms and coordinated efforts across government levels, which favours “cherry-picking” practices. Therefore, a science-based, whole-of-government, and whole-of-society approach that fosters alignment, policy coherence, and coordination across domains and stakeholders is needed (Karlsson-Vinkhuyzen et al., 2018; OECD, 2019a).

Additionally, science-policy interfaces are required to manage complexities and support systemic transformations. SDG implementation also depends on having effective monitoring and impact assessment frameworks, as they support accountability and inform policy adjustments.

However, numerous challenges persist, including data gaps, inconsistent indicators, inadequate methodologies, and limited statistical capacity to assess progress across geographies and time. In light of the caveats and opportunities identified, as well as the disconnect between policies, disciplines, and research agendas, this dissertation aims to capture and organize existing knowledge, by categorizing the key SDG challenges and prospects, to provide a more cohesive understanding of the field.

In terms of metrics, as of 2024, the indicator framework included 157 Tier I indicators with complete data and methodology, 66 Tier II indicators lacking data coverage, and a few multi-tiered indicators. The current reliance on institutional indicators risks overlooking complex interactions and local context, which are essential for understanding progress and effectiveness.

The limited data availability, especially for environmental and health goals, and the lack of comprehensive metrics for trade-offs and transboundary impacts persist. Digital technologies and innovations, including data-driven analytics and data capture solutions (e.g., IoT, geospatial systems), hold substantial potential to enhance SDG accountability, by providing novel tools, capacities, ecosystems, and data sources. Though, they remain underutilized and insufficiently integrated into existing frameworks. For that reason, addressing this research gap has been identified as a priority of this dissertation. If effectively managed, responsible digitalisation and innovation can act as catalysts for sustainable systemic change.

As of 2024, progress toward achieving the SDGs remains off-tracked, uneven, and hindered by numerous global crises from 2020 onward, such as the COVID-19 pandemic, economic slowdowns, and geopolitical tensions. Notably, no country has achieved all goals, only 15% of targets are on track, and even high-performing nations face significant challenges, particularly on environmental and equality goals. In part, this has been caused by the lack of cohesive governance, low engagement, and outdated policies.

Research advocates establishing more ambitious commitments and developing innovative tools to support progress towards sustainable development at both national and global levels. Promoting an equitable digital transformation emerges as a critical enabler for that purpose. Addressing these challenges is, therefore, another core priority of this dissertation.

Another crucial aspect relies on cohesive collaboration, ownership, shared responsibility, and active engagement among all the stakeholders, including civil society. Yet, the 2030 Agenda lacks clarity around stakeholder roles and responsibilities which limits a fully integrated and engaged approach. Reinforcing multi-stakeholder cooperation is essential for achieving the SDGs, as each actor brings unique strengths. Given the relevance of this aspect, this dissertation aims to explore pathways to promote closer collaboration through enhanced ecosystems and meaningful contributions from all stakeholders towards achieving the 2030 Agenda.

In conclusion, the valuable insights drawn from the SLR have allowed the preliminary categorization of the most relevant challenges and opportunities within the SDG context. Furthermore, this critical and holistic review has identified key research priorities, which are further examined in the following chapters. Particularly, Chapter 3 analyses the interplay between digital transformation and sustainability, and its role in addressing the uncovered SDG caveats and opportunities.

It is important to note that part of the findings presented in this chapter have been included in an article that has been published with the following reference in a Q1-indexed journal: Del Río Castro, G., González Fernández, M. C., Uruburu Colso, Á. (2021). *Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review*. Journal of Cleaner Production, 280(Part 1), 122204. <https://doi.org/10.1016/j.jclepro.2020.122204>.

The next chapter focuses on the examination of the interplay between sustainability and digital transformation, analysing the risks and opportunities that digital paradigms pose to social and environmental well-being.

3. The Interplay between Sustainability and Digital Transformation

3.1. Understanding Digital Transformation

The advent of digital paradigms, together with the explosion of computational power and data availability, has triggered a new era, heralded to disrupt science (Schmidt and Cohen, 2013), facilitated a data-driven economy (WEF, 2019c), and knowledge society (Grech and Camilleri, 2017).

The IIASA's TWI2050 report (2019) considered this novel era as the “Digital Anthropocene”, transforming humanity. Yet, a paradox emerges in this new era: while digitalization is crucial for achieving sustainability transformations, it also challenges society's absorptive capacity.

Indeed, digital paradigms have disrupted every facet of the economy and society (Feroz et al., 2021). The data deluge, processed by intelligent algorithms and powerful computing, alongside advanced connectivity, provides unprecedented capabilities to explore, understand, predict, optimize, and innovate in areas that were inscrutable before (Hey et al., 2009; Manyika, 2011; McKinsey, 2016). Physical and virtual worlds are converging giving birth to novel realities and defies (e.g., Virtual Worlds) across sectors (Shi et al., 2023; Zainab et al., 2022).

Digital transformation is propelled by diverse and powerful digital paradigms that synergistically interact together to harness the data deluge and available analytics for enhancing all areas of activity. In this regard, IoT networks and Space Technologies such as Earth Observation capture relevant data, Big Data Analytics and AI distil data into knowledge with the support of advanced computing, and Blockchain allows transparency and traceability. Together, these technologies can unlock novel insights, which drive more informed decision-making across sectors and all areas of life.

Nevertheless, digital transformation transcends mere technology, giving rise to novel cultural, social, and multidimensional phenomena (Boyd and Crawford, 2012) that extend across disciplines, blurring boundaries (Etzion and Aragon-Correa, 2016), and fostering a complex and highly interconnected network (Letouzé and Pentland, 2018).

Notably, digital transformation has occurred abruptly and disruptively, without the theoretical, and regulatory development necessary for its adequate governance and guidance. Initially, this phenomenon began with the integration of digital technologies as mere enablers, but over time, it evolved into a succession of disruptive waves. Therefore, a consensus terminology has yet to be agreed upon.

UN (2023d) emphasized that digital transformation is a broader phenomenon than “digitisation” and “digitalisation”. Digitisation involves the conversion of analogue information into digital formats, while digitalisation refers to the use of digital technology to enhance business processes, and productivity, and bring social benefits.

In this regard, Vial (2019) defined digital transformation, as a process driven by disruptive digital technologies, triggering strategic responses from organizations to alter their value creation paths and addressing structural changes with a consideration of dynamic capabilities and ethical concerns. Similarly, Feroz et al. (2021) defined DT as the “unprecedented disruptions in society, industry, and organisations stimulated by advances in digital technologies”.

Certainly, the literature described digital technologies as inherently disruptive (Karimi and Walter, 2015), impacting behaviours, and communication capabilities, and reshaping business models by bringing disintermediation, new actors, and networks (Chawla and Goyal, 2022).

They also allowed novel trends that radically change business and society, such as the “product-as-a-service models” (Andrae, 2021), personalization, or the quantification of reality through data.

This dissertation interprets digital transformation as a dynamic process wherein the economy and society undergo a profound evolution driven by digital technologies, capacities, and ecosystems. This evolution engenders new opportunities for enhanced value creation across all spheres and dimensions of society.

The cornerstones of the digital era offer immense potential to create new value propositions (Gartner, 2020), enabling operational performance and efficiency, supporting decision-making and accountability, and building capacities and awareness. Given its exceptional power to approach complex societal issues, it has become an integral part of governmental agendas (Etzion and Aragon-Correa, 2016; UN, 2019b; World Bank, 2018b).

Thus, the digital revolution grants a powerful tool to build up smart and green development (Perez, 2019), and sustainable governance (Etzion and Aragon-Correa, 2016; Seele, 2016a). This primarily relies on harnessing the so-called “data revolution for sustainable development” (Jacob, 2017; UN, 2014).

However, where there is light, shadows inevitably follow. Digitalisation is often surrounded by hyperbolic expectations and unrealistic promises (Kiron and Unruh, 2018; Becker, 2023). It also brings about multiple concerns and yet unknown risks (Letouzé and Pendtland, 2018; Bremer et al., 2023; D4S, 2023). Therefore, the potential of digital paradigms to drive sustainable development remains controversial (Fernández-Portillo et al., 2019).

A critical aspect to underline is that digital technologies must be integrated and harnessed in conjunction with human oversight and expert judgment to ensure proper governance and interpretation. The significance and power of digital transformation have provoked a sense of urgency to ensure that digital advancements are compatible with human values and environmental well-being.

Therefore, a balance between promoting the development of enabling technologies potentially benefiting sustainable development, with sound ethical principles and fair regulations becomes imperative to navigate the future where technology is seamlessly integrated into everyday aspects.

As a result, science and society are at a crossroads, facing either an upheaval or a metamorphosis, where digital paradigms will reshape how humanity lives, and will transform society's imaginaries and fabric (Helbing et al., 2017).

3.2. Digital Transformation and Sustainability

Digital transformation and sustainability are game-changers and strategic imperatives which are converging, triggering major transformations (Kiron and Unruh, 2018; Osburg and Lohrmann, 2017; Seele and Lock, 2017; Kürpik et al., 2022).

The interplay between digital transformation and sustainability is perceived as a winning combination, not exempt from challenges (Kürpik et al., 2022), offering opportunities within and across organizational boundaries for overcoming extant informational voids (UN, 2023a). Notwithstanding, an increasing number of experts consider that both domains are seen as conflicting, thereby driving paradigm shifts in social and ecological systems (Gebhardt, 2017).

In this research, the intricate relationship between digital transformation and sustainability unfolds in two crucial directions that converge (see Figure 3.1).

First, this interplay demands a meticulous examination of how digital disruptions affect sustainability. The primary objective is to ensure that digital transformation not only prevents harm but also contributes positively to promoting both societal well-being and environmental revitalization. Hence, digital transformation must be sustainable and aligned with regeneration practices.

Second, it also calls for harnessing digital paradigms as powerful catalysts for sustainability and regenerative development. Therefore, digital solutions must be responsibly and sustainably unlocked to enable beneficial social and environmental contributions.

The challenge lies in effectively confronting and mitigating the detrimental consequences of digital transformation, while concurrently maximizing its outstanding capacity to drive positive change and eco-social transformations. This bidirectional phenomenon with twin directions is represented in Figure 3.1.



Figure 3.1. Twin Directions of the Convergence between Digital Transformation and Sustainability
(Own elaboration)

Despite its potential and growing interest, the nexus between sustainability and digital transformation remains poorly explored and leveraged (Feroz et al., 2021). Little is known about whether and to what extent the digital era could contribute to or jeopardize sustainable landscapes (Seele and Lock, 2017), and how to enable sustainable digitalisation. Therefore, a responsible and well-enunciated synergy between digital transformation and sustainability is unavoidable but, thus far, remains untapped.

On one hand, the potential of digital paradigms to spur sustainability has been widely recognized by numerous experts and organisations (Corbett, 2018; De Camargo-Fiorini et al., 2019; Harwell, 2019; Gijzen, 2013; Gouvea et al., 2018; Hilty and Aebischer, 2015; ITU, 2017a,b,c; El Hilali and El Manouar, 2020; Madudova et al., 2018; Seele, 2017; Seele and Lock, 2017; UN, 2019b; WEF, 2020a; World Bank, 2018b; Zhao et al., 2017).

In this regard, El Hilali and El Manouar (2019) contended that both digitalisation and sustainability necessitate radical shifts in value creation and have the potential to mutually reinforce each other. Notably, digital paradigms are increasingly recognized as enablers of sustainable development in multiple ways (Fernández-Portillo et al., 2019; Van der Velden, 2018a). According to Holst et al. (2017), they facilitate human progress, personalization, and reframe business models for investors and consumers, thereby encouraging behaviour shifts and circular economy adoption.

Additionally, digitalisation can enhance transparency and accountability, thus facilitating better ESG analysis (Kiron and Unruh, 2018; Seele, 2016b). It also accelerates innovation (WEF, 2020a), promotes education (Ahel and Lingenau, 2020), and supports evidence-based decision-making (GeSI, 2019; ITU, 2017b; Tjoa and Tjoa, 2016).

Complementing these perspectives, Feroz et al. (2021) argued that digital transformation can drive positive disruptions in terms of pollution control, waste management, sustainable production, and urban sustainability. Nevertheless, further research, robust strategies, and capabilities are needed to fully leverage its potential.

Similarly, Gomez-Trujillo and Gonzalez-Perez (2021) emphasized that digital transformation can promote corporate sustainability by enhancing new digital capabilities while simultaneously managing in a more balanced manner the economic, environmental, and social impacts. In addition, Meré et al. (2020) underlined that digitalisation can enhance knowledge creation in manufacturing and service industries, thereby facilitating more sustainable practices. Popovs and Drinke (2022) proposed a reciprocal relationship where sustainability efforts drive digital transformation, and vice versa, creating a mutually reinforcing cycle.

According to the UN (2023d), digital transformation can bring significant social benefits and is useful for addressing societal challenges such as urban smart management, cleaner energy, remote healthcare access, access to government online services, online learning, environmental conservation, and disaster management, among others.

On the other hand, the benefits of digital transformation are not equally distributed, with relevant disparities in Internet access between genders, nations, income levels, and rural or urban areas. While digitalisation presents opportunities for achieving the SDGs, it also poses significant and poorly managed risks, such as the misuse of digital technologies for harmful purposes, such as cybercrimes, and power concentration, and ethical challenges, like privacy violations and data misapplication (UN, 2023a). Sachs et al., (2023) claimed that universal digital access and services should be granted while ensuring online Human Rights and sustainable development. For such purpose, concerted actions by all the stakeholders, including governments, businesses, academia, and civil society are required.

Therefore, digital transformation poses sustainability concerns, yet to be disentangled, related to environmental impacts, social divides, and ethical issues. In this context, a huge space for policy action exists (IEEE, 2018), along with a glaring new field of research (Scholz et al., 2018). This claims urgent structural change and normative safeguards to shape digitalisation towards the common good (Lane et al., 2013).

The literature also reveals a gap in understanding change management pathways for a sustainable digital transformation (Pacolli, 2022), based on responsible leadership, effective communication, and inclusion (Philip, 2021). In this regard, ambidexterity is identified as crucial for navigating DT (Nyagadza, 2022), by promoting the coexistence of exploration and exploitation (Peng et al., 2019).

Open innovation platforms and hybrid governance models offer opportunities to achieve a more inclusive digital transformation driving better societal outcomes, but challenges persist (UNDP, 2019). Indeed, society must harbour potential digital pitfalls. As argued by Casilli (2019), despite that digital platforms were expected to promote democracy, they have resulted in power concentration, misuse of technology, and hazarding privacy and labour rights, alongside inducing “technological solutionism” (Morozov, 2017).

Therefore, to ensure whole-of-society participation and sustainable outcomes, all digital ecosystems and technologies should evolve to fully embed sustainability values.

As argued by Teli et al. (2021), technological development and social transformations have historically arrived in waves, each influencing the other. The digital revolution represents one of such waves, where technological advancements and their subsequent societal and environmental changes are profoundly interconnected.

Similarly, Sautter (2021) pointed up that participatory approaches and collective actions are crucial elements for shaping digital ecosystems toward sustainability and aligning them with the SDGs. This scholar also underlined the need for a "multi-actor, multi-sector, and multi-level" approach to realizing a sustainable digital transformation. Certainly, digital ecosystems have been evolving with unclear differentiation of the boundaries (Gupta et al., 2019), acting as a nexus connecting individuals (crowds) and communities with shared interests.

Thus, grassroots movements, civic activism, and the active participation of social communities are also vital in achieving the "sustainable appropriation" of digital technologies, by focusing on eco-social concerns (Teli et al., 2021). Indeed, digital transformation plays a transformative role in empowering citizens (Ghilic-Micu et al., 2019). The global social fabric encourages innovations that foster relationships, trust, cohesion, and cooperation (EC, 2019). In this regard, collaborative governance involving governments, companies, and civil organizations is essential for long-term sustainability in complex global value chains related to the digital realm, like electronics (Evans and Vermeulen, 2021).

According to Carayannis and Campbell (2021), to ensure inclusive and effective digital and sustainability transformations, the involvement of citizens and co-creation approaches must be prioritized, especially in light of the massive amount of personal data generated by digital technologies. In this sense, novel paradigms such as the "web4.0" ecosystem aim to empower citizens and mitigate risks in the digital world (EC, 2023a), underscoring the importance of integrating the triple transition in this realm.

Besides, when used responsibly, novel digital paradigms can facilitate novel alliances and promote the rise of the commons, peer production, user data markets, and global value networks (EC, 2019), which potentially, could promote sustainability.

Despite the optimism presented in both literature and policy regarding the potential of digital transformation for sustainability, there exists limited concrete evidence of its net positive impact. The lack of systemic and holistic studies evaluating the impacts of digital transformation underscored the need for a more profound analysis to understand the true sustainability effects of digital transformation efforts.

Furthermore, critical experts such as Becker (2023) asserted that the current digitalisation landscape is insolvent to sustainability and advocated for its redirection. Similarly, Akande et al. (2019) argued that a substantial gap between digital technology and sustainability is evidenced. In this regard, Van der Velden (2018b) suggested the reorientation of the digital revolution towards sustainability within the planetary boundaries. While El Hilali and Manouar (2019) claimed to unleash sustainability through digitalisation.

Thus, tackling the dark side of the digital age (Turel et al., 2021; Aldhafferi, 2018), demands a "digital reset" (D4S, 2023) to reorient the digital transformation towards a regenerative and inclusive design, through systemic innovation inspired by sustainability values such as circularity, sufficiency, social equity, and resilience. Both mindful research and policies should guide a sustainable digital revolution (Pouri and Hilty, 2018; Khakurel et al., 2018).

Another relevant aspect, as argued by Berendt (2019) relies on the so-called "for good" or "common good" movement, which is emerging in the context of digital transformation. These concepts do not only allude to non-profit activities but also to purpose-driven actions creating shared value for society.

Nevertheless, a lack of consensus about the meaning of "social good" persists which may drive misleading practices in the name of the common benefit. In addition, the "for good" movement represents only a small drop of pilot projects in the vast ocean of digital transformation.

One of the most critical challenges in this field is the lack of understanding and awareness about the true sustainability impacts of digital transformation and the key factors that shape the interaction between these domains. The intricate nature of this interplay is further complicated by a glaring absence of conceptual frameworks, implementation strategies, and methodologies for measuring progress, as essential elements for realizing a sustainable digital transition. These challenges hamper the ability to effectively navigate the complexities inherent in this transformation.

Hence, there is a need for multidisciplinary and multistakeholder approaches to characterize, assess, monitor, and model the full impacts of digital transformation across all the relevant societal dimensions, to unlock its potential for sustainability and ensure its responsible development (Bremer et al., 2023).

This gap is often reflected in both the scientific literature and the digital strategies that treat sustainability as a superficial rhetorical element, rather than as an integral part of digital development. This misalignment hinders the potential of digital transformation to meaningfully contribute to sustainability goals. As a result, the research landscape on digital transformation lacks holistic perspectives and sustainability is underrepresented, as argued by Hausberg et al. (2019).

A notable exception in the policy realm is Japan's "Society 5.0" strategy, which aims to create a human-centred digital society by integrating digital technologies such as AI, IoT, and robotics into all aspects of life. It envisioned a highly advanced and sustainable society where technology is used to tackle societal challenges and environmental sustainability, while fostering economic growth, leading to greater prosperity and well-being for all citizens.

In the European context, the EU's Digital Decade Communication (2021) emphasized a human-centred, sustainable, and prosperous digital future within a global context. In addition, Muench et al. (2022) explored the EU's strategy for achieving "twin green and digital transitions" as the foundational pillars for a competitive and resilient future.

To address the risks and leverage the transformative potential of digital transformation for sustainability, Luers (2020) suggested five actions including formulating a new social contract, ensuring open access to knowledge, fostering collaboration, promoting research and innovation, and enhancing communication, engagement, and education.

Additionally, the Montreal Statement (Sustainability in the Digital Age, 2020) advocated for an equitable digital future and underscored the importance of inclusive efforts, along with collaborative approaches to guide the responsible integration of digital technologies for sustainability. Moreover, the UNEP's Coalition for Digital Environmental Sustainability (CODES, 2022) recommended promoting and acting for sustainable digitalisation.

In conclusion, the convergence of digital transformation and sustainability presents significant opportunities for driving sustainable development and the SDGs. Yet, these opportunities are accompanied by substantial challenges that must be addressed. It is crucial to further understand and address the potential impacts of digital transformation on both social and environmental sustainability by multistakeholder, multidisciplinary, and mindful approaches to responsibly harness the full potential of the digital era for sustainable development and the triple transition.

3.3. Unveiling the Digital Dimension within the Agenda 2030

As previously introduced, digital transformation and sustainability have become journey fellows on the transition towards a greener, flourishing, and socially just future. Indeed, sustainability and digitalisation are both transformative forces with a vocation to confront the traditional economy and society models, creating novel enhanced realities. Both have innovation (from the Latin “*innovatio*” meaning create something new) in their heart as the main driver of change.

The integration of technology and digital transformation within the framework of the 17 Sustainable Development Goals is a multifaceted and continuously evolving landscape, brimming with significant potential for societal impact. Indeed, the role of digital transformation as one of the six key driving transitions to achieve the 2030 Agenda for sustainable development is widely acknowledged (Sachs et al., 2019). Particularly, Sachs et al. (2023) underlined the relevance of universal digital access and services, including education, for reaching the SDGs.

The UN (2023d) emphasized that, while digitalisation offers opportunities to achieve the SDGs, it also poses risks, underscoring the need to address these challenges to ensure that they truly contribute to sustainable development. Fuso Nerini et al. (2024) underscored the role of emerging digital technologies, such as Artificial Intelligence (AI), in both advancing and potentially hindering SDG progress.

The SDG Summit 2023 and the Summit for the Future (UN, 2024a) highlighted the crucial role of digital transformation in advancing the SDGs. These global fora underlined the commitment to bridging global digital divides, especially in developing nations, by bolstering digital infrastructure, capacities, and access to technological innovations through robust partnerships.

Indeed, ensuring responsible use of digital technologies plays a crucial role in enhancing social protection systems by promoting inclusivity. This approach supports equitable access to technological advancements and digital resources, essential to bridging the digital divide. Collaborative efforts between governments, private sectors, and civil society are vital for creating accessible digital infrastructures and policies that prioritize fairness and equality. These partnerships enable a more comprehensive integration of technological innovations, ensuring that the benefits of digital transformation are widely shared and contribute to sustainable and inclusive growth.

Furthermore, the recently launched Global Digital Compact (GDC) and Pact for the Future by the UN (2024b) placed a significant emphasis on aligning digital transformation with the SDGs. This framework underlined critical aspects such as closing the digital divides, accelerating the SDGs, and safeguarding Human Rights online to the same standard as offline rights.

It also claimed that potentially risky technologies, such as AI, are developed and deployed in ways that prioritize societal benefit and contribute to the SDGs. This framework, while mostly aspirational at the policy level, is expected to serve as a blueprint for aligning digital advancements with global sustainable development objectives.

Despite the relevance of digital transformation for the 2030 Agenda and the aforementioned high-level commitments, in practice, there remains a notable absence of a comprehensive framework and practical tools to ensure its responsible implementation (Sachs et al., 2022).

In this regard, Luers (2020) argued that the 2030 Agenda falls short of comprehensively addressing the challenges posed by the digital age. This expert proposed a collective initiative for addressing this caveat, along with a profound enhancement of the current SDGs framework.

Moreover, the literature reveals that the integration of digital transformation within the 2030 Agenda is vague and fragmented. Indeed, there are only five targets related to digital aspects, and they are distributed across four goals (SDG9, SDG17, SDG4, and SDG5).

The lack of a robust, coherent, and clearly defined framework for integrating digital transformation into the SDG framework may hinder the effective implementation of digital technologies in advancing global challenges holistically. Besides, the absence of a unified framework for monitoring the sustainability of a critical phenomenon such as digital transformation further exacerbates the challenge. As a result, digital transformation efforts remain largely siloed and disconnected from sustainability values, preventing their broader application in tackling intertwined issues like climate change, inequality, and poverty at scale.

Hence, establishing a more cohesive, goal-oriented framework that fully embeds digital transformation potential into the 2030 Agenda for sustainable development, is crucial for harnessing digital innovations in the service of sustainability and human development.

The ambitious triple ecological, socially just, and inclusive digital transition has not been fully integrated either into the SD frameworks. Hence, it is imperative to address the ethical, social, and environmental concerns that may arise in digital transformation and reflect them into the global agenda for sustainable development.

In this regard, Yamamoto (2023) advocated for the development of a digital SDGs framework, aimed at enhancing knowledge integration across sectors. In addition, this study underscored the need for a holistic approach to integrating the implementation of both the SDGs and digital transformation in a more coherent and aligned manner.

The UNEP's Coalition for Digital Environmental Sustainability (CODES, 2022) also emphasized the need to reinforce the sustainability dimension of digital transformation and to align it more effectively with the 2030 Agenda. This includes addressing path dependencies and ensuring stakeholder involvement and transparency.

Another key aspect of digital transformation is knowledge management, yet it is not adequately developed in the current design of the 2030 Agenda and remains ambiguous according to Barrantes-Briceño and Santos (2019).

In this matter, Hübscher (2020) pointed out the critical role of knowledge management in this integration. This author underlined the relevance of developing a flexible system supporting knowledge-intensive work and a comprehensive framework for managing technological knowledge. Ilvonen et al. (2018) explored how digital transformation impacts knowledge protection. They underlined the growing importance of knowledge sharing in physical work settings, alongside increased inter-organizational collaboration. However, this shift presents new challenges for protecting knowledge, particularly in networked environments.

Collectively, these studies underscored the critical importance of adopting a comprehensive and integrated approach to leveraging technology and digital transformation in advancing the SDGs.

Kadom and Kader (2021) explored the dynamics of digital transformation, analysing both the challenges and opportunities that come with its implementation. They elucidated the necessary rules of change required to support the adoption of digital transformation while emphasizing the subsequent positive impacts on the economy in the context of the SDGs. The authors conclude that while digital technology offers outstanding opportunities, its success relies on the institutional capacity to adapt and integrate them into broader development strategies,

The deficient integration of digital technologies into the 2030 Agenda also extends to broader aspects related to science, technology, and innovation (STI). Despite high-level policies emphasizing their importance, the relevance of STI aspects is not reflected in the design of the agenda nor its targets.

Indeed, the relationship between Science, Technology, and Innovation (STI), digitalization, and sustainability remains unclear and underdeveloped, both in terms of scientific evidence and practical implementation. Despite the growing political and societal interest in these intersections and an increasing number of publications, concerns persist regarding genuine systemic integration. Additionally, there is a lack of comprehensive understanding of the interplay between eco-social systems and digital innovation. This fragmentation undermines the potential of digital technologies to facilitate genuine progress toward global sustainability.

According to Walsh et al. (2020), the technological aspects included within the 2030 Agenda primarily emphasized technology transfer. However, the planetary and social boundaries, along with their respective ecological and societal dimensions are overlooked (Eichler and Schwarz, 2019).

Digital paradigms have the potential to profoundly influence knowledge creation and expedite the shift towards sustainability (Fukuda-Parr and McNeill, 2019), particularly when the interconnectedness among key innovation stakeholders is strategically utilized to amplify added value. Nevertheless, current knowledge management within the agenda is not properly addressed as previously exposed.

Thus, the convergence and co-evolution of the agendas for innovation, sustainability, and digital transformation are necessary to encourage systemic change towards sustainable development (Walsh et al., 2020). For that purpose, further understanding of the role of STI dynamics in the digital era is needed to bridge current barriers and promote societal opportunities (Vatananan-Thesenvitz et al., 2019).

Notably, the future of the world hinges on the strategic alignment of digital transformation and innovations with sustainability, fostering a harmonious balance that effectively mitigates risks while capitalizing on abundant opportunities.

In conclusion, while the potential of digital transformation to foster sustainability and contribute to the achievement of the SDGs is outstanding, current shortcomings unveil the urgent need to reorient both digital systems and the 2030 Agenda framework for better alignment. This renovation is crucial to ensure that both sustainability and digital transformation are fully aligned and integrated, thereby jointly contributing to a sustainable and inclusive future.

3.4. The Emergence of the Triple Transition

Having introduced the interplay between sustainability and digital transformation, this section focuses on underlining the significance of the emerging paradigm of the "triple transition". This novel approach encompasses the concurrent digital, environmental, and socially just transitions that are reshaping global systems. The triple transition recognizes that each of these transitions is interconnected, and progress in one area can substantially impact the others. Thus, they need to be managed in an integrated and aligned manner.

As previously introduced, sustainability has been heralded as an imperative for digital transformation (Etzion and Aragon-Correa, 2016). According to Helbing (2012), without considering sustainability, the digital era would lead to serious threats and increasing vulnerabilities. Indeed, deprived of a responsible approach, the exponential development of digital technologies could lead to dire consequences for humankind and the planet. Thus, society must accept the responsibility of making digital technology more sustainable, ethical, and human-focused, as argued by Leonhard and Graf-von-Kosporoth (2017).

In this regard, the nexus between digital transformation and sustainability implies bidirectional phenomena. Digitalisation is a powerful tool for contributing to sustainability, and a sustainable digital transformation is also an imperative for society.

The turbulent global landscape, featured by planetary crises, deepening inequality, green hypocrisy, and disruptive technologies has rendered existing frameworks obsolete for driving the systems-wide eco-social transformations that the world needs (Reyers et al, 2022; Seyfang and Haxaltine, 2012). The present and future trajectory of digital transformation is critical for sustainable development. This demands its full alignment with the values represented by the 2030 Agenda, the Paris Agreement for tackling climate neutrality (COP21), and the Montreal Protocol for the protection of biodiversity.

While the so-called “twin digital and green transitions” (Muench et al., 2022) have been influencing recent policy developments, such as the European Green Deal, there is a growing recognition of the need to also ensure a socially just digital transformation for a fair distribution of the related cost and benefits. As argued by Kyriakopoulos et al. (2022) and Muench et al. (2022), the green and digital transitions must be synchronized and work together, as their complementary goals and synergies require effective integration. Nevertheless, there exists also tension and conflicting goals amid these realms, and besides, they are affected by social, economic, and political factors. Concerning the just transition approach, it represents a novel eco-social contract (Krause et al., 2022).

Furthermore, Norström et al. (2023) underscored the risks of decoupling digital transformation and sustainability. Moreover, Pauliuk et al., (2022) emphasized the imperative of sustainability in this context, while Kürpik et al., (2023) pointed out the challenges of achieving such a “dual transformation”. According to Muench et al. (2022), the materialization of the twin transition relies on proactive management and widespread stakeholder collaboration to leverage the synergies and address the trade-offs between green and digital ambitions.

This momentum has given rise to the “Triple Transition” paradigm (OECD, 2023a; Caro-González et al., 2023), which seeks to harmonize the digital, environmental, and social transitions into a cohesive framework for novel development models prioritizing both people and the planet. The triple transition advocates for systemic change, by leveraging social dynamics to foster sustainable development. Yet, this is still an emergent concept which remains poorly explored in literature and largely neglected in policies. A comprehensive and global-scale strategy that integrates the triple transition is thus far lacking. (i.e., EU's Global Gateway strategy). (OECD, 2023a). Thus, further research and policy development is needed to align and harmonize these realms to drive the triple transition.

Nevertheless, because of their complex multidimensional nature and the nascent state of play, the triple transition and the nexus between digitalisation and sustainability remains untapped, and little is known about how to seize its opportunities while minimizing pitfalls, evidencing manifest research and policy gaps. Consequently, further research on this interplay is needed, as well as new policies and governance approaches.

Certainly, the realization of a sustainable digital transformation that contributes to the triple transition will be determined by how digital technologies, regulations, and policies are shaped today. Hence, it is crucial to ensure that digital development is aligned with both ecological and social objectives (Adams et al., 2018; Osburg and Lohrmann, 2017; WBGU, 2019).

As previously described, digital transformation holds great potential for overcoming societal problems. While digitalisation can accelerate sustainable transitions, particularly, ecological, and social shifts in the industrial domain (Beier et al., 2017), some prerequisites should be ensured to manage its potential impacts (Khakurel et al., 2018; Pappas et al., 2018; Stuermer et al., 2017).

However, according to Chazhaeva et al. (2019), the extant conception of the digital realm does not ensure its sustainability. In addition, further dialogue across sectors and actors is needed, since ICT or digital for sustainability, and a sustainable digital system even when related are different notions, as underlined by Hofstetter et al. (2020).

In this challenging context, there is an urgent need to cultivate novel imaginaries that steer digital transformation towards a genuinely sustainable trajectory, aligning it with the environmental and socially just transitions.

Pansera et al. (2019) raised concerns about the alignment of digitalisation with degrowth principles and democracy, while Vandeventer et al. (2019) advocated for interdisciplinary collaboration and a “pluriverse” approach to transformative processes, conceptualizing degrowth as a radical niche innovation. Wiek et al. (2012) emphasized a paradigm shift towards transformational science through stakeholder collaboration, while Dignum et al. (2023) stressed the significance of interdisciplinary for understanding the complex impacts of DT.

As introduced in the previous chapter, regenerative sustainability has emerged as a great promise for transformative development which balances and aligns the values and needs of society and living systems (Gibbons, 2020; Umantseva, 2022). Nevertheless, its current adoption in the digital realm is scarce. Yet, it potentially brings outstanding opportunities for reorienting digital solutions for a positive contribution to social and ecological renewal and long-term sustainability, thereby driving the triple transition.

When envisioning potential directions for reorienting digital and sustainability transformations towards better alignment with the triple transition vision, and regenerative perspectives, a variety of approaches coexist, yet a clear consensus remains elusive.

Petmesidou and Guillén (2022) analysed the synergies and trade-offs in the triple transition, while Becker (2023) acknowledged the triple planetary crisis and emphasized the need for decoupling economic progress from resource consumption in the digital context. Caro Gonzalez et al. (2023) also advocated for a “triple transition” approach guided by eco-centric and systemic principles. Also, Elkington (2018), Raworth (2017), and Krev (2022) proposed transformative frameworks and complex systems thinking for a sustainable future. Complementing these perspectives, Haklay et al. (2023) promoted the co-creation of digital tools fostering a pluriverse of pathways to the future.

Furthermore, Dervishaj (2023) proposed a shift towards regeneration as a net-positive and stakeholder-centric ethos. Naboni and Havinga (2019) established foundational pillars for regenerative design, while George and Schillebeeckx (2022) advocated for a purpose-driven approach to the convergence of digitalisation and the regeneration paradigm. Similarly, Morsetto (2020) suggested the integration of the circular economy to promote restoration and regeneration.

Overall, while the triple transition paradigm and the regenerative perspectives hold outstanding promise in harmonizing the ecological, social, and digital realms, its practical implementation remains nascent. At present, a salient disconnection between digital transformation and sustainability is evidenced and needs to be tackled, in light of the relevance of understanding the interlinkages and co-dependencies amid the three realms for achieving long-term sustainability goals.

Multiple research gaps, along with a clear absence of robust governance frameworks are hindering the advancement of the regenerative triple transition. Therefore, further research and policy efforts are required for the synchronization of the digital, ecological, and social transition in a way that promotes a regenerative and sustainable outcome.

3.5. Sustainability of the Digital Transformation

The digital revolution offers transformative opportunities but simultaneously presents significant challenges for achieving sustainability. The next sections introduce the research context concerning the sustainability of digital transformation, by emphasizing both opportunities and hurdles. After the introduction, a concise overview of the environmental and social impacts of digital transformation is presented, followed by an outline of the rise of deceptive practices like greenwashing and ethics washing in the digital realm.

3.5.1. The Uncertainties about the Sustainability of Digital Paradigms

The future trajectory of digitalization holds significant implications for global development. Therefore, it is imperative to enhance the alignment of digital development with sustainability values, along with ensuring its contribution to the advancement of the 2030 Agenda. As argued by Messner et al. (2019), the digital revolution has been heralded for its transformative potential, but it is characterised by a dual nature with both opportunities and challenges for sustainable development.

According to Xu (2022), digital transformation brings opportunities for promoting a more sustainable society by tackling enduring sustainability challenges and fostering equitable development. However, achieving holistic sustainability demands that the fundamental tenets of this realm guide the trajectory of digital technology development. Yet, thus far, this alignment is lacking, as digital advancements often fail to prioritize sustainability imperatives (Sparviero, 2021).

The impacts of digital transformation on the societal realm depend on how is shaped and governed (Asongu and Odhiambo, 2019; Tchamyou et al., 2019). In this regard, the classical principle of technology neutrality has been controversial within the digital sphere (Shadikhodjaev, 2021), due to its legal uncertainties and potential future consequences. Craig (2013) contributed to this discourse by examining the future evolution of policy, advocating for functional approaches that ensure an equitable impact across technologies.

Nevertheless, the literature provides substantial evidence that digital paradigms can lead to unintended negative environmental and social effects, which have not been adequately considered in policy and practice (Scholz et al., 2018; Van der Velden, 2018a; Bremmer et al., 2023). According to Becker (2023), digital technologies contribute to unsustainable consumption patterns and their ethical implications are sparking lively debates. These adverse effects present significant challenges for sustainable development.

Behind the promising prospects and hype around digital transformation, there remains a notable prevalence of controversies and uncertainties surrounding its interplay with sustainability, particularly within the corporate domain, as denounced by Jones et al. (2017), Saunila et al., (2019), Ziemba (2019).

Furthermore, this is a bidirectional phenomenon since existing policies and governance structures for sustainability and sustainable development, also fail to fully encompass the multifaceted nature of digital transformation. This inadequacy leaves a significant gap in managing the potential benefits and risks associated with digital solutions, thus hindering their alignment with broader sustainability goals.

Certainly, the scientific literature lacks a comprehensive taxonomy, conceptual frameworks, and robust measurement tools to fully depict a sustainable digital transformation.

Despite the surge in publications and the growing interest in this realm, the concept of “sustainable digital transformation” remains undefined by a universally agreed-upon terminology. In addition, it lacks the necessary standardization which creates confusion and hinders the development of cohesive strategies to harness its potential. This circumstance is aggravated by the breaches amid disciplines, which hamper the promising convergence of both domains.

Therefore, the need for developing novel approaches that better reflect and align digital, and sustainability transformations is evidenced.

The literature is highly fragmented, showing contradictory views, resulting in a lack of consensus about the net consequences of the rapid adoption of digital paradigms without the proper regulations and governance structures. Thus, it is indispensable to shape sustainable digital transformation towards a more defined, coherent, and enduring trajectory.

In essence, developing a thorough understanding of the interplay between digital transformation and sustainability, along with a responsible governance framework for this nexus is critical. Current theory and practical frameworks need further elaboration and evolution, in order to be able to contribute to a sustainable digital transformation, where potential benefits are fully harnessed and negative effects are properly prevented and mitigated.

3.5.2. The Unaddressed Environmental and Social Impacts of the Digital Paradigms

As previously introduced, the literature in this research context is still relatively nascent and characterized by considerable fragmentation and contradictions. As a result, the projected impact of digital paradigms on both environmental and social realms varies significantly across different studies, contexts, and technologies. This heterogeneity and dispersion difficult to determine the overall contribution of DT to sustainability, making it challenging to extract consistent, generalizable conclusions in this regard.

The most relevant and insightful studies in recent literature, covering the environmental and social impacts of digital paradigms, emphasized the complex and dual nature of digital transformation.

In this regard, Bremer et al. (2023) underscored the vast and uncertain digital impacts, with both positive and negative consequences. According to Bremer et al. (2023) and Coroama et al. (2022), direct environmental benefits brought by digital systems, for instance, to dematerialise and decarbonise the economy, could be offset by the rise of economic growth, consumption, and other related rebound effects. While digital transformation brings positive impacts on economic development, it also entails environmental and social costs often as externalities. Thus far, digital transformation has not succeeded in effectively decoupling economic growth from environmental damage. Similarly, Mac Feely (2019) argued that digitalisation challenges outshine its opportunities.

As argued by Becker (2023), the digitalisation phenomenon, rather than serving as a “beacon of progress” appears to be “insolvent” to the ideals of sustainability. This expert also presented a compelling argument for a paradigm shift in the existing approach to the digital domain, reorienting it towards sustainability.

Complementing these views, Pérez-Martínez et al. (2023) suggested that while digitalisation influences various domains, its impacts on sustainability, particularly in advancing environmental goals, remain unclear due to its complex and multivariable nature. A high-level analysis on this matter indicated non-causal correlations, but a closer look at specific indicators yielded inconclusive results.

Thus, the literature falls short in covering most of the environmental impacts of DT, especially the indirect effects, spillovers, and changes in human behaviour. Furthermore, multiple studies revealed the intricate relationship between digitalisation, sustainability, and governance. In this regard, Brenner and Hartl (2021) underlined the diverse perspectives of stakeholders on the connection between digitalisation and sustainability, emphasizing the influence on ecological, social, and economic dimensions. Verhoef et al. (2021) introduced a framework for analysing digital transformation, outlining its impact on organizations, individuals, and society across dimensions like technology, organization, strategy, customer, and society.

It is worth mentioning that the interplay between digitalisation and sustainability is still nascent, and so far, is mainly related to philanthropic-based projects or incidental findings from efficiency-focused efforts lacking purpose (Lee, 2014a; Shin, 2016; Watson, 2010), evidencing a clear research gap. Indeed, research regarding the sustainability of ICTs is an emerging issue itself (Yan et al., 2018), which was initially focused on narrow quantitative issues, such as energy and carbon footprints, under the term “Green IT” or “Sustainable ICT”. These terms refer to those technologies with reduced environmental impacts in comparison to conventional approaches. The genesis and most environmental-based research are related to the term “ICTs” instead of “digital technologies.”

Green IT is supposed to reduce impacts while enhancing sustainable development, thereby contributing towards the SDGs (Imasiku et al., 2019). The evolution of this field requires a broader conceptualization that transcends traditional boundaries, encompassing a wider array of digital technologies, and novel studies are addressing this need.

Certainly, the potential impacts of digital transformation on the environmental realm include a variety of effects from increased energy consumption and subsequent carbon footprint, water consumption and pollution, over-reliance on critical raw materials linked to harmful mining activities and human rights risks, generation of e-waste, degradation of natural ecosystems (Bekaroo et al., 2016).

Samuel et al. (2022) scrutinized the environmental sustainability of digital technologies, underscoring their negative impacts in terms of GHG emissions, raw materials extraction, and e-waste generation. These scholars cautioned against the dominant “carbo-centric” approach, which overlooked relevant impacts and advocated for a broader ethos of sustainability in the digital realm. For instance, Kreps et al. (2015) discussed the “Ecological World Systems Theory” (WST) as a holistic framework to assess the environmental impact of ICTs.

Some studies also reflected the potential impact of digital solutions on environmental well-being and health (LaPointe, 2018). These impacts are often linked to electronic waste (Aksin-Sivrikaya and Bhattacharya, 2017; WEF, 2019b; WEF, 2020a), raw materials production and disposal, which also impacts biodiversity and natural ecosystems (Baldé et al., 2017; Khakurel et al., 2018; Osburg and Lohrmann, 2017; WEF, 2020a). Certainly, the electronics industry, particularly semiconductors, is highly polluting (Kuo et al, 2022).

Also, ICTs have been implicated in dire ecological and human rights consequences associated with supply chains and mineral extraction, notably exemplified by conflicts over resources such as Coltan (Aksin-Sivrikaya and Bhattacharya, 2017).

Furthermore, digital infrastructures are associated with growing energy and water consumption (Mytton, 2021), together with pollutant emissions (ITU, 2017b; Tjoa and Tjoa, 2016; Becker, 2023) and generation of e-waste. Without a doubt, the most prominent area of research revolves around the energy consumption and associated GHG emissions of digital infrastructures, such as data centres, along with other digital systems and devices.

In contrast, the ICT sector is relatively committed to achieving climate neutrality by 2050 (e.g., Climate Neutral Data Centre Pact, n.d.), but the current narrow focus on carbon aspects has led to what is termed “carbon myopia”, where the broader environmental and social impacts of digitalization are overlooked.

Even in this area, the literature reveals controversies regarding the actual potential of digital transformation to mitigate climate change, with advocates in favour (Dong et al., 2022, Khan et al., 2020), and detractors against it (Lange et al., 2020). Moreover, as argued by Lange et al. (2020), positive effects may be offset by increased consumption and rebound effects.

In this matter, Bremer et al. (2023) justified that studies on the climate and energy effects of digitalization are fragmented, with divergent results. The carbon footprint and energy consumption of digital paradigms are, in fact, “Janus-faced,” opening controversial debates (Schulte et al., 2016; Wang et al., 2015; Yan et al., 2018).

While digital or ICTs technologies are perceived as low-carbon enablers (Wang, et al., 2023), holding the potential to promote an efficient energy landscape (Bekaroo et al., 2016; Bull, 2015; Gouvea et al., 2018; Jacob, 2018; Mirza et al., 2019), their massive development is expected to yield a huge energy and raw materials demand (Bekaroo et al., 2016; Strubell et al., 2019).

Optimistic research settings are proliferating, yet many suffer from inconsistencies in their methodologies for assessing carbon emissions across scopes 1, 2, and 3. Often, these studies relied on simplistic assumptions and technocentric approaches, lacking science-based robust environmental assessment protocols to encompass not only organizational impacts but also those along the entire value chain, including indirect effects and spillovers.

Additionally, Belkhir and Elmeligi (2018) assessed the ICT footprint, concluding that the digital sector would be responsible for 14% of the GHG emissions. Perils exist concerning growing negative footprints or perverse cascading effects increasing vulnerabilities due to the interconnected global system (Helbing, 2012).

On the contrary, Jacob (2018) explored the role of ICTs towards enabling a climate-friendly carbon future, concluding that a net-positive impact is possible, provided that suitable policy, infrastructures and means are implemented. Other scholars (Gelenbe and Caseau, 2015; Moyer and Hughes, 2012) and studies (GeSI, 2016) underlined the ability of digital solutions to reduce emissions, evidencing an “inverted-U” relation (Añon-Higon et al, 2017; Haseeb et al., 2019).

While most studies focused on direct impacts, Bieser and Hilty (2018) and Bremmer et al. (2023) underscored the significant gap in understanding the indirect environmental impacts of ICTs, which extend to influencing production and consumption patterns, notably consumer behaviour. Consequently, various facets of digital solutions may inherently harbour sustainability challenges (Unwin, 2017; Becker, 2023), yet these aspects remain inadequately explored (ITU, 2017b; Letouzé and Pentland, 2018; MacFeely, 2019).

Another noteworthy area of inquiry revolves around the interplay between efficiency gains and rebound effects, prompting experts to advocate for caution (Coroamă and Pargman, 2020). While digitalisation can improve resource efficiency and optimisation across industries, it also sparks rebound effects and exacerbates consumption patterns (Bremer et al., 2023; Coroamă et al., 2022; Coroamă and Friedemann) that can outweigh the positive effects.

Yet, the relationship between digitalisation, sustainable consumption and production, and related rebound effects remains unclear (Bremmer et al., 2023; Coroamă et al., 2022; Coroamă, Vlad C. and Friedemann).

Notably, the rebound effects in the digital domain represent an intricate challenge. In this matter, Coroama et al. (2019) and Gossart (2015) examined the potential of digitalisation to spur increased resource consumption (i.e., digital rebound). Adelmeyer (2017) studied this phenomenon within the realm of cloud computing, identifying potential rebound effects and advocating for a framework to mitigate them. Freeman (2018) contributed with a theoretical perspective, proposing that the magnitude and repercussions of the rebound effect may evolve in the future due to constraints on natural resources.

Considering the broad assessment of the impacts, Bolte et al. (2022) suggested that a comprehensive approach integrating all relevant impacts is imperative and should consider the entire life cycle and hidden risks of the digital technologies and supporting value chains. Nevertheless, an in-depth assessment of the environmental and social impacts of digital paradigms has not yet been developed in the literature.

Indeed, Bordage et al. (2021) emphasized the multitude of challenges and limitations inherent in conducting a comprehensive environmental assessment of digital services. These obstacles encompassed the swift pace of technological advancement, restricted access to high-quality data, opacity in reported data, and discrepancies among data sources. However, their study, employing a rigorous Life Cycle Assessment (LCA) methodology, provided compelling evidence that digital services indeed carry a significant carbon and material footprint.

Recent literature has been focused on the specific impacts of relevant digital technologies such as Artificial Intelligence (AI), recognizing their profound implications for global sustainability and development (Van Wynsberghe, 2022 and 2023; Saetra, 2021).

Thus, the notion of digital transformation as a potent force for resolving global environmental challenges is met with scrutiny by numerous experts, underscoring the imperative to acknowledge and mitigate rebound effects (Coroamă and Mattern, 2019).

Given the net impact of digital technologies on the sustainability realm, it remains uncertain (Horner et al., 2016). Despite the burgeoning literature, contradictory views, lack of understanding and poor accountability prevail in this matter (Becker, 2023; Bremmer et al., 2023). This is mainly caused due to the insufficient understanding of rebound and induction effects of digitalisation (Gensch et al., 2017; Pohl et al., 2019; Coroamă et al., 2019, 2020).

Therefore, there is a growing need for comprehensive in-depth research and integrated management strategies that address both environmental and social considerations of digital solutions (Wang et al., 2015). To understand and effectively manage the environmental impacts of digital paradigms, systematic and quantitative assessments are needed, but thus far are lacking. This encompasses Life-Cycle Analysis, including the assessment of the energy and water consumption, material footprint, biodiversity assessment and e-waste, among other impacts.

Furthermore, digital transformation also provokes negative impacts on the social realm, such as those derived from power asymmetries, misinformation, human rights abuse, and digital divides, among many others (ITU, 2017b).

Understanding the social impacts is even more complex, with limited clarity on how digital technologies either support inclusion and well-being or exacerbate divides and social problems.

For instance, phenomena like “neocolonialism,” and digital “neo-feudalism” in trade and increasing digital service consumption widen inequalities and pose threats to democracy (D4S, 2023). Ethical issues are particularly significant, and thus far, insufficiently addressed (Floridi, 2019).

In addition, the emerging digital realities pose risks to mental health, and research and policy have yet to adequately address the adverse consequences (OECD, 2024; Beyari, 2023; Naslund et al., 2020; Twenge and Campbell, 2018; Berry et al., 2018). In terms of labour, digital transformation also poses risks to local communities due to potential job changes (Muench et al., 2022).

Szalkowski and Johansen (2024) emphasized a significant gap in methodologies, tools, and real-world data for measuring the social sustainability of digital technologies. Although publications in this area are increasing, the field remains under-researched, with underdeveloped methodologies. The existing literature mainly focused on the adverse impacts of digitalisation on equality, inclusion, and labour conditions, while acknowledging positive effects on health outcomes.

Hence, the net social impact also remains under-researched and uncertain, demanding further research and more suitable policies, methodologies, and empirical data.

It is worth mentioning that, achieving an all-out net-sustainable benefit is always challenging in every technological domain due to tensions amid the different dimensions (Tura et al., 2018). Sustainability needs a balance within the planetary and social limits, whereas conventional development is fuelled by growth-based perspectives (ITU, 2017b).

However, sustainability issues should be pursued from a systemic perspective (Kane et al., 2019), and be supported by robust governance (Letouzé et al., 2019). Thus far, the potential to tackle all sustainability pillars has not yet been fully proven (Bonilla, 2018; Madudova et al., 2018; Pouri and Hilty, 2018). Strong gaps exist regarding the characterization of value creation, delivery, and capture (Parida et al., 2018). Yet, social aspects are gaining attention spawning new schools of thought (Fors and Lennefors, 2018).

Despite the emerging literature, several research limitations persist, and a thorough understanding of the topic at the micro-level has yet to be achieved. There is a need for the development of a comprehensive analysis (Sachs et al., 2016).

Bremer et al. (2023) advocated for the active involvement of all stakeholders, improved measurement methodologies, robust data provision, and enhanced use of standards. A multidisciplinary approach is deemed essential to comprehensively address systemic boundaries in understanding the intricate dynamics of digital impacts. To address this complexity, there is a call for the improvement of measurement and prospective modelling methodologies, the provision of robust and high-quality data, and a more effective utilization of standards. Ardito et al. (2021a) underlined the ongoing debate on the impact of digital and environmental orientations on innovation, finding positive effects independently but negative or non-significant effects when pursued together.

In essence, the environmental and social impacts of digital transformation are varied and remain insufficiently understood and addressed. Additionally, current research is highly fragmented, with abundant contradictory studies, and overly focused on narrow aspects, impeding a broad consideration of relevant impacts. Therefore, it is imperative to develop a holistic approach to characterize the intersection of digitalization, sustainability, and governance.

This should be accompanied by robust methodologies that address the full spectrum of impacts across the life cycle of all digital systems. Both theoretical and practical frameworks need further development to maximize potential benefits while mitigating the negative consequences of digital transformation.

3.5.3. The Pervasive Influence of Greenwashing and Machine-Washing

The phenomenon of “greenwashing,” meaning the deceptive environmental claims to cover questionable records (Watson, 2016), or the widespread practice of falsely portraying environmental responsibility (Jones, 2019), has garnered significant concerns in the sustainability community due to its detrimental impact.

Greenwashing is associated with deliberate misleading claims that harm society and the environment (Bowen, 2014), including hidden trade-offs, vagueness, false labels, irrelevant initiatives, and selective disclosures. This trend is especially recurrent in the digital industry (De Freitas Netto et al., 2020).

Notably, the frequent application of green and ethics hypocrisy within the digital domain has been observed, giving rise to novel deceptive practices, such as “machine-washing,” with significant and adverse consequences.

In this regard, greenwashing and machine-washing are seen as twin phenomena reflecting the disadvantages of the triple transition. Machine-washing, as coined by Wagner (2018), is a deceptive corporate strategy that involves disseminating misleading communications about ethical AI and algorithms while evading regulatory scrutiny. Similarly to greenwashing, machine-washing involves fabricating an illusory façade of positive change in digital technologies, potentially shaping regulatory directions, and surpassing legislative efforts (Floridi, 2019; Rességuier & Rodrigues, 2020).

In this matter, Seele, and Schultz (2022) identified new forms of “greenwashing” and “ethical washing” expanding into policymaking, raising concerns about the authenticity of corporate AI ethics initiatives (Johnson, 2021; Ochigame, 2019).

Indeed, according to Hazel and Morrison (2020), digital companies, aware of the relevance of sustainable practices for consumers and governments, often apply greenwashing, climate washing, or ethical washing, covering up unsustainable and dangerous practices.

Ethical concerns extend to the behaviour of big digital platforms, with experts debating whether they genuinely transform business processes into eco-friendly ones or hide risky models under fake green claims (Moskal, 2022). The notion of “ethification of ICT governance”, particularly in AI, is also analysed by Van Dijk et al. (2021) who emphasized the proliferation of non-genuine ethics in the digital context.

The debate on machine-washing extends beyond corporate boundaries to broader societal discussions, including the balance between automation and preserving high employment rates. Macro-level deliberations in Corporate Social Responsibility (CSR) explored more systemic perspectives on social and environmental concerns (Kopnina, 2019; Murray et al., 2017).

Scholars emphasized the importance of genuine Corporate Social Responsibility in the digital realm to curb misleading practices (Lyon and Montgomery, 2015; Seele and Gatti, 2017). Potential motivations behind machine-washing include reputational gains, competitive advantages, and business legitimacy (Benkler, 2019; Douek, 2019). Technology corporations increasingly engage in Machine Washing to influence AI ethics regulations (Floridi, 2019; Zuboff, 2019). Motivations may also include obscuring responsibilities (Chesney and Citron, 2019; Wagner and Winkler, 2019; Yeung, 2019).

“Machine-washing” encompasses various actions, such as adherence to voluntary ethical principles with vague claims, use of technical or legal jargon in privacy policies, and introduction of AI certification schemes lacking control (Floridi, 2019; Obar and Oeldorf-Hirsch, 2020). It involves fabricating a false public image to enhance an organization's reputation, triggering unintended network effects and potentially influencing consumer choices (Floridi, 2019; Johnson, 2019).

The hidden automation agenda of business leaders exemplifies the disconnect between public endorsements of ethical AI and the private pursuit of automation (Roose, 2019; Vasist and Krishnan, 2023). The call for regulation and transparency is evident among most experts, emphasizing the need for standardized assessment schemes and penalties for misinformation (Hazel and Morison, 2020; Marcatajo, 2022).

The European Union Directive on green claims (EC, 2023e) holds relevance in this context, albeit criticized as insufficient by numerous experts. This scepticism is particularly pronounced, as the same European Union is considering digitalisation as a green solution for sustainability (e.g., Green Taxonomy) without accounting for its environmental and social impacts.

Furthermore, the rise of ESG reporting obligations is contradictory accompanied by concerns about its accuracy due to greenwashing practices (Lyon and Montgomery, 2015; Yang et al., 2020; Yu et al., 2020).

Greenwashing and ethics-washing are not confined to corporate practices, but they also extend to other actors, including public bodies. Certainly, governmental, and international organizations have also been criticized for deceptive claims to influence public perception (MacKay and Munro, 2012). In 2019, Kevin Roose exposed influential business leaders at the World Economic Forum who publicly advocated for ethical and "human-centred AI" but privately acknowledged rushing to automate their workforces without much consideration for the consequences.

Kuntsman and Miyake (2022) examined the intricate links between digital impositions and social injustice, stressing challenges in resisting digital pressures across various domains. These authors also introduced the concept of “digital disengagement” and explored the difficulties in opting out of pervasive digital systems. Besides, they addressed issues like surveillance, algorithmic bias, data monetization, digital labour exploitation, and environmental concerns.

To navigate the intricacies of green and ethical hypocrisy, Nemes et al. (2022) proposed a tool for assessing green claims. Additionally, the insights from Adams et al. (2016) suggested that sustainability-oriented innovation (SOI) may play a role in intentional change to organization values, products, or practices for social and environmental value beyond economic returns.

However, the current understanding of SOI is dichotomous and may not fully capture contemporary practices.

Overall, deceptive practices are permeating the digital realm, posing severe challenges for tackling environmental and social risks derived from the new digital era. Robust mechanisms for impact assessment, risk management and policy interventions are needed to curb these phenomena towards instilling genuine sustainability commitments.

3.6. Digital Transformation for Sustainability

This section builds on the previous one, by focusing on how digital transformation can contribute to sustainability. First, an introduction to the research context is presented, followed by an overview of the most relevant paradigms that exemplify the application of digital technologies for sustainability purposes.

This includes mature technologies such as the Internet of Things and Big Data Analytics, emergent paradigms such as Artificial Intelligence and High-Performance Computing, alongside future promising concepts such as Quantum Technologies.

3.6.1. The Role of Digital Transformation for Sustainability and the SDGs

As previously introduced, digital transformation offers far-reaching potential in the sustainability arena. Indeed, digital solutions are increasingly used for addressing societal, environmental and governance challenges in an unprecedented fashion, as acknowledged by numerous experts and institutions (ITU, 2021; UN, 2019d; Walker et al., 2019; ECOSOC, 2019c; Sachs et al., 2019b; Smith and Neupane, 2018; UNCTAD, 2018; UN DESA, 2018; World Bank, 2018b; ITU, 2017a; UN Global Pulse, 2016).

According to UNCTAD (2024), the International Panel on Climate Change (IPCC) acknowledged the potential role of digital technologies in mitigating climate change, improving energy management and energy efficiency, as well as promoting the adoption of low-emission technologies (IPCC, 2022a).

Certainly, a relevant strand of literature is focused on digital technologies for climate change mitigation by reducing carbon emissions and adaptation in urban contexts (Akanke et al., 2019).

Muench et al. (2022) argued that digital advancements such as monitoring, simulation, virtualization, and optimisation, can bring benefits in five key areas: agriculture (e.g., precision farming), buildings and construction (e.g., energy monitoring), energy (e.g., smart grids and renewables management), energy-intensive industries (e.g., monitoring for resource efficiency and circularity), and transport (e.g., optimisation and emissions reduction).

Furthermore, the recently adopted Global Digital Compact (UN, 2024b) advocated for accelerating digital technologies for sustainable development towards the SDGs, particularly AI, while also encouraging responsible governance frameworks and global cooperation for that purpose.

Notwithstanding, digital disruptions extend beyond technology, reflecting the complex interplay between innovation, social change, and policy (Hilbert, 2016). Socio-economic enablers and a deeper understanding of the human element are equally essential in this transformation (Grech and Camilleri, 2017).

Notably, the nexus between digital transformation and the 2030 Agenda has been perceived as a “vector of hope”, not exempt from threats (Bissio, 2018). While a convergence of both the digital and sustainability transformations is compelling (Villani, 2018), thus far remains still untapped (Hampton et al., 2013; Becker, 2023).

Hong and Xiao (2024) underlined the transformative role of digital technologies, such as Blockchain and AI, in achieving sustainability goals. Particularly, these technologies can enhance supply chain coordination and accountability, mitigate environmental impacts, and promote circular business models. However, realizing these benefits relies on collaborative innovation frameworks, alongside inclusive and democratic governance, which integrate social and ecological considerations.

In this context, leveraging the benefits of digital transformation depends on harnessing the significant synergies among various digital paradigms. The convergence of the Internet of Things, Big Data Analytics, AI, Industry 5.0, Blockchain, advanced connectivity, and computing paradigms has created unprecedented capacities for sustainable development (SDG Action, 2024; ITU, 2021; BDVA, 2017; EESC, 2017). These digital paradigms enable the capture of novel data sources and transform them into actionable knowledge for better decision-making, complementing traditional techniques by augmenting human capacity, and enhancing connectivity and collaboration.

Despite its relatively early stage, emerging literature revealed the potential of digital paradigms to support, monitor, and advance sustainability and the SDGs across sectors. However, the research landscape remains highly fragmented, underdeveloped, and unevenly distributed across contexts and industries. Additionally, it lacks a comprehensive approach, exposing significant research gaps and misalignment in both the digital and sustainability realms.

The SDG Action framework (2024) emphasized the essential role of digital technologies, and particularly AI, in advancing the SDGs, by enhancing societal resilience, promoting sustainability, and improving healthcare, quality education, and climate modelling. Yet, persistent challenges remain, including issues related to data privacy, digital sovereignty, and inequalities.

Mondejar et al. (2021) explored the potential of digital solutions in achieving the SDGs and promoting a "Smart Green Planet". In particular, these authors underlined the potential benefits of the water-energy-food nexus, sustainable manufacturing, and healthcare access for vulnerable communities. They also underscored the potential for combating biodiversity loss and mitigating climate change.

Nevertheless, multiple gaps persist. In this regard, Wu et al. (2018) reviewed the correlations among SDGs and ICTs from practical use cases, identifying research gaps within the three pillars of sustainability. Tjoa and Tjoa (2016) claimed a holistic approach to include ICT impacts on the SDGs. Besides, ITU (2017b) outlined risks and opportunities behind ICT for SDGs, while the ICT-Benchmark (Huawei, 2017) reinforced the related correlations. Fernández-Portillo et al. (2019) underlined a positive relationship between ICT and SD in European countries, underscoring the need to enhance connectivity and digital skills.

Considering novel approaches, Van der Velden (2018a) suggested that sustainable digitalisation within the Planetary Boundaries is imperative. This scholar compared two frameworks: the SDGs considering digitalisation as a neutral tool and the "Doughnut Economics" framework, more integrative, and able to reveal potential negative impacts. Similarly, Townsend and Coroama (2018) plead for a "digital acceleration" of sustainability, underscoring three opportunities: resource efficiency, clean technologies, and circularity. Moreover, the WEF (2020a) called for increasing the relevance of digital technologies within the SDGs by aligning the 2030 Agenda with the 4th Industrial Digital Revolution, through novel platforms.

Additionally, Kostoska and Kocarev (2019) proposed a more inclusive ICT framework for accelerating the SDGs, reflecting both local and global perspectives, along with vertical and horizontal relationships among stakeholders, by integrating data, sustainability, and governance. In a similar perspective, El Massah and Mohieldin (2020) argued that digital transformation can impact the localization and achievement of the SDGs.

Other scholars explored the, yet poorly understood, relationships and interactions between specific digital paradigms and the SDGs, inter alia: AI (Vinuesa et al., 2020), Industry 4.0 (Beier et al., 2017; Bonilla, 2018; Ghobakhloo, 2020; Nhamo et al., 2020), IoT (Salam, 2020) or Blockchain (Adams et al., 2018). In addition, Fukuda-Parr, and McNeill (2019) discussed how Big Data Analytics holds disruptive implications for the SDGs governance.

The literature demonstrated that some sustainability goals are more suitable for profiting the digital transformation than others (Letouzé, 2015; Pentland, 2015; Vinuesa et al., 2020).

Nevertheless, the potential benefits and risks of digital transformation span multiple sectors and disciplines (ITU, 2021; UNCTAD, 2017a). Digital paradigms directly influence the SDG targets nine, c, 4, b, 5, b and 17.8, which focus on ICT aspects such as broadband access and digital skills. According to GeSI (2019), 103 out of 169 SDG targets are impacted by digital transformation, with a potential to benefit by 22%, but also to threaten or inhibit some targets. Similarly, another study by WEF (2020a) stated that digital paradigms could impact ten out of 17 SDGs, thereby enhancing 70% of their related challenges.

Critical voices denounced a scattered consideration of the digital transformation within the 2030 Agenda. For example, Novak and Tjoa (2018) argued that, despite its relevance, none of the SDGs is solely devoted to digitalisation and the potential impact of ICTs is poorly considered.

Indeed, the massive development of digital technologies without proper governance and means could lead to unsustainable and uneven landscapes (Hong and Xiao, 2024). Therefore, digital and sustainability policies should be aligned with the SDGs. For that purpose, responsible and ethics-driven governance, and means of implementation are urgently needed to ensure a sustainable scale-up (WEF, 2020a; ECOSOC, 2018; UN DESA, 2018; EESC, 2017; UNDG, 2017). Building up digital capacity among governments is also crucial for the SDGs implementation (Janowski, 2016).

Therefore, making the digital revolution work for the SDGs relies on several leapfrogs, including sound enabling frameworks and responsible principle-based regulation, funding mechanisms, and sustainable business models allowing collaboration across stakeholders (Walker et al., 2019; ITU, 2019a,b; ECOSOC, 2018; Letouzé and Pentland, 2018; Letouzé, 2015).

Digital opportunities for the SDGs should be responsibly harnessed, accelerated, and scaled up, unleashing the full potential of digital transformation for global sustainability goals. This advancement relies on aligning better ethics-driven policies, sound regulation and enablers, multi-stakeholder alliances and ecosystems, building digital literacy and capacities, along with investments, for driving the 2030 Agenda (UN, 2024b; WEF, 2020a; Sachs et al., 2016). Indeed, the coordination of international efforts among all the ecosystem actors is essential, for building-up public-private multi-sectorial partnerships and promoting market demand (ITU, 2019a, b; ECOSOC, 2018; Data-Pop Alliance, 2017; UN Global Pulse and GSMA, 2017; Yayboke et al., 2017).

In conclusion, while digital transformation is a key facilitator for advancing numerous aspects of sustainable development, and for contributing to the SDGs, significant research gaps remain that may hinder its potential in this realm. These caveats require further research and policy development to ensure that digital promises contribute to sustainable development genuinely.

The Link Between Digital Transformation and the Circular Economy

The integration of circularity principles within digital practices offers a promising path toward sustainability in the ICT sector. Technologies such as the Internet of Things (IoT), Big Data Analytics, and Blockchain are increasingly recognized for their potential to enhance resource efficiency. Research underlined their role in enhancing knowledge generation and operational efficiencies across industries, thereby supporting sustainable production practices.

Indeed, the emergence of digital technologies as enablers for the circular economy represents a significant step toward decoupling industrial development from environmental degradation (Bressanelli et al., 2018; Nobre and Tavares, 2017; Pagoropoulos et al., 2017).

Digital solutions have become critical in facilitating the transition to circular economy practices. According to Ranta et al. (2021), digital transformation drives business model innovation for the circular economy, by enabling both incremental and radical improvements in resource flows, along with value creation, and value capture. Liu et al. (2022) identified key functions of digital technologies relevant to circular economy strategies, including IoT for real-time monitoring, Big Data Analytics for predictive maintenance, and Blockchain for transparent supply chains. These functions also underscored opportunities for innovation and efficiency in resource management.

Furthermore, Kristoffersen et al. (2020) proposed the Smart Circular Economy (Smart CE) framework, which integrates digital technologies with circular strategies tailored for manufacturing companies. By aligning circularity and digitalization, the Smart CE framework helps firms enhance resource efficiency and productivity.

Expanding on these perspectives, Çetin et al. (2021) developed the “Circular Digital Built Environment framework” based on regeneration, in which ten digital technologies are identified as critical for enabling a circular economy in the Built Environment sector, namely: additive robotic manufacturing, AI, BDA, Blockchain, Building information modelling (BIM), Digital Twins, IoT, Digital Platforms or marketplaces, Databanks (material passports), and Geographical information systems (GIS).

Khan et al. (2021) explored the role of Blockchain in circular economy practices and organizational performance, noting that it enhances circular procurement, design, recycling, and remanufacturing practices. Therefore, the alignment of financial and sustainable goals through improved transparency, traceability, and efficiency in material flows can foster organizational performance.

However, while IoT, Big Data Analytics, and other digital tools offer functionalities that can support circular business models by enhancing resource efficiency, extending product lifespan, and facilitating closed-loop systems, there is still a need for further research to fully comprehend their potential net impact on sustainability (Ardolino et al., 2017).

Despite that digital solutions provide transformative opportunities for embedding circularity principles into business models, challenges such as scalability and interoperability of digital platforms, along with the need for regulations to ensure data privacy and security in circular economy contexts, require further research and policy development.

Following this introduction, the next sections provide a more detailed analysis of the most relevant digital paradigms and their relationship with sustainability. This includes both their potential impacts and beneficial contributions on the social and environmental dimensions. This analysis sheds light on their unique characteristics concerning their potential contribution to advancing sustainability and the SDGs.

3.6.2. Artificial Intelligence and Sustainability

The study of the interplay between Artificial Intelligence (AI) and sustainability is rapidly expanding, though it remains in its initial stages. Thus far, the development of AI, including ethical frameworks, has overlooked sustainability considerations. Indeed, the development of AI for sustainable applications has been mostly driven by pilot initiatives and niche communities, such as “AI for Good” (ITU, 2024a; Tomašev et al., 2020; ITU, 2019a, b). In addition, while research in “AI for sustainability” and “Sustainable AI” is growing, scaling these applications to mainstream use remains a challenge.

Foundational to this context, is establishing a clear definition of AI and its role in addressing sustainability challenges. While Artificial Intelligence (AI) is not a recent phenomenon, since it has been researched and applied for decades, it has experienced significant advancements over the last decade.

The AI concept was coined by John McCarthy in 1956, although rudimentary algorithms can be traced back to Babylonian tablets from 3,800 years ago (Knuth, 2018). Since then, the AI concept has evolved through various transformative shifts, including symbolic reasoning, probabilistic models, and more recently, Generative AI (GenAI) (e.g. Large Language Models or LLMs) that can perform human-like tasks, and reinforcement learning (Horvitz and Mitchell, 2024). Indeed, AI is an umbrella term encompassing Machine Learning, Deep Learning, Cognitive Computing, LLMs, and more related concepts.

Other experts considered the concept unhelpful and claimed terms such as “Augmented Intelligence Systems” (IBM, n.d.), “Extended Intelligence” (Global Council on Extended Intelligence - IEEE, n.d.) or “Cognitive computing”.

Despite its long history, AI has been often misunderstood, overhyped, and even feared. Recent advancements towards a “General AI” similar to human intelligence (University of Stanford, 2023), have intensified the debates on the ethical impacts of this paradigm, and the urgent need for its responsible governance (Horvitz and Mitchell, 2024). Generative AI is reigniting debates about dystopias and utopias and is disrupting all artistic, educational, business, and scientific realms to the extent that the journal *Nature* named these non-human systems as scientists of the year 2023, for the first time in its history.

In this research, Artificial Intelligence (AI) refers to “algorithm-based and data-driven computer systems that equip both machines and individuals with digital capabilities such as perception, reasoning, learning, and autonomous decision-making. AI relies on a portfolio of technologies, including algorithms, software, and methods supporting human-based decision-making or automated actions” (BBVA, 2018). Furthermore, it is worth clarifying that in this dissertation, the term “regenerative” does not refer to “Regenerative AI,” nor should it be confused with GenAI. Regenerative AI is an emerging application, inspired by biological systems, where AI systems possess self-healing capabilities (Ragab, 2023).

After tracing the evolution of AI, it becomes evident that it is not a futuristic concept but a present reality that is shaping existing trajectories of science, the economy, and society. Its future is currently being shaped, eliciting both a sense of urgency and responsibility among world leaders (EC, 2018; OECD, 2019e), and concerns about its risks among citizens and ethical experts.

The alignment of AI with sustainability presents a dual challenge, encompassing both opportunities and risks (Horvitz and Mitchell, 2024). A significant concern stems from the unpredictability of AI models and the difficulty in predicting their future capabilities. Considering the vast power of AI, a responsible and equitable approach to its deployment is imperative, making regulation essential to mitigate risks and optimize its potential in healthcare, education, and sustainability. AI still faces significant research challenges that need to be addressed, most of them affecting sustainability, described as follows.

Opportunities and Hurdles

AI and Cognitive Computing techniques in general, enable a wide range of capabilities, including data-driven perception, reasoning, learning, and decision-making (BDVA, 2018). These capabilities can be applied across diverse areas, from automating critical processes to providing advanced decision support in complex systems and recognising patterns to deliver novel solutions. Overall, when applied responsibly, AI can augment human capabilities (Broussard, 2018), facilitating decision-making and predictions, therefore, the realm of applications is vast across all sectors and disciplines, including sustainability (BDVA, 2018; Smith and Neupane, 2018).

However, concerns are emerging over an “AI divide”, where “winner-takes-most” dynamics dominate adoption, thereby deepening the disparities among nations and stakeholders. Despite the high expectations about AI, the evolution of this paradigm generates enduring concerns.

Currently, little is known about how AI will evolve and its impact on society. In addition, huge complexities exist across multiple levels, jurisdictions, and domains, making it highly challenging to establish and distribute liabilities in such complex and evolving systems (BDVA, 2018). Another hurdle arises from striking a balance between pervasive warnings against AI (UN DESA, 2018) and unrealistic expectations driven by "naïve political agendas" (Letouze and Pentland, 2018).

Floridi et al. (2019) emphasized both the advantages and risks of AI, underlining its potential for enabling self-realization, enhancing human or social capabilities, and spurring social progress. Yet, there are significant opportunity costs associated with underutilizing AI, as well as severe perils of its misuse, including devaluing human potential, removing responsibility or control, and eroding self-determination or democracy. In this context, a sense of urgency is rising among governments, scientists, and citizens to establish the foundations for ensuring a human-centred and ethical AI (HCAI) (Tahaei et al., 2023). This should not be viewed as a "techno-utopia" but rather as an aspirational analogy to good governance (Letouze and Pentland, 2018).

Most experts asserted that AI evolution should acknowledge the significant disruptions and be guided by ethical principles and responsible frameworks that leverage opportunities while protecting human values and rights. Yet, sustainability has been largely ignored in these frameworks and policies.

Safety and explainability factors pose additional challenges for ensuring that AI system decisions align with human values and comply with societal norms and regulations. Indeed, explainable AI is critical for ensuring safety, transparency, and accountability (Smith and Neupane, 2018). In this regard, the use of Fair, Accountable, and Transparent Machine Learning (FATML) is essential, along with reinforcing interoperability, scalability, liability, and standardization (BDVA, 2018).

Concerning the legal and ethical challenges, Artificial Intelligence is perceived as a Pandora's box bringing remarkable potential for both good and evil. Experts are worried about the prominence of algorithms and underscore their potential to exacerbate existing problems, reinforce inequalities or social troubles, overlay biases, threaten jobs, and lead to unknown risks (UN DESA, 2018; Smith and Neupane, 2018).

Notably, AI presents profound normative and ethical challenges, which can affect labour, bias, inclusion, human rights, freedoms, and governance (Campolo et al., 2017). Nevertheless, existing legal and regulatory frameworks are struggling to keep up with the demands of the digital era, making it difficult to adapt to the digital era demands. Hence, a critical perspective and dialogue on the ethical implications of AI are needed (Smith and Neupane, 2018).

This debate must also consider environmental sustainability (CODES, 2023). Confronting the risks and challenges associated with AI will not only shape the direction of this technology but will also have a profound impact on the future of humanity. Furthermore, academic research remains disconnected from the multidimensionality of the AI phenomenon.

These aspects are particularly relevant concerning GenAI, as the "democratisation" of access to these technologies without adequate control or training, has enabled the generation of content prone to errors and susceptible to misuse for disinformation, harassment, or activities disregarding intellectual property and ethical principles in cultural creation. Moreover, the major platforms developing these technologies often fail to provide clarity on privacy conditions. In addition, GenAI may amplify biases in the generated information, replace creative and professional activities, and aggravate the environmental impacts of AI due to its high energy consumption and subsequent carbon footprint.

In this regard, numerous principles have been established to reinforce ethical and responsible approaches to AI development. These principles include the OECD's AI Principles (OECD, 2019c, 2024), the G20's AI principles (2019), the Asilomar AI Principles (Future of Life Institute, 2017), the EU's Ethics Guidelines for Trustworthy AI (EC, 2019), the IEEE's Ethically Aligned Design Principles (IEEE, 2019), the Montreal Declaration (Université de Montréal, 2018), the Toronto Declaration (Amnesty International & Access Now, 2018), the G7 Hiroshima AI Process (2023), the Bletchley Declaration (2023), the UN General Assembly AI Regulation (2024), and the EU's AI Act (2024), among others.

Indeed, some of these principles are starting to integrate sustainability, along with areas where AI can contribute to the SDGs. Yet, only a few countries have consistently integrated the SDGs into their AI strategies (Van Roy, 2020). Furthermore, the European Union has introduced the AI Act regulation (EU, 2024), marking the world's first transnational effort to regulate responsible AI. Nevertheless, sustainability is barely mentioned even in this pioneering framework.

Thus, environmental sustainability and ethics dimensions remain peripheral in the AI Agendas and must be reinforced to curb potential risks. In this regard, the recently launched Global Digital Compact (UN, 2024b) has also established principles for promoting the responsible development of AI for sustainable development and the SDGs. Considering that AI knows no borders, domestic policies have limited impact without a universal commitment to AI good governance.

Artificial Intelligence and its relation to Sustainability and the SDGs

Regarding the contribution of AI to sustainable development, it is widely acknowledged that this paradigm harbours significant potential, but it also entails severe risks (ITU, 2024a; Khakurel et al., 2018; Saetra, 2021; UNEP, 2024b). Indeed, when used responsibly, AI capabilities have the potential to advance most SDGs, as recognized by numerous experts (UNSDG, 2024; Leal Filho et al., 2022; Cowls et al., 2021; Saetra, 2021; Palomares et al., 2021; Di Vaio et al., 2020; Vinuesa et al., 2020; Khakurel et al., 2018; Chui et al., 2018).

Hence, AI has the potential to significantly advance sustainable development across the three pillars of economy, ecology, and society (ITU, 2024a; Vinuesa et al., 2020). An increasing number of experts advocated for the application of inclusive and responsible AI solutions to promote social good, support humanitarian action, and pursue the SDGs (AI for Good Summits, 2019-2024; ITU, 2024a; Cowls et al., 2021; Letouze and Pentland, 2018).

Pilot applications of "AI for Social Good" have been proliferating across various sectors, including education, healthcare, and environmental research (Tomašev et al., 2020). Yet, scaling "AI for Social Good" remains difficult, especially in low-income regions (Bankhwal et al., 2024), which suffer resource scarcity, capacity limitations, inadequate logistics and weak or missing regulations. In addition, barriers such as data accessibility, talent availability, and organisational readiness also hamper its broader implementation.

Moreover, as argued by Gupta et al. (2023), AI holds remarkable potential for enhancing the monitoring of many SDGs, specifically when remote sensing and satellite "Earth Observation" (EO) data are integrated. When coupled with Big Data Analytics, AI becomes a catalyst for innovation. Certainly, to maximize the contribution of AI to sustainable development, it is crucial to integrate it with other digital paradigms (e.g., IIoT, blockchain), while ensuring trustworthy regulation, transparent accountability, and cross-disciplinary collaboration across sectors.

However, despite its potential, the application of AI to address "wicked" social, environmental, and governance challenges remains in its infancy (Cowls et al., 2018; Di Vaio et al., 2020; Saetra, 2021), resulting in a fragmented research landscape. This underlines the need for further research to fully understand the impact of AI on sustainable development and the extent to which it can effectively contribute to achieving the SDGs.

Considering the sustainability of AI, as contended by Saetra (2021), due to its nascent stage the influence exerted by large tech companies, and the policy fervour surrounding this strategic technology, the literature tends to exaggerate the positive impacts while overlooking potential negative effects. Thus, the net sustainability effects of AI remain unclear and lack sufficient empirical evidence. Indeed, numerous trade-offs and ambivalent impacts remain, notably concerning its carbon footprint and material footprint, along with unresolved social dilemmas, and ethical implications (Gupta et al., 2023). Furthermore, most case studies predominantly reflect perspectives from the Global North, neglecting the particularities of the Global South, as well as structural and capacity barriers (Cowls et al., 2021).

Pueyo (2018) argued that machines are advancing towards superintelligence with the promise of boosting economic growth, but without exploring the potential social and environmental effects of AI evolution. This scholar advocates for a digital transformation towards degrowth, sustainability, and equity.

In the environmental realm, akin to many digital technologies, AI presents a dual nature (Saetra, 2021; Horvitz and Mitchell, 2024). While it holds great potential to explore and safeguard the natural environment, it also poses risks and could exacerbate existing problems (Vinuesa et al., 2020; Nahar, 2024). On the one hand, AI can optimize resource utilization and circularity across industries (Kotsiopoulos et al., 2020; Pigola et al., 2021), promote the energy transition and climate action (Mosavi et al., 2019; Rolsnick, 2022), help to forecast extreme weather events, or safeguard biodiversity (Kwok, 2019; Giuliani et al., 2020).

However, its operation (e.g. algorithms, data centres) often entails substantial energy and water consumption (Banipal and Mazumder, 2024), growing carbon footprint, security vulnerabilities, rebound effects, and contributes to the accumulation of electronic waste (Gupta et al., 2023; UNEP, 2024b).

In this regard, Robbin and Wynsberghe (2022) cautioned against the substantial environmental footprint of AI systems and introduced the concept of carbon lock-in. Saetra (2021) proposed a comprehensive framework aligning AI impacts with SDGs, preventing misleading green claims. Debnath et al. (2023) advocated for less biased AI systems aligned with a planetary health-focused epistemic. Li et al. (2023) used the affordance theory to examine how companies can integrate green digital practices in this domain.

Furthermore, the growth of GenAI is aggravating the environmental impacts of AI development. MIT Climate Impact (2024) underlined the significant challenges posed by the rapid expansion of GenAI, due to its substantial energy consumption and subsequent carbon footprint. The increasing demand for GenAI is driving the construction of novel data centres, intensifying the competition for energy and water resources, and adding pressure on supply chains, thereby disrupting essential goods and services.

In addition, Ligozat et al. (2022) explored the hidden environmental impacts of AI through an LCA, emphasizing the need for a comprehensive taxonomy. Initiatives such as the Biosphere Code provide guidelines for the development of environmentally sustainable algorithms, yet their adoption remains limited.

Other sustainable AI practices include fostering green algorithms, integrating renewable energy sources and sustainable cooling practices in infrastructures, securing ethical raw material supply chains, and advancing circular economy and sufficiency principles, among other measures.

In the social realm, ethical threats like bias, discrimination, inequalities, power asymmetry, misinformation, privacy concerns, and ethics-washing are also growing concerns (Gupta et al., 2023; Saetra, 2021). Uneven access to AI systems and skills across geographies, coupled with AI-driven automated work, could amplify inequalities against vulnerable populations. In this regard, according to Vinuesa et al. (2020), SDG 10 is negatively affected by AI systems.

Horvitz and Mitchell (2024) emphasized the potential negative impacts on job displacement, cybersecurity threats, and ethical concerns (e.g. safety and human oversight), alongside geopolitical issues tied to the strategic use of AI, including non-peaceful defence. In this matter, Van Wynsberghe et al. (2023) stressed the societal and ethical implications of the rapid integration of AI systems, urging a re-evaluation of them as a “world object”. Meanwhile, Halsband (2022) expanded the discussion to intergenerational justice towards genuine sustainable AI, and Genovesi and Mönig (2022) advocated for integrating sustainability into AI ethical certifications. Also, WEF (2024) claimed to align AI systems with human values like justice and fairness.

The growth of GenAI is also exacerbating social and ethical dilemmas. Hagendorff (2024) comprehensively reviewed potential ethical implications of these technologies, focusing on LLMs and text-to-image models. These scholars underlined concerns about fairness, safety, security, harmful content, the so-called “hallucinations”, privacy, interaction risks, and societal impacts. Similarly, Al-kfairy et al. (2024) explored the ethical challenges of GenAI, identifying concerns such as privacy violations, data protection issues, copyright infringement, dissemination of disinformation and misinformation, inherent biases, and the exacerbation of societal inequalities. These scholars emphasized the need for ethical principles and responsible development and governance of GenAI technologies ensuring that human rights and values are respected.

Furthermore, the sustainability aspects of AI remain largely ignored in the policy realm where this technology represents a wildcard. Existing strategic agendas and ethical principles often neglect environmental sustainability (Villani et al., 2018). While more than 190 nations have adopted recommendations on ethical AI, most do not cover the environment. Even the most advanced regulations, such as the European AI Act (EU, 2024), lack concrete means for effective sustainable implementation (UNEP, 2024b). Thus, environmental sustainability remains the missing piece in the AI debate.

Ensuring a sustainable, responsible, and inclusive application of AI for achieving the 2030 Agenda goes beyond setting voluntary principles. It requires trustworthy regulation that adopts a human-centric approach and strictly adheres to ethical standards (How et al., 2020; Truby, 2020), also incorporating sustainability. Thus, a shift in focus is needed to place ecological and social sustainability at the forefront of AI development.

Establishing standardized procedures and reporting to assess the environmental impact across the entire lifecycle of AI is crucial (UNEP, 2024b; CODES, 2022; Lannelongue et al., 2020; Schwartz et al., 2019). Moreover, resource-efficiency practices, along with better embedding of environmental requirements into AI policies, ensure the sustainable development of this technology (UNEP, 2024b). In this sense, the global “Hamburg Declaration on Responsible AI for the SDGs”, to be finalized in 2025, and the recently adopted Global Digital Compact also pursue to promote a more sustainable implementation of AI in alignment with the five pillars of the 2030 Agenda (BMZ and UNEP, 2024b).

Nevertheless, beyond policy, uncertainty also arises from the intrinsic limitations of the SDG targets, indicators, and lacking data. In this regard, potential biases in dataset selection, the application of black-box algorithms, and the reliance on expert opinions and pilot cases can result in misleading conclusions. Additional research is also required to tackle algorithmic bias, improve the explainability of AI systems (Vinuesa and Sirmaçek, 2021), and integrate multidisciplinary approaches and sustainability considerations into AI strategies.

The use of FAIR (Findable, Accessible, Interoperable, and Reusable) data principles (Wilkinson et al, 2016), and Explainable AI (XAI) can help to mitigate discrimination and biased outcomes, thereby fostering a more equitable AI use. Nevertheless, further research is required and should be done by addressing various contexts and co-creation with communities (Alonso et al., 2021), especially those in the Global South, to bridge digital divides (Vinuesa et al., 2020; Dignum, 2019; Visvizi, 2022).

Consequently, AI could trigger an ideal world achieving the 2030 Agenda or a dystopian future far for the SDGs (Goralski and Tan, 2020; Smith and Neupane, 2018), depending on how it is governed. Therefore, robust governance frameworks, ethical principles, and future-proof and binding regulations are vital to responsibly harness AI for sustainable development.

In conclusion, while AI holds outstanding potential for promoting sustainable progress, its responsible management is critical to effectively address inherent challenges and ensure that it aligns with human and ecological values (WEF, 2024; UNEP, 2024b; UN, 2024b). Policies and regulations insufficiently cover the sustainability aspects. In addition, the scientific literature on the environmental and social impacts of AI is underdeveloped and current insights from pilot projects are unable to scale. Further multidisciplinary research and policy development are needed to promote the responsible and sustainable application of AI for regenerative development.

3.6.3. Big Data Analytics and Sustainability

Big Data Analytics (BDA) refers to the systemic processing and analysis of large amounts of data and complex datasets, which make it possible to extract valuable insights (IBM, n.d.). It could also be interpreted as the conjunction of data crumbs, communities, and capacities (Letouzé, 2015).

The evolution of BDA has been intrinsically linked to the advancement of AI, indeed, both technologies are deeply intertwined, as the emergence of improved data sources enriches the input of the algorithms, thereby generating meaningful outcomes and amplifying the value derived from data (BDVA, 2018).

The potential of Big Data Analytics for advancing the SDGs has garnered attention from scholars and practitioners (Gupta et al., 2023; Guo, 2020; Williams et al., 2019; Shiroishi et al., 2019; ITU, 2019b; Smith and Neupane, 2018; Malhotra et al., 2018; Alemanno, 2018; Seele and Lock, 2017; Lepri et al., 2018; Song et al., 2017; Chandy et al., 2017; ITU, 2017a; UN Global Pulse, 2016; Hilbert, 2016). However, the scientific literature in this area is still relatively limited and nascent, lacking theory development, and underlining the need for further research (Uddin Murad et al., 2023).

Indeed, despite numerous pilot and philanthropic initiatives, the literature reveals that Big Data Analytics applied to sustainable development remains still in a nascent stage, with heterogeneous studies offering contradictory conclusions and outcomes highly context-dependent and difficult to scale. Significant knowledge gaps remain regarding whether BDA and AI could facilitate or impede the SDGs. Thus, further multidisciplinary research is needed to fully understand its multiple complexities and interconnections with other technologies and data challenges.

In this context, one of the most salient values of digitalisation for the SDGs precisely relies on the data revolution (Jacob, 2017; UN SDSN, 2019; ECOSOC, 2019c). Indeed, one of the critical challenges for achieving sustainability and the SDGs relies on the difficulties of grasping timely and high-quality data, along with subsequent analytics (Andries et al., 2019; Guo, 2020).

Thus, data-driven technologies are essential to overcome current critical data gaps, by complementing traditional data sources and enhancing granularity (Letouzé et al., 2019). This is particularly problematic in deprived countries (Chandy et al., 2017).

Novel sources of Big Data such as Earth Observation Data (Andries et al., 2019; Guo, 2020), or citizens' mobile data (Malhotra et al., 2018), can be highly useful for feeding SDGs indicators, monitoring the SDGs, and tackling global crisis (Bullock et al., 2020; Oliver et al., 2020). Thus, human-centred Big Data Analytics could enhance SDGs accountability (Williams et al., 2019).

Furthermore, considering the relevance of interpretation and context awareness, Van den Homberg and Susha (2018) suggested merging Small Data and Big Data to feed better SDG indicators, creating proxies, and affordably complementing official statistics. Data ecosystems could also enrich sustainability reporting, overcoming fragmentation, and data vacuum, thereby enhancing sustainable development effectiveness (Letouzé et al., 2019).

Notwithstanding, the power of Big Data goes beyond metrics. Indeed, data is unworkable without interpretation (EESC, 2017). It provides enhanced capacities for scientific discovery, decision-making, and governance, becoming the new cornerstone to advance social research and transform behaviours towards sustainability (Bright, 2017; Fazekas, 2014; Paulus et al., 2014).

Notably, the fusion of Big Data Analytics and AI holds exceptional descriptive, predictive, prescriptive, and discursive functions (Letouzé, 2015), which could contribute holistically across all dimensions of sustainability (Maaroof, 2015; Khakurel et al., 2018).

Thus, digital capacities are essential for addressing complex social problems (Lepri et al., 2017; Pappas et al., 2018; Smith and Neupane, 2018), and enhancing governance towards SD (Athey, 2017; Letouzé, 2015; Lowman, 2017).

Furthermore, digital paradigms enable novel collaborative digital ecosystems (Jensen and Campbell, 2019; Pappas et al., 2018; Stuermer et al., 2017), expanding global connectivity and facilitating knowledge-sharing and management (Stafford-Smith et al., 2017; Fukuda-Parr and McNeill, 2019).

Beyond their benefits, digital technologies like BDA have also changed the information landscape, raising ethical and social concerns (Fukuda-Parr and McNeil, 2019; Metcalf et al., 2016; O'Neill, 2016; Smith and Neupane, 2018; UN DESA, 2018). Lytras et al. (2019) argued that BDA services influence individuals and societies.

Thus, several conditions should be ensured for responsibly harnessing the data revolution for sustainability (UN DESA, 2018). This includes ensuring data accessibility and significance, fairness, accountability, and transparency. Besides, ownership, trust, and user-centric approaches are also relevant (Fjeld et al., 2020; Lepri et al., 2018; Letouzé and Pentland, 2018; Smith and Neupane, 2018).

Additionally, there must be consensus on data-sharing models (Data-Pop Alliance, 2017) and privacy standards to mitigate ethical risks (Campolo et al., 2018; Herschel and Miori, 2017; Fjeld et al., 2020; Metcalf et al., 2016; Smith and Neupane, 2018; Yayboke et al., 2017). Strengthening statistical systems and building digital literacy further support responsible data usage (Letouzé et al., 2019).

Hence, since controversies prevail, demonstrating whether and to what extent digital capacities, and particularly BDA, can be used in a responsible and sustainable manner towards the SDGs is crucial (Letouzé and Pentland, 2018; Smith and Neupane, 2018).

Nevertheless, so far, a lack of systemic perspectives remains, and little is known yet about how such capacities could be achieved without inducing bias or manipulation (Niño et al., 2017).

Concerning the application of BDA to the sustainability domain, it is characterized by a fragmented landscape, with stand-alone pilots difficult to scale (UN Global Pulse and GSMA, 2017). Indeed, an ambiguous “for good” approach and “ethic-washing” tactics can be often found (Campolo et al., 2018; Stocker, 2016).

According to Corbett et al. (2018), BDA can lead to more sustainable decision-making, but may also have undesirable consequences, some of them unpredictable. Indeed, BDA can enable data-driven insights and innovations to enhance the sustainable governance of sectors like manufacturing (Dubey et al., 2017), agriculture, energy (Ponnusamy et al., 2021), and water management (Sun et al., 2019).

As argued by Yang et al. (2020) BDA applications can enhance environmental quality by accelerating clean technologies but must be accompanied by regulation and conducive settings. Similarly, Benzidia et al. (2021) and Singh et al. (2019) suggested that BDA and AI could promote green supply chains.

On the contrary, Lucivero et al. (2019) stated that BDA initiatives raise questions about the related environmental impacts, demanding responsible strategies. Cetindamar et al. (2021) argued that studies on sustainable supply chain performance are lacking. While Jabbour et al. (2020) emphasized that complementary capacities are needed to ensure a sustainable contribution to sustainable supply chains.

Furthermore, structural challenges and policy barriers persist, together with a lack of tools, infrastructures, and capacities to face the challenges ahead (Lee, 2014a; Letouzé, 2015; Shin, 2016; Smith and Neupane, 2018; UN Global Pulse and GSMA, 2017). Hence, a huge gap between potential and implementation performance remains (Chandy et al., 2017; Janowski, 2016).

These hurdles cannot be solved by technology alone and are even magnified in deprived contexts (Yayboke et al., 2017). Therefore, addressing contextual specificities in this context is highly relevant (Hesse et al., 2018; ITU, 2019b; Letouzé and Pentland, 2018).

Overall, considering the potential opportunities, but also current barriers and insufficient understanding of the net impacts, a profound characterization of the BDA impacts for sustainability is required, followed by a responsible scale-up of the efforts to unleash the full potential of this paradigm for sustainable development.

3.6.4. Quantum Technologies and Sustainability

Quantum Technologies (QTs) are rapidly advancing, opening new research avenues that could revolutionize various fields, including AI, healthcare, climate change mitigation, sustainable materials, and energy systems. With their outstanding potential to solve complex problems beyond the capacity of classical computers, QTs are expected to address pressing global challenges. However, these potential benefits come with significant environmental, ethical, and social concerns that must be tackled to ensure responsible and sustainable development of these promising technologies.

This section explores the opportunities and challenges of QTs, particularly in terms of their environmental footprint, ethical dilemmas, and the need for collaborative governance in this crucial realm. According to the literature, QTs are heralded as the next frontier in computation and communication, with the capacity to enhance scientific discovery and technological innovation across various industries. In particular, Quantum Computing (QC), which represents a core area of QT, has already demonstrated its ability to outperform classical computers (Pattani et al., 2020; Preskill et al., 2018) in specific tasks, mainly in fields requiring high computational power, such as drug discovery, materials science, and complex system modelling (Paramita Chatterjee et al., 2018).

As argued by Möller et al. (2017), QC can bring breakthroughs in applied mathematics, enabling future developments in scientific computing which could disrupt society. Additionally, Gill et al. (2020) underlined the computational advantages of QC, which could enable the resolution of problems that are currently unsolvable with classical computing.

Nevertheless, despite these hopeful perspectives, the deployment of QTs is still in its early stages and the research efforts and literature are mainly focused on technological aspects. Therefore, sustainability issues are overlooked as commonly happens with most nascent technological developments. Yet, the landscape of QTs presents significant gaps in the understanding of their potential future implications for the ecological, social, and governance realms.

Due to its nascent stage, QTs still face technical and performance challenges such as noise in quantum gates (Preskill et al., 2018), and high error rates (Huggins et al., 2018), which makes them unprepared for commercially viable applications. While the studies on sustainability aspects are very limited, there are some relevant works in fields closely connected with environmental aspects and ethical issues. One of the key potential benefits of QTs is their application to climate modelling, ecology, and the optimisation of energy systems.

In this context, Nammouchi et al. (2023) suggested that Quantum Machine Learning (QML) could accelerate decarbonization efforts by improving climate data forecasting, predicting hazardous events, and optimizing renewable energy systems. Similarly, Ajagekar and You (2022) explored the potential of QC and Quantum AI (QAI) in advancing renewable and sustainable energy systems towards climate neutrality, enhancing the computational efficiency in energy applications.

Recent advancements in Hardware and algorithms offer promising alternatives to enhance computational efficiency in sustainable energy materials. However, limitations in current QC Hardware may hinder the materialisation of such advantages for large-scale energy systems.

Otgonbaatar et al. (2023) also explored the potential of QML and QC for climate change modelling, along with the energy consumption of Quantum Machines, in comparison to classical computers. They concluded that these technologies can be useful for enhancing climate digital twins and can be applied together with classical computers for more efficiency.

Van Erp et al. (2022) outlined the transformative potential of QTs in shaping value creation, in manufacturing systems. They proposed various QT applications, underlining their role in fostering industrial symbiosis and promoting sustainable development within ecological boundaries.

Rayhan and Rayhan (2023) examined the convergence of QC and AI, underscoring its transformative potential across industries, and unique properties, such as Qubits and entanglement. These authors also considered the ethical aspects and suggested a future where responsible innovation and global collaboration drive responsible advancements in QC accessibility. Woolnough et al. (2023) discussed the potential of QC to revolutionize ecology, focusing on statistical methodologies commonly used in this field. Despite current limitations in noisy Qubits and Quantum Logic Gates, advancements in error mitigation techniques are expected to overcome these challenges.

As evidenced by studies such as those by Rayhan and Rayhan (2023), and Van Erp et al. (2022), the literature remains overly optimistic about the future potential of QTs, without fully addressing the associated environmental and social challenges that these technologies may generate.

Considering the sustainability challenges the QTs may present in the future, one of the most pressing concerns is related to the potential negative environmental impacts.

Particularly QC is expected to require significant energy resources, potentially leading to increased GHG emissions and higher energy consumption. In this regard, Auffèves (2021) emphasized the need to address the energy footprint of QTs, which has been overlooked in current deployment strategies. This circumstance echoes earlier technological cycles, such as the Big Data Analytics and AI revolutions, where environmental considerations were considered secondary to technical innovation, or even completely neglected. Indeed, the future commercial deployment of QTs will likely demand a considerable raw materials footprint, raising concerns about the subsequent impact on resource depletion and broader sustainability goals.

As Frąckiewicz (2023) argued, the energy consumption required for cooling purposes and infrastructure support in QTs, along with their reliance on rare materials, requires collaboration among stakeholders to develop sustainable practices and regulations. Otherwise, the expected environmental impacts of QTs could undermine their potential contributions to sustainability.

Furthermore, Dawton (2023) suggested that QC brings a dual challenge in terms of energy consumption. These technologies can accelerate scientific progress related to climate and energy modelling, while also increasing power consumption linked with quantum algorithms and supporting infrastructures. This researcher underlined the work done by initiatives such as the “Quantum Benchmarking Programme,” which develops metrics related to efficient and fault-tolerant computers that can balance speed and sustainability. Quantum computers function at very low temperatures, near absolute zero, to preserve the states of the unstable Qubits, which implies intensive energy consumption for cooling purposes.

Nevertheless, novel cryogenic systems and energy efficiency advances could also reduce the energy footprint in the future. Efforts to address energy challenges and mitigate environmental impacts are crucial for ensuring that QC contributes positively to combating climate change. Besides, as the WEF (2021) and Berger (2021) argued, while energy consumption is high, QCs are much more efficient in performing complex tasks. Thus, the net impact of QTs remains uncertain.

When it comes to the ethical and social dimensions, QTs also raise concerns. Research recognized that these technologies could introduce ethical challenges that must be addressed to ensure equitable development and deployment. In this matter, Major and Yampolskiy (2015) underlined the potentially catastrophic risks posed by QTs, particularly in terms of cybersecurity.

In addition, the consideration of resilience in the development of QTs, and particularly, QC is crucial and is highly related to digital preparedness. The advent of Quantum Computers threatens the current cryptographic systems, rendering them obsolete and the digital infrastructures highly vulnerable, with significant risks to global security, safety and privacy. Specifically, the literature underlined the challenges that quantum computing poses to already vulnerable technologies such as IoT (Lhakami, 2024).

Addressing these vulnerabilities will require the development of “post-quantum cryptographic algorithms,” and other safeguards, to protect sensitive information, alongside new resilience strategies to counter potential attacks, particularly in military applications and scenarios involving malicious uses (Villegas, 2024). Yet, these technologies still faces challenges related to computational efficiency and compatibility with existing hardware (Liu et al., 2024). Additionally, the combination of efficient blockchain and quantum computing offers a promising approach to enhancing security in critical sectors such as defence and industry, ensuring more secure communications (Akhai & Kumar, 2024).

Additionally, As Kaur (2022) pointed out, QTs could exacerbate existing divides and power asymmetries, as its development is currently concentrated in a few powerful countries and large enterprises, which may widen the divide between technologically advanced nations and actors, and those with less resources.

Thus, this divide raises concerns about the equitable distribution of the benefits of QTs and the potential to deepen global inequalities.

Considering the significant environmental, social, and ethical challenges posed by QTs, it is crucial to develop a comprehensive and multidisciplinary approach to ensure a mindful and robust governance of these powerful paradigms. The governance approach must involve collaboration between scientists, policymakers, ethicists, and industry experts to ensure that QTs are developed and deployed responsibly and sustainably. In this regard, a key strategy relies on the early integration of sustainability and ethical considerations into the strategies and policies for QTs development.

As noted by Becker (2023), past technological advancements, including those in AI and computing, have often been based on unsustainable practices. Sustainability and ethics are already recognised as key design criteria for digital development.

Thus, to avoid repeating the same mistake, it is essential to embed environmental and social considerations into the design and development of QTs from the outset. This includes establishing ethical frameworks, cybersecurity protocols, and guidelines for responsible use, as suggested by several scholars in the field (Kop et al., 2023; Pupillo et al., 2023). Pupillo et al. (2023) provided guidelines to facilitate a more ethical and sustainable adoption of QTs in the EU, particularly, addressing the cybersecurity risks associated with this realm. The Open Quantum Institute (GESDA) is a pioneering initiative to enhance access to these technologies and provide a multilateral framework to harness QTs for the SDGs.

Similarly, Kop et al. (2023) proposed the “Quantum SEA Principles” to promote responsible quantum R&D, which are aimed to be embedded in policies and practices across stakeholders. These ten principles cover all aspects of responsibility, including sustainable development, society values, RRI, and collaboration. Considering the incipient and uncertain research directions of QTs and their intersection with AI, these principles should be taken with caution.

As the literature shows, there is a lack of critical analysis on the sustainability dimensions of QTs, since the discourse is mainly focused on their potential benefits. Addressing this gap will require in-depth studies on the long-term environmental and social consequences of QTs, as well as the development of policies and regulations to steer a responsible evolution of these powerful technologies.

In conclusion, Quantum Technologies hold outstanding opportunities for addressing many global challenges related to sustainability, but their potential could be undermined if their inherent environmental, social, and ethical challenges are not robustly addressed. As QTs are still in a nascent stage and rapidly evolving, therefore it is crucial to balance innovation and regulation, ensuring that they progress adequately while addressing potential impacts and contributing to social and environmental benefits, rather than harm. Thus, further research, science-policy interfaces, dialogue, and collaboration among stakeholders, along with policy awareness are needed to steer the evolution of QTs toward a sustainable and just development.

3.6.5. Internet of Things (IoT) and Sustainability

This section is focused on the sustainability aspects of IoT, covering both the potential impacts of this technology and the expected opportunities that its application can bring for sustainable development and the SDGs. The Internet of Things (IoT) represents a transformative technology, serving as a key enabler of a responsible digital transformation. It facilitates the connection of objects and people, allowing the convergence of the physical and digital worlds.

This offers unprecedented opportunities for capturing data-driven insights and enhancing connectivity between systems. As a result, the IoT has significant potential to generate social value while unlocking new market opportunities (WEF, 2018).

Therefore, the IoT offers immense potential to provide massive amounts of real-time data, fuelling other digital paradigms such as BDA and AI, thereby enabling the monitoring of environments, infrastructures, and human behaviours. This influx of data, including sustainability analytics, holds the promise of supporting the realization of numerous SDGs (WEF, 2018).

In addition, Mondejar et al. (2021) argued that the integration of the IoT with BDA, and smart systems can address critical sustainability challenges, by building a “Smart Green Planet”.

Furthermore, this technology is particularly relevant in the context of industry, where it is often referred to as the “Industrial Internet of Things” (IIoT). This digital paradigm plays a crucial role in the evolution of the industrial sectors towards the “Industry 4.0,” and “Industry 5.0” paradigms, characterized by more advanced and sustainable practices by the integration of digital technologies (Beier et al., 2018). These concepts are further described in the next section.

However, the full potential of the IoT is hindered by significant challenges regarding connectivity, reliability, interoperability, cybersecurity, and privacy. Moreover, concerns regarding the environmental impact of IoT deployments are also rising, such as increased energy consumption, and subsequent GHG emissions, along with electronic waste (Ahmed et al., 2017).

Recent literature suggested that, while IoT offers efficiency gains and productivity, it also brings environmental impacts, encompassing carbon and material footprint, dependence on critical raw materials, and hazardous electronic waste. Some of these impacts can be partially mitigated by energy efficiency, circularity, integration of renewable energy, and policies for sustainable practices. Yet, further research is needed to understand the net impact of this technology on the environment, as well as novel strategies for reducing its environmental risks (WEF, 2018).

In this regard, while some studies are optimistic about the net positive impact, others unveiled negative effects on both the environment and society. For example, Bibri et al. (2018) asserted that IoT, in combination with BDA applications, could support energy efficiency and help to mitigate environmental effects.

Research also demonstrated that IoT enables the optimisation of energy systems through Smart Grids, the efficient management of water resources by Smart Water systems, or the enhancement of precision agriculture (AgriTech), thereby supporting sustainability across multiple sectors. IoT devices are also often integrated in the building sector, to manage the related systems more efficiently, by reducing energy and water consumption. Moreover, the literature reflected that IoT contributes to air quality monitoring and waste management, by supporting real-time interventions to address pollution and optimize logistics (WEF, 2018).

According to Talavera et al. (2017), IoT has also been successfully used in ecological monitoring, for tracking wildlife and monitoring habitats, therefore, supporting nature conservation efforts through data-driven strategies. IoT applications have been mainly focused on monitoring, control, prediction, and logistics.

Regarding the broader impacts on the economy and society, according to Shenkoya et al. (2020), the IoT could improve business process efficiency, and job creation, leading to social change in society. This requires careful monitoring to address potential issues. Similarly, Nižetić et al. (2020) noted that IoT technologies can simplify processes, improve efficiency, and enhance life quality, but must be monitored and evaluated to limit harmful impacts and ensure mindful utilization of limited resources.

In essence, these multiple applications with environmental and social benefits illustrated the far-reaching potential of IoT in contributing to sustainability and the SDGs.

Following this introduction about the promising application of IoT for sustainability, the potential impacts of this technology on the environment and society are also acknowledged as follows. First, achieving the full impact of IoT is hindered by significant technical challenges, including connectivity, interoperability, cybersecurity, and privacy issues. Indeed, security is a key concern in IoT adoption, specifically in critical sectors such as energy, water, and healthcare.

In this sense, Asplund et al. (2016) noted a lack of consensus on the risks related to IoT security, underscoring the need for robust cybersecurity measures to protect sensitive data and infrastructure.

Notably, IoT devices enable the collection of large volumes of data, including personal and sensitive information from critical infrastructures. This raises ethical concerns concerning privacy and security, alongside potential malicious uses, such as massive surveillance or cyberattacks. A critical aspect of IoT is its vulnerability, as these devices are highly exposed to threats that could compromise essential infrastructures and sensitive data. In addition, the massive deployment and increasing autonomy of these devices create additional challenges in terms of ethical governance, accountability, and transparency in their use and operation. Thus, it is crucial to integrate adaptive security mechanisms, resilience and technological recovery strategies to address these vulnerabilities, ensuring the sustainability and security of this technology.

Furthermore, the massive spread of IoT devices is expected to significantly increase the material and carbon footprint, electronic waste, pollution, and resource depletion. Therefore, the environmental impacts of IoT deployment represent a major concern. As argued by Xilong-Liu et al. (2019) and Memić et al. (2022), IoT devices consume a substantial amount of energy. In this regard, Pirson et al. (2021) conducted a Life Cycle Analysis (LCA) of IoT edge systems, concluding that the carbon footprint of the related devices could range from 22 to 562 MtCO₂-eq/year by 2027, depending on the deployment scenario. In worst-case scenarios, this figure could reach nearly 1,000 MtCO₂-eq/year, underscoring the urgency of addressing the environmental footprint of IoT technologies.

According to Ahmed et al. (2017), the environmental concerns of IoT are exacerbated by the growing proliferation of these devices, which poses a threat to sustainability, despite the potential mitigation strategies related to energy efficiency and renewable energy integration.

Notably, the significant material footprint of IoT devices, along with their dependence on critical raw materials, worsens the already significant problem of e-waste. As the IoT adoption is rapidly expanding, robust e-waste management and circular economy strategies are needed to minimize environmental harm, that are not always available or are technically possible. All these potential impacts raise concerns about the long-term sustainability of IoT technology.

Nevertheless, some studies provided strategies to mitigate these environmental challenges. Bibri et al. (2018) argued that IoT, combined with BDA, can support sustainability by optimizing energy efficiency. Similarly, Xilong-Liu et al. (2019) emphasized the need for green energy solutions, wireless charging, and energy-balancing techniques to lower the energy consumption of IoT devices. Memić et al. (2022) and Alsharif et al. (2023) advocated for the development of “Green IoT”, which focuses on reducing energy use, minimizing pollution, and promoting sustainable practices. A relevant trend in this realm is to integrate IoT networks with edge computing, leading to the Edge-of-Things (EoT) paradigm.

As suggested by Akhunzada et al. (2023) a large number of IoT can be connected to the Cloud through edge devices, which have more computing power but can be managed to reduce energy consumption for sensitive applications, such as real-time disaster recovery.

Another approach proposed by Abualigah et al. (2023), relies on swarm intelligence (SI), which emulates insect behaviours and can be used to address some IoT challenges related to heavy network traffic and a high volume of dynamic data. Reducing traffic by efficient routing algorithms based on SI and power-aware techniques can help to enhance the system response and decrease energy costs.

When it comes to social impacts, Brous et al. (2020) argued that IoT can trigger dual effects on organizational structures. While it can streamline processes and enhance the quality of life, it could also lead to unexpected social changes and uncertain structural transformations that must be effectively managed.

In this matter, Parise et al. (2018) underlined the ethical and social impacts of IoT, particularly, its influence on globalization. The dual nature of IoT demands a balanced approach to leverage its transformative opportunities for embedding sustainability practices, enhancing resource efficiency and closed-loop systems while preventing the aggravation of environmental degradation and social inequality.

In conclusion, while IoT is expected to play a critical role in promoting sustainability and contributing to several SDGs, it must be deployed responsibly and sustainably by tackling the associated environmental and social risks. For that purpose, sustainable practices, Green IoT approaches, along with robust governance frameworks and mindful policies are needed to ensure that this technology genuinely contributes to sustainable development.

3.6.6. Industry 5.0 and Sustainability

Industry 5.0 represents the evolution of the Industry 4.0 paradigm, which has already revolutionised manufacturing through digital technologies (IoT, BDA, AI, blockchain) and automation. By combining a human-centric approach with advanced digital technologies, Industry 5.0 emphasizes the collaboration between humans and machines, sustainability practices and social welfare.

Besides, the intersection of the circular economy with intelligent assets towards Industry 5.0 presents a fertile ground for innovation and value creation. This combination provides real-time data to monitor resource use, with circular economy principles, to drive environmental efficiency and performance in industrial production (Narkhede et al., 2023; Beier et al., 2017). According to UNIDO (2017), this paradigm can transform linear production models towards circularity, optimize resource flows, minimize waste, and support the extension of product lifecycles and transparency in supply chains, which are critical factors for achieving the SDG9 on industry, infrastructures, and innovation. Similarly, Ghobakhloo et al. (2020) underlined its potential for industrial sustainability.

However, the Industry 4.0 paradigm has also raised environmental and social concerns (Nunes et al., 2022). As argued by Scholz et al. (2016), in analogy with other digital technologies, it implies increased energy consumption, intensified raw material demand, and generation of e-waste. In addition, Oláh et al. (2020) argued that Industry 4.0 causes negative impacts due to air pollution, and resource depletion.

Moreover, in terms of labour, Siltori et al. (2021) contended that automation may provoke job displacement, but also can enhance ergonomics. In addition, Bonilla et al. (2018) concluded that it can have both positive and negative impacts on sustainability, mainly as secondary effects, while Benitez Nara et al. (2021) considered that the environmental benefits are smaller than the economic gains.

In this regard, Bai et al. (2020) noted that the effects vary by sector, with automotive and electronics experiencing more relevant environmental impacts. The advent of Industry 5.0 is expected to reduce environmental concerns, by integrating advanced technologies, human values, collaboration human-machine, and sustainability practices, which provides further value (Rijwani et al., 2024; Rame et al., 2024).

Indeed, circularity and adaptability are central components of this paradigm, which prioritises material reuse and waste reduction, thereby minimising the environmental footprint, while creating new value chains (Niehoff and Beier, 2018).

Studies on eco-industrial parks and smart cities underlined the potential of the integration of Industry 5.0 with circular economy and digital innovation. Rijwani et al. (2024) underscored the great potential of Industry 5.0 for reconciling industry with human values and sustainability while promoting resilience.

These researchers linked the evolution of Industry 5.0 to the advancement of technologies such as Edge Computing, IIoT, Blockchain, AI, BDA, and advanced connectivity, from 5G to future 6G and beyond. In this regard, Edge Computing results are critical for processing real-time data with low latency, while IIoT provides the needed interconnectivity for data exchange, and blockchain allows transparency and traceability across the supply chain.

The massive data capture is processed by BDA allowing enhanced decision-making. When it comes to human-machine collaboration, these authors underline the relevance of “cobots” or collaborative robots. Yet, these authors also underlined the persisting implementation challenges, such as implementation challenges persist, such as high costs, infrastructure compatibility and security, privacy concerns, and the needed adaptation of the workforce.

Rame et al. (2024) emphasized the outstanding potential of Industry 5.0 for driving resilient and sustainable industries with Zero Defects in Manufacturing and equitable working conditions but also underscored the need to overcome caveats such as emissions reduction, skill gaps, social equity, and economic viability. This must be achieved through multidisciplinary collaboration, education, and robust methodologies to measure the efficacy holistically.

Nevertheless, the literature in this field is still immature and fragmented, often presenting contradictory or incomplete perspectives. Thus, further research is required to fully understand the net environmental and social impacts of this transition across different industries (Rame et al. 2014).

Furthermore, collaboration between stakeholders and the cultivation of novel ecosystems able to extract value from waste are also required to unlock the potential of this paradigm for sustainable development (UNIDO, 2017). Therefore, the emergence of “Intelligent Assets” and Industry 5.0 marks a crucial momentum in the transition towards a sustainable digital future. This transition is expected to be guided by robust policy frameworks, reinforced by sound scientific research.

In essence, Industry 5.0 can enable more resilient, environmentally sustainable, and socially responsible industries by the integration of diverse digital technologies with circular economy principles and human-machine collaboration. Yet, this domain is still nascent and further research along with collaborative efforts across stakeholders are needed to achieve an in-depth understanding of their positive and negative impacts on sustainable development.

3.6.7. Digital Ledger Technologies, Blockchain, and Sustainability

The Distributed Ledger Technology (DLT), with Blockchain being the most recognized form, has attracted substantial media attention, often exceeding the actual scope of its capabilities. Blockchain is essentially a DLT that facilitates transactions or document authentication without the need for intermediaries, using decentralized and encrypted systems to record and timestamp transactions chronologically and publicly. Despite the hype surrounding blockchain, it is important to approach it with caution, dispel misconceptions and understand its true potential within the appropriate context.

Concerning the application of Blockchain for sustainability, a relevant trend is the concept of "Blockchain for Good", which has attracted a growing number of researchers and practitioners, to explore its potential to generate social value (Byrne, 2017; Gupta, 2017; Hanson et al., 2017; Morabito, 2017; Piscini et al., 2016). In this context, Blockchain technology is appreciated because it offers advantages such as trust, transparency, decentralization, and immutability, making it a promising tool for addressing numerous social and environmental challenges (Au, 2017; Lewis, 2017). Notably, as demonstrated by UNDP (2018) and the World Bank (2018), Blockchain has the potential to improve efficiency, transparency, and accessibility, thereby supporting sustainable development.

Its decentralised and immutable structure is useful to address inefficiencies in development aid and humanitarian assistance. Blockchain has the potential to enable financial inclusion through digital identity solutions and decentralised services contributing to SDG1 and SDG10. It can also enhance the traceability of global supply chains while encouraging ethical and sustainable sourcing and manufacturing, thereby contributing to SDG12 and SDG9 (Courcelas et al., 2020; UNDP, 2018). In this regard, Munir et al. (2022) argued that Blockchain can revolutionize the sustainability of supply chains by enhancing resource efficiency, and developing trust through smart contracts, thereby preventing fraud and enhancing reporting with reinforced accountability.

Indeed, Blockchain can be used for tracing the origins of materials, ensuring accountability and ethical practices. In this regard, Zhang et al. (2020) emphasized that the combination of Blockchain with IoT and BDA can support operational excellence and improve the sustainability of supply chains and LCA studies. Similarly, Courcelas et al. (2020) underlined the role of Blockchain in fostering transparency and efficiency in energy management, through decentralized, renewable energy systems, peer-to-peer (P2P) energy trading, and efficient data management, supporting the SDG7 and SDG13 by reducing carbon footprints and enhancing green energy initiatives.

Moreover, Blockchains have been explored for sustainable cities and communities (SDG11), education (SDG4), and securing land ownership, to empower communities and economic stability, in line with SDG16 (UNDP, 2018). Indeed, institutions and public-private alliances have been promoting Blockchain platforms for social and industrial transformations, in combination with other digital paradigms.

Charalambous and Damvakeraki (2024) also underscored their potential for healthcare, supply chain enhancement, reduction of defects in manufacturing, tracking environmental and sustainability performance, and verification of suppliers or qualifications. Rana et al. (2019) suggested that Blockchain technology could contribute to promoting practices that reduce environmental impacts and enhance governance efficiency. Similarly, Arim-Park et al. (2021) noted that Blockchain has the potential to improve sustainability performance in areas of environmental protection and social equity.

Nevertheless, Blockchain comes with its challenges, and the potential of these technologies to address sustainability issues and drive social change is still untapped. Reaping the benefits of DLTs requires understanding their strategic implications, context, underlying value, and hurdles while developing scalable, efficient, and sustainable solutions to social challenges.

Furthermore, it is crucial to acknowledge the range of technical, legal, social, and environmental challenges that Blockchain and DLTs still face, which demand careful consideration (De Vries, 2018). Key controversies include the potential misuse of these technologies, insufficient security, high operational costs, and environmental impacts associated with specific types of energy-intensive consensus mechanisms (De Vries, 2018).

The European Union Blockchain Observatory and Forum (EUBOF, 2018) underscored four critical challenges: affordability, accountability, reliability, and marketability, suggesting a roadmap to overcome them through focus, forecasting, funding, and feedback.

In addition, as argued by Ali Syed et al. (2019) scalability remains a significant issue, since as the number of transactions increases, the Blockchain must manage them without compromising speed or costs. Therefore, further research is necessary to fully understand the uses, impacts, and future scenarios of DLTs, as well as to shape regulatory frameworks accordingly. Charalambous and Damvakeraki (2024) explored emerging areas like NFTs, DeFi, and Central Bank Digital Currencies, while addressing environmental concerns, regulatory landscapes, and interoperability challenges.

Regarding the impacts of these technologies on environmental sustainability, Charalambous and Damvakeraki (2024), Nishant Sapra et al. (2023), and Ali Syed et al. (2019) underlined that some Blockchain systems, such as Proof-of-Work (PoW) algorithms (e.g. Bitcoin, pre-merge Ethereum), pose sustainability concerns due to their high computational power to secure the network, which leads to extensive energy consumption and subsequent GHG emissions. Additionally, the turnover of hardware contributes to electronic waste.

Yet, alternative consensus mechanisms like Proof-of-Stake (PoS) and Proof-of-Authority (PoA) are being explored to reduce energy consumption, since they rely on validators staking cryptocurrency rather than on resource-intensive computational tasks (Charalambous and Damvakeraki, 2024). Moreover, the integration of renewables and innovations in hardware efficiency (e.g. energy-efficient ASIC models) can also contribute to reducing the impacts. While the potential of Blockchain has been applied for addressing climate change, by supporting individuals and organisations to manage their emissions by verified data, the net environmental costs in this realm remain unclear (Howson et al., 2019).

As argued by Howson et al. (2019), social costs and benefits also remain uncertain, demanding further research and regulatory oversight. Moreover, social and governance aspects have not been sufficiently examined, showing a lack of robust ethical frameworks. Absent a fair and suitable ecosystem, the principles and ambitions of this paradigm could be undermined.

Blockchain technology was originally developed to improve transaction security, but the storage of sensitive information within its records increases its vulnerability to potential malicious exploitation. Similar to other data-driven technologies that handle large volumes of decentralised information, Blockchain encounters significant ethical challenges primarily concerning privacy and security. Moreover, it presents social risks associated with access disparities, inequalities, and vulnerabilities, which can further deepen digital exclusion.

While DLTs can make possible the appealing concept of citizen-led solutions to social problems, some experts deny the real potential of Blockchain to create democratic solutions, arguing that it merely replaces traditional structures with digital ones. This shift demands new ways of collaboration and appeals to multilateralism (Mulligan, 2019), to understand concepts such as transparency and trust, along with new approaches to data management. Building the necessary ecosystems for engaging all stakeholders, developing standards and regulations, and resolving security and scalability issues are crucial preconditions for accelerating its adoption.

In this context, Shapiro (2024) proposed a “grassroots architecture” as an alternative to global digital platforms, designed to empower local communities and foster digital sovereignty through self-managed, citizen-led digital networks. This approach envisions a “federated global digital democracy,” which relies on the “blocklace,” an alternative to blockchain that offers conflict-free data structure, along with a comprehensive protocol stack to support democratic governance.

In conclusion, while DLTs show promise in the sustainability and social good domain, it is necessary to address their multiple challenges to fully realize their potential. These challenges are multifaceted, covering technical, environmental, ethical and governance issues, which should be carefully considered in driving positive change, through suitable governance and multistakeholder collaboration.

3.6.8. Advanced Connectivity and Sustainability

The environmental and social impacts of advanced connectivity technologies such as 5G (Five Generation) and the future 6G (Sixth Generation) are subject to controversies and contradictory perspectives. Advanced connectivity is critical and represents a cornerstone for digital transformation and sustainable development (UN, 2024b).

Advanced technologies such as 5G or 6G are expected to provide more efficient and powerful connectivity, with faster speeds, lower latency, enhanced capacity, and novel wireless services (Devi and Priya, 2024), but they come with sustainability concerns that need to be addressed.

In this regard, some studies suggested that 5G connectivity may lead to negative environmental and health impacts, including increased energy consumption, carbon emissions, and radiation exposure (Gandotra et al., 2017), while other studies underlined its potential benefits for sustainability. Indeed, 5G technologies are heralded as key enablers of Sustainable Smart Cities (Shehab et al., 2022), Intelligent Transport Systems, Vehicular Communications (Guevara et al., 2020), and many more innovations.

In terms of the potential environmental impacts of 5G, key concerns rely on the increased energy consumption and subsequent carbon footprint, along with the material footprint required for the 5G infrastructures, reliant on a massive number of small cell antennas for providing coverage. In this regard, Gandotra et al. (2017) underlined that 5G connectivity can augment energy consumption, leading to higher carbon emissions. The deployment of new infrastructure and the continuous operation of antennas place additional pressure on energy and raw materials resources, creating a sustainability dilemma.

Nevertheless, other studies argued that 5G connectivity operation is more efficient in terms of energy and costs in the long term (Vanelli-Coralli et al., 2020; Patwary et al., 2019). Besides, it enhances the scalability, flexibility, and reliability of global connectivity, which benefits numerous areas of life (Vanelli-Coralli et al., 2020).

Furthermore, 5G has been associated with potential, but uncertain, health risks. Some studies such as those by Russell et al. (2018) and Suresh et al. (2023) suggested that prolonged exposure to 5G radiation may lead to negative health outcomes. Indeed, such radiation has been recognized as a new form of environmental pollution (Russell et al., 2018). Similarly, Kostoff et al. (2020) pointed out that electromagnetic radiation from 5G networks may induce adverse systemic effects.

However, such potential health risks have been questioned by other studies. In this matter, Sofri et al. (2022) researched 5G base stations and found no significant effects on cognitive function or physiological well-being. In a similar perspective, Simkó et al. (2019) emphasized the need for further research, to assess potential health risks associated with 5G radiation. Governments and industry must collaborate to establish robust safety standards that assure that 5G deployment minimizes potential environmental and health-related risks. Moreover, Suresh et al. (2023) underscored that 5G connectivity also poses social impacts associated with privacy, while Guevara et al. (2020) recognised that these technologies still face technical, economic, and legal uncertainties and challenges.

While these observed environmental, ethical and health effects are legitimate, advanced connectivity also offers outstanding potential for promoting sustainability and the SDGs. As argued by Shehab et al. (2022), 5G networks are recognized as key enablers for realizing sustainability goals, specifically in urban environments. Indeed, 5G could drive improvements in resource efficiency, energy management, and urban mobility, as argued by Guevara et al. (2020).

Better connectivity with low latency can support the optimisation of transportation systems and the monitoring of energy systems, thereby contributing to cleaner urban environments. Besides, as 5G offers more reliable and cost-efficient connectivity (Vanelli-Coralli et al., 2020), it can enhance critical areas such as agriculture, healthcare, and education.

Beyond 5G, the future 6G generation is still at a nascent stage and is expected to be ready for 2030. Few robust studies about the sustainability of 6G can be found since the incipient status and the naïve and overly optimistic perspectives without tangible evidence dominate this research field.

The 6G networks are anticipated to offer ubiquitous wireless connectivity (Akyildiz et al. 2020), and advanced services beyond conventional telecommunication, such as precise positioning and sensing. At this crucial stage, it is imperative to align the development of 6G with sustainability goals, not only in terms of the technology but also concerning the associated business models.

Rijwani et al. (2024) included an overview of the relevance of connectivity for realizing the sustainability potential of other digital paradigms such as Industry 5.0. In addition, Devi and Priya (2024) argued that 6G networks are expected to provide even higher speed connectivity allowing a wide range of devices and services beyond traditional telecommunication. Besides, future 7G may enable low-cost and unbroken services by seamless and wireless connectivity with augmented coverage and bandwidth.

Alsharif et al. (2024) suggested that the emergence of 6G opens a promising opportunity for enhancing aspects such as the energy grids, but challenges remain such as scalability and security. In this regard, Strinati et al. (2021) suggested integrating semantic and goal-oriented matters to improve both effectiveness and sustainability, while Akyildiz et al. (2020) emphasized the importance of developing energy-efficient systems, “THz band” and space-based networks, intelligent communication settings, dynamic spectrum access, among other aspects.

Yrjölä et al. (2020) examined diverse potential scenarios for future 6G deployment, suggesting that the “sustainable future scenario” is the most desirable. This scenario emphasizes the relevance of addressing privacy and security concerns to balance business interests, regulatory requirements, and community needs. Furthermore, these scholars underlined the need to adopt an open ecosystem and a decentralized, poly-nodal power structure, for a more inclusive, resilient 6G.

Overall, the relationship between sustainability and advanced connectivity technologies like 5G and 6G is a multifaceted and complex issue, which remains underexplored. Despite the significant opportunities that enhanced connectivity can offer for sustainability-related areas, there exist also substantial concerns about the environmental, health and social impacts of these technologies that must be addressed. These novel infrastructures will require a massive material footprint, but in the long term, they can be more efficient. The deployment of 5G and future 6G should be accompanied by further research, robust standards, and collaborative governance to ensure a responsible advancement of these technologies towards sustainable development.

3.6.9. Cloud, Edge Computing, and High-Performance Computing

Cloud and Edge Computing technologies, along with other related concepts such as Fog Computing, are often promoted as environmentally friendly and cost-efficient solutions (Schniederjans et al., 2016), due to their potential to optimise energy efficiency and reduce the impact of data processing infrastructures.

In this regard, Cloud Computing allows users to store and process data remotely and often uses green data centres that pool resources to be more efficient and scalable. It provides flexibility and scalability, but it also generates a significant energy footprint if the supporting data centres are not sustainable. Besides, novel data-intensive services where latency and bandwidth are critical can suffer an increasingly saturated network (Perez et al., 2021).

Considering Edge and Fog Computing, they process data closer to the user, thereby reducing long-distance transmission, network congestion, and latency, while also enhancing network efficiency (Perez et al., 2021). Depending on how these technologies are managed they can enhance overall energy efficiency or augment energy consumption.

Besides, they require a large number of devices which leads to an increase in the material footprint and e-waste concerns. In this matter, Cao et al. (2020) examined the caveats posed by the increasing number of devices connected to the Internet, giving rise to the “Internet of Everything” (IoE).

In terms of security, some studies argued that Edge Computing enhance this aspect by processing data closer to the source (Perez et al., 2021), while others suggested the opposite (Tian et al., 2019), arguing that decentralization and dissociation of data, control and processing stages may induce vulnerabilities.

According to Tian et al. (2019), Edge Computing may enhance “backhaul” (transmission of data) impacts and user experience, while Ning et al. (2019) argued that Edge Computing can improve bandwidth saturation and energy constraints.

Hence, research shows that both Cloud and Edge Computing have a dual nature, potentially bringing both positive and negative impacts on sustainability, akin to many other digital paradigms. The sustainability literature is limited, fragmented and often contradictory.

Nevertheless, most studies suggested that negative environmental impacts may include increased contribution to energy consumption and carbon footprint, pollution, and e-waste (Arif et al., 2015). Yet, virtualisation techniques in this context may also facilitate energy efficiency across digital systems, and therefore, reduce carbon emissions.

In this sense, Gonzalez Monserrate et al. (2022) emphasised the material nature of the Cloud, alongside the significant environmental impacts linked to Data Storage, due to cooling and thermal management, water cycling, and e-waste disposal.

Therefore, the net sustainability impact remains uncertain (Arif et al., 2015), since it depends on the energy source used, the efficiency of the infrastructure and the specific operational and maintenance impacts.

Despite the potential impacts, mitigation and “Green Cloud” strategies can help to reduce the negative effects while reinforcing energy efficiency. In this regard, Park et al. (2022) examined Green Cloud services and concluded that they can reduce the electricity used by 31.8 to 143.8 billion kilowatt-hours.

Considering potential sustainable strategies, Savoia et al. (2024) explored the “Eco-Federated Learning” concept (Eco-FL) in the context of Green Edge Cloud Computing (GECC), which is expected to revolutionize Machine Learning (ML) by enhancing privacy and decentralization. These strategies reduce the energy required for data transfer and promote efficient computing at the edge, but they also face challenges due to limited computational power and energy storage capacity.

Rijwani et al. (2024) provided an overview of potential computing paradigms, such as Edge Computing, which can contribute to a sustainable Industry 5.0. In this regard, Edge Computing can enable technologies such as connectivity, IoT, extended reality (XR), or vehicle-to-vehicle communication with low latency for applications where a quick response is critical.

In addition, recent advancements such as Mobile Edge Computing, Cloudlet, and Fog Computing represent outstanding applications in real-world scenarios.

Indeed, Shruti et al. (2024) emphasized the role of Fog Computing in enabling real-time data processing for IIoT applications, by improving both efficiency and security. In this context, Sharma et al. (2024) further explored the sustainability and privacy challenges.

When it comes to High-Performance Computing (HPC), it has transformed diverse industries and research fields, by facilitating scientific breakthroughs in areas such as health improvement, climate modelling, and material science. Barykin et al. (2023) suggested that the combination of HPC and BDA could lead to economic, environmental, and social progress.

Hobby et al. (2009) argued that HPC and sustainability could co-exist through standards review processes that influence product development towards greater sustainability. These studies suggest that HPC could be more sustainable through energy-efficient techniques, more integrated infrastructures, and algorithmic approaches that minimize computational costs.

However, research suggested that HPC causes significant environmental impacts throughout its lifecycle. In this regard, Kocot et al. (2023) noted that energy consumption is considered a crucial factor in HPC, due to its environmental impacts and high economic costs. Similarly, Wlotzka et al. (2017) and Cai et al. (2011) argued that energy-aware HPC and energy efficiency practices are crucial to address the related impacts of building a more sustainable computer infrastructure.

Furthermore, there is ongoing debate in the scientific community about whether science truly requires such advanced and potentially unsustainable computing paradigms, instead of more conscious and efficient systems. Two opposing trends are observed: one emphasizes increasing the computational power through technologies such as HPC or Quantum Computing, while the other advocates for sustainable computing, more focused on sufficiency-inspired solutions.

In this matter, Singh et al. (2023) argued that a holistic focus on sustainability in computing is needed, as environmental impacts span all stages of the lifecycle, including manufacturing, operation, and disposal. Zwart et al. (2020) examined the ecological impacts of HPC in astrophysics, concluding that non-optimised code on “overpowered” hardware brings unnecessary environmental impacts that are a menace to science.

Huerta et al. (2018) argued that an integrated, unified infrastructure is required to overcome the current separation between high-performance and high throughput computing for scientific discovery.

Moreover, Chien et al. (2019) suggested that the growing reliance on computing power led to increasing direct environmental impacts which must be responsibly addressed within the computing community. Gupta et al. (2020) addressed the environmental footprint of computing, concluding that the overall carbon footprint is keeping growing, mainly due to mobile and data centre hardware, manufacturing, and operation of infrastructures.

While Kline et al. (2017) advocated for more rational paradigms and proposed “GreenChip”, as a tool for assessing the sustainability of computing systems. According to these scholars, using a smaller cache and main memory sizes in computing systems may provide an overall positive environmental trend without dramatically reducing performance.

Therefore, research suggested that HPC should be used where it brings more value, in combination with other more sustainable computing for less critical tasks. Sustainability must be integrated in the computing design and development, to tackle the potential impacts and ensure a responsible and efficient deployment of computation capacities.

Overall, there is a wide range of advanced computing paradigms (Cloud, Edge, Fog, HPC) with unique advantages and disadvantages from the sustainability point of view. The net environmental impact is largely dependent on how they are implemented and managed. The literature is still incipient and presents uncertainties and contradictory findings.

Future research is needed which should explore novel mitigation strategies, such as green practices, integration of renewable energy to reduce the carbon footprint, security solutions for distributed systems, and circular approaches for reducing the material footprint and e-waste.

3.6.10. Digital Space Technologies and Sustainability

Digital Space technologies, specifically Earth Observation (EO), Satellite Communication (SATCOM), and Global Navigation Satellite Systems (GNSS) represent outstanding opportunities for sustainable development. These technologies provide tools for environmental monitoring, disaster management, and improving connectivity. However, they also present significant environmental and social impacts which considerably challenge sustainability outcomes.

Research has demonstrated the value of Earth Observation (EO) for environmental monitoring. Global databases related to sustainable development frequently face challenges regarding resolution, granularity, and accuracy, which can be addressed through Earth Observation (EO) data, which provides widespread availability, long-term data continuity, and usually, open access (ESA, 2020; NASA, 2022).

Indeed, EO satellites offer data for monitoring climate change, deforestation, pollution, and biodiversity loss, among other aspects and SDGs. Governmental satellites like NASA's Terra and ESA's Copernicus have transformed the monitoring of environmental issues, enabling better decision-making in response to ecological and social challenges (UNCTAD, 2021a). These technologies contribute to conservation efforts, the mitigation of natural disasters, sustainable agriculture, healthcare, and education.

According to Paravano et al. (2024), ESA's EO applications have shown significant benefits for SDGs such as SDG11 (sustainable cities), SDG2 (food security), and SDG15 (land ecosystems). Furthermore, Satellite Communication (SATCOM) enables crucial realms such as telemedicine (SDG3), urban management (SDG11), and distance learning (SDG4) in remote areas, and has been demonstrated to be critical during global crises (Paravano et al., 2024).

Regarding GNSS, it has proven critical for optimising fields such as food production (SDG2), resource efficiency, water management (SDG6), and precision agriculture by providing accurate data on soil conditions, water demand, and crop health (Paravano et al., 2024).

In addition, according to UNCTAD (2021a), digital space technologies are crucial for supporting disaster management, by providing early warnings, predicting, and monitoring natural disasters, and supporting governance during the mitigation and recovery stages.

Paladini et al. (2021) emphasized the relevance of the circular economy principles for the sustainability of space technologies. Nevertheless, the sector is not particularly advanced in terms of integrating these principles, and circularity initiatives are limited (Donou-Adonsou et al., 2024).

However, space technologies also generate substantial environmental and social impacts that are often neither properly acknowledged nor effectively managed in most strategies and governance frameworks, alongside their practical implementation.

The rhetoric surrounding space activities is dangerously simplistic and burdened with misleading green claims. Organisations like UNOOSA which should be advocating for environmental responsibility glorify space technologies as silver bullets for the SDGs while disregarding their damaging environmental and social costs.

Indeed, research evidenced that digital space technologies have significant environmental impacts, including the generation of space debris, high energy consumption, pollutant emissions, waste production, and the extraction of raw materials throughout the life cycle of space operations.

These factors raise serious concerns about the long-term sustainability of space activities and highlight the need for more responsible practices in the sector.

In this regard, ITU (2024b) emphasized that space technologies must adopt a more responsible approach to resource use and place further emphasis on sustainability.

This is particularly critical at this crucial period when the increase in satellite launches, space debris, and the growing involvement of private ventures pose significant risks to achieving true sustainability in space operations. The space activity may help to contribute to social challenges but also exacerbates space debris, orbital congestion, and environmental footprints. These authors considered that current policies are inadequate, and space should be recognised as a global common, ensuring sustainability for future generations. For that purpose, they suggested a framework encompassing three pillars: sustainability from space, in space and for space. Besides, net-zero targets and circularity should be adopted to ensure zero debris and environmental impacts on Earth.

Considering the environmental impacts, a critical concern is the growing generation and accumulation of space debris, which poses a significant threat to existing satellites and future scientific missions, with dangerous cascading effects and potential collisions (Donou-Adonsou et al., 2024). As of 2024, millions of pieces of debris are orbiting Earth, yet only a small fraction is actively monitored. The inadequate control and management of space debris threaten the long-term sustainability of the space industry and could also negatively impact global communications and pose potential security and safety risks on Earth (Wilson and Vasile, 2023).

Moreover, the manufacturing, launching, and operation of satellites generate a significant carbon footprint and other negative emissions. Rockets rely on fossil fuels, and their launches emit GHG emissions and black carbon, which aggravates climate change, reduce the ozone layer (Goldstein, 2022; Donou-Adonsou et al., 2024; Wilkinson et al., 2024), and affect Earth's energy balance (Sirieys et al., 2022). With the new space race and the subsequent increase in space launches, many driven by commercial ventures, these risks are further intensified and require regulations (Goldstein, 2022).

Additionally, as Sirieys et al. (2022) pointed out, current scientific understanding of the impacts is limited and besides, the lack of international regulations addressing these impacts remains a critical gap. Indeed, the 1967 Outer Space Treaty, which governs space exploration is obsolete and unable to address modern problems. Sirieys et al. (2022) claimed that policies for reducing emissions and metrics should be created to encourage the assessment of atmospheric impacts.

Space technologies also require large amounts of energy for both satellite operations and ground-based data processing and infrastructures. Wilkinson et al. (2024) underlined that the environmental costs of EO data processing are often overlooked, and transparency is needed to understand the carbon footprint of these technologies.

Additionally, the manufacturing of satellites and ground infrastructure consumes significant amounts of critical raw materials, thereby aggravating resource depletion and environmental degradation. These manufacturing processes also generate GHG emissions and toxic pollutants, impacting the ozone layer and local ecosystems. The lack of circular economy practices in the aerospace industry further exacerbates these impacts (Donou-Adonsou et al., 2024).

Wilson and Vasile (2023) argued that there exists a "space sustainability paradox", by which the growth of space activity may help to contribute to social challenges, but also exacerbates space debris, orbital congestion, and environmental footprints. These authors considered that current policies are inadequate, and space should be recognised as a global common, ensuring sustainability for future generations. For that purpose, they suggested a framework encompassing three pillars: sustainability from space, in space and for space. Besides, net-zero targets and circularity should be adopted to ensure zero debris and environmental impacts on Earth.

The sustainability impacts go beyond the environmental domain and affect the social dimension. Despite that space technologies can provide social opportunities like improved access to healthcare and education, they can also aggravate existing inequalities. In this regard, access to satellite data and space services is unevenly distributed, with most developed nations reaping the benefits and less developed countries assuming the costs (e.g. materials, climate change events).

In addition, the current monopolization of space by a few powerful actors, particularly for commercial purposes or non-peaceful activities, raises significant ethical concerns regarding the equitable and responsible use and distribution of space technologies and resources (Sirieys et al., 2022; Wilson and Vasile, 2023). For instance, unequal access to satellite data may lead to the exploitation of natural resources, such as fish reserves or minerals, resulting in unsustainable practices. Thus, considering the significance and likeability of the impacts, a multifaceted approach is needed to mitigate the evident negative environmental and social effects brought by space technologies.

In this regard, circularity principles, energy-efficient strategies, international regulations, and cooperation, could help to reduce the environmental footprint. Besides, proper international regulation and cooperation that ensures ethical and equitable access to space is imperative for steering space technologies towards sustainability.

In conclusion, while digital space technologies are strategic and offer outstanding potential for environmental monitoring, and global communication, along with advancing many SDGs, they also raise significant environmental and social concerns that need to be tackled. Addressing these issues entails placing a stronger emphasis on sustainability throughout all space operations and adopting circularity and energy-efficiency practices. Additionally, it is crucial to establish an updated and robust global governance framework, which prevents unethical exploitation of space technologies and reduces current inequalities, thereby ensuring sustainable, fair, and equitable access for all nations and actors.

3.6.11. Digital Twins and Sustainability

Digital Twin technology is considered a relevant tool for sustainability goals, particularly in fields like manufacturing, healthcare, energy, and urban development. A Digital Twin is a virtual replica of a physical system that enables continuous monitoring, analysis, and efficient optimization of operations. In addition, this paradigm can also represent a tool for enhancing resilience by enabling systems to anticipate, adapt, and respond to disruptions more efficiently. Another key advantage of this technology relies on its capacity to optimise the use of resources, reduce waste, and enhance efficiency.

Fukui et al. (2021) argued that Digital Twins enable the integration of spatial-temporal data, thereby enhancing processes monitoring and optimisation, and subsequently contributing to the green transformation. For instance, as suggested by Zhang et al. (2024), Digital Twins can help to streamline operations in the construction industry, through real-time data of a building throughout its life cycle.

Huang (2024) emphasized the relevance of dynamic sustainable decision-making enabled by Digital Twins since they support multi-objective optimization by using time-variant data and handling uncertainties. In that way, this technology enables predictive capacities to mitigate environmental risks and achieve long-term sustainability goals efficiently. A more proactive response to environmental and operational risks also reinforces system resilience.

Digital Twins also play a relevant role in the implementation of the circular economy. In this regard, Mugge et al. (2024) underlined that this technology can provide life cycle data from production to disposal, thereby facilitating the monitoring and implementation of circular strategies, such as material reuse and end-of-life decisions. Thus, the contribution to circularity also enables reinforced resilience, by reducing reliance on critical resources and supply chain vulnerabilities.

Considering the social dimension, Digital Twins can also contribute in different ways. Omrany et al. (2024) argued that this technology can support social aspects by promoting inclusivity, diversity, and workforce safety. They can also contribute to optimising urban infrastructures for improved quality of life and resilience. Besides, Digital Twins are also being used in medicine, accelerating the discovery of treatments (Helbing and Argota, 2022).

Despite the evident benefits, this technology also faces challenges. In this matter, Tzachor and Richards (2022) identified issues related to digital divides, data quality, and deficient optimisation. In contexts with limited digital infrastructures, the full potential of Digital Twins remains untapped.

Helbing and Argota (2022) explored the sustainability and ethical issues of Digital Twins. This technology, like other digital paradigms, increases the energy consumption required for data processing, transmission, and storage. The massive amount of data requires advanced computing which often leads to an increased carbon footprint. Additionally, the capture of data relies on sensors and other hardware, thereby increasing resource depletion and electronic waste. In this regard, the integration of resilience-focused approaches can help to mitigate potential impacts and ensure more sustainable operations.

Besides, for these scholars, the concept of “optimising the world” is problematic and unfeasible. In addition, from an ethical perspective, Digital Twins raises concerns about data privacy and security, particularly in relation to personal data or health information. Besides, this technology contributes to inequalities since they are often controlled by powerful organisations. In sum, they could encourage technocratic approaches to governance.

Therefore, it is crucial to ensure an inclusive, sustainable, and responsible design and implementation of Digital Twins, grounded in resilience principles, to leverage their opportunities for sustainability monitoring, while avoiding inequalities, environmental damage, and ethical issues.

3.6.12. Extended Reality, Virtual Worlds, and Sustainability

Extended Reality (XR), Augmented Reality (AR) and Virtual Worlds (previously known as Metaverse) represent an evolution of virtual spaces and Digital Twins, where users interact with computer-generated settings (Owusu-Antwi et al., 2023). These paradigms are transforming how people interact with technology (Jenifer et al., 2023) and are expected to create potential benefits in areas such as education, culture and design, entertainment, and communication.

Jin et al. (2022) and Park et al. (2022) suggested that these paradigms could be used to promote pro-environmental behaviours and sustainable learning. However, there is limited evidence to support this claim. According to Doughan et al. (2022), the metaverse may provide a virtual space for architecture and historical heritage, overcoming physical boundaries and design constraints. Huynh-The et al. (2022) suggested that AI may enhance immersive experiences and humanlike intelligence, with applications in healthcare, manufacturing, smart cities, and gaming.

The literature mostly reflects critical perspectives on the relevance of these paradigms for sustainability purposes. Allam et al. (2022) argued that while Virtual Worlds may redefine urban design and the provision of some services, they also imply significant and unresolved ethical, social, and cultural concerns. Similarly, Jenifer et al. (2023) argued that these virtual universes with immersive technologies raise ethical concerns about privacy and addiction.

Paquin et al. (2022) explored the potential effects of Virtual Worlds on mental health, concluding that it could bring both benefits, like control and cognitive activation, and risks like addiction and disrupting sleep rhythms and less social capital.

Helbing and Argota (2022) criticised the “Metaverse” concept, as it involves an immersive experience with “privacy-invasive” technologies that create virtual replicas of real systems. Besides, these novel paradigms make use of augmented reality devices, holograms, and neurotechnology, with the potential to create digital avatars in the future.

While these virtual environments are expected to enhance remote collaboration or reduce commuting-related impacts, they merely serve as entertainment. In addition, they raise ethical concerns and may increase the already alarming dependency on digital environments, rather than addressing real-world problems.

In conclusion, despite the hype and substantial investments in these technologies, their true potential for contributing to sustainability seems limited and is outweighed by significant ethical concerns and similar environmental impacts like other advanced digital technologies reliant on AI and massive amounts of data. As the technology evolves, further research will be needed to fully understand its long-term impacts and explore whether these advancements can support sustainable development or exacerbate existing challenges.

3.6.13. Smart Sustainable Cities and Communities

Some of the most promising and widespread applications of digital transformation for SD are the Smart Sustainable Cities and Communities (SSCC). Indeed, they allow multifaceted and multi-governance interactions (Caragliu et al., 2009) and have been one of the most relevant examples of digital transformation applied to societal challenges (Ghilic-Micu et al., 2019).

In this research, the Sustainable Smart City and Community (SSCC) concept is understood as “a system that enhances human and social capital wisely, by using and interacting with natural and economic resources via technology-based solutions to address public issues and efficiently achieve sustainable development and quality of life, based on multi-stakeholder and partnerships” (Fernandez-Anez, 2016).

Indeed, SSCC holds the potential to combine technology, public purpose, and citizen participation (Taratori et al., 2021). Yet, the effectiveness of extant approaches in the urban domain has been questioned by several scholars (Borghys et al., 2020; Schütz et al., 2019).

Digitalisation can be regarded as an outstanding tool for sustainable cities (Bifulco et al., 2016). The widely acknowledged framework for Smart Cities designed by Giffinger and Gudrun (2010) comprises six dimensions, namely: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance. As urbanization grows and digitalisation permeates the entire society, cities are becoming complex and multidimensional networks, engines of economic growth which account for most of the population and 70% of the GHG emissions (Elmqvist et al., 2019).

Given that city planning becomes critical for the SDGs (Giles-Corti et al., 2019), addressing sustainable and resilient cities by leveraging digital capacities constitutes an imperative for attaining the 2030 Agenda as a whole.

An emerging body of literature reveals how urban policy and management could benefit from the digital revolution to foster well-being and eco-innovation, supporting both the “New Urban Agenda” (Valencia et al., 2019), alongside the SDG11 and related sustainability goals (Allam and Dhunny, 2019; Amini et al., 2019; Balogun et al., 2019; Bibri and Krogstieb, 2017; Bifulco et al., 2016; Croese et al., 2020; Kharrazi et al., 2016; Vaidya and Chatterji, 2019; Valencia et al., 2019; Zheng et al., 2020).

In this regard, Ismagilova et al. (2019) reviewed the alignment of Smart Cities with the SDGs, underlining limitations, and future directions. Amini et al. (2019) considered Smart Cities as computationally and socially complex, multi-sectorial, multi-actor and interdependent networks whose objective is promoting SE, and quality of life, together with efficient operation and efficient services.

Valencia et al. (2019) underscored the relevance of localisation and transdisciplinary research regarding boundaries, governance, actors, synergies and trade-offs, and indicators. Even when several literature reviews exist in the domain, a lack of systemic quantifiable and multidisciplinary perspective remains (Zheng et al., 2020), along with a lack of consensus. Indeed, some experts argued that cities cannot be smart and sustainable at the same time (Akande et al., 2019), while others noted that the potential of digitalisation to tackle climate adaptation in these contexts has not yet been proved (Balogun et al., 2019).

Furthermore, some experts criticized the lack of sound governance, and the dominance of techno-centric approaches over eco-social aspects (Taratori et al., 2021; Crumpton et al. 2021; Sebastian et al., 2018; Trencher, 2019). The insufficient effectiveness and added value of co-creation and citizen involvement (Borghys et al., 2020; Puerari et al., 2018), along with the technocratic and reductionist structures (Calzada, 2020) have also been exposed.

Additionally, power imbalances for the benefit of elites and business interests at the expense of public good have also been denounced (Crumpton et al., 2021). Indeed, technology itself does not induce citizen and public engagement, as argued by Borkowska et al. (2018).

The literature also reveals caveats and complexities. Urban sustainability is still not well understood at the policy level (Elmqvist et al., 2019), and neither is the concept of Smart Cities. As a result, current indicators for the SDG11 are not consistent, and robust benchmarks are lacking (Giles-Corti et al., 2019). Therefore, the implementation issues remain poorly understood, especially concerning resilience (Croese et al., 2020).

Regarding urban digitalisation, multiple open issues persist, such as data privacy and security, misconstructions both on the policy and technology side, along with lack of systemic perspectives able to balance social and environmental issues (Allam and Dhunny, 2019; Amini et al., 2019; Bibri and Krogstie, 2017; Kitchin, 2015; Israilidis et al., 2019). In this regard, Kharrazi et al. (2016) underlined the key role of urban Big Data in feeding innovative indicators, thus helping policymakers to achieve SD. Yet, leveraging the data deluge demands culture and skills advancement, together with investment and dedicated programs.

Bibri and Krogstie (2017) argued that ICT development should be better linked with SD and well-being, while underscoring numerous critical issues which remain overlooked, lacking theory development. Similarly, Yigitcanlar et al. (2019) contended that limited evidence exists about the integration of genuine sustainability since policies are techno-centric and multiple complexities remain, suggesting a knowledge-based development and policy enhancement.

In addition, Allam and Dhunny (2019) claimed that sustainability, inclusivity, and well-being, must not be disregarded in this realm. Thus, social, and cultural nuances should be integrated, by balancing technological, social, and environmental factors.

Israilidis et al. (2019) argued that research is mainly focused on technical issues, overlooking social approaches, knowledge-sharing and learning capabilities. These scholars conceived cities as multi-stakeholder and citizen-centred knowledge hubs.

Complementing these views, Michalec et al. (2019) underlined the lack of awareness about how different actors understand Smart Cities, and urban climate justice is scarcely embedded in this topic, where policy needs enhancement. Cowley and Caprotti (2019) regarded Smart Cities as spaces for experimenting, in opposition to critical experts who consider them as top-down impositions for policymaking and planning purposes. Öberg et al. (2007) stated that organisational aspects of management are poorly considered, and lacking theoretical ground.

Despite the limitations and caveats, sustainable, “green” and smart concepts for SD can converge provided that environmental quality and resilience remain central in policy and planning (Gazzola et al., 2019). To achieve inclusive and sustainable SSSC, urban stakeholders must prioritize citizen involvement, sustainability, and social values while creating a culture of dialogue and trust.

Knowledge intermediaries like brokers, boundary spanners, and gatekeepers can play a crucial role in coordinating interactions between stakeholders and fostering innovation in SSCC (Lepore et al., 2023). These intermediaries can support capacity building and enhance the effectiveness of SSCC and industry 5.0 initiatives in achieving the triple transition. Understanding lessons learned in SSCC is crucial for the implementation of the n-helix innovation models in other digital contexts.

In conclusion, further research is needed to fully understand the limitations and provide policy and governance recommendations for truly embedded sustainability as a core value and feature of Smart and Sustainable Cities and Communities.

3.6.14. Smart Energy Communities

Local Energy Communities (LEC) have received both praise and criticism. They are expected to reinforce eco-social innovation, citizen participation and ownership, promote renewable energy, tackle energy poverty and combat climate change in line with energy transition policies (EC, 2020; Geels et al., 2017).

However, LECs also struggle with challenges that hamper their diffusion, such as local culture, “NIMBYism” (e.g. the citizens’ opposition to developments in their local area), participatory barriers, lack of trust, conflicting interests among actors, unclear regulation, insufficient incentives, readiness, and capacities (EC, 2020; Boulanger et al., 2021; Ceglia et al., 2022). Besides, the inherent complexities of the energy transition also pose challenges (Sovacool et al., 2022).

According to Galan et al. (2017), the Smart Energy Communities (SECs) offer outstanding opportunities for SD, along with the Positive Energy Districts (PED), where collaboration, co-creation, and hybrid top-down and bottom-up leadership help to bridge gaps and uncertainties (Otamendi-Irizar et al., 2022; Mihailova et al., 2022). Indeed, digital paradigms play a significant role in enabling multisided energy markets, empowering novel energy actors (e.g., prosumers, peer-to-peer trading), enhancing power flexibility and management, and creating decentralized and distributed virtual communities (Loock, 2020; Husiev et al., 2023).

Yet, digital technologies are only present in a few initiatives (Ghiani et al., 2019; Reis et al., 2021; Barone et al., 2020). Besides, leveraging the social dimension and citizen engagement within these communities is a key component for their success and thus far has been overlooked (Boulanger et al., 2021; Husiev et al., 2023). Therefore, Smart Energy Communities present an excellent context for implementing innovation for sustainable development and the green transition. Further research is needed to fully understand the potential of digital paradigms and business models for eco-social innovations in SECs to overcome current bottlenecks (Loock, 2020; Otamendi-Irizar et al., 2022).

3.6.15. Society 6.0: Human-Centred and Sustainable Digital Society

Digital transformation and its encompassing technologies have been strongly focused on technology with little attention to human or eco-social factors which remain peripheral (Beier et al., 2020). Recent literature underlines that DT, if managed responsibly, could bring societal benefits (Bai et al., 2020; Beier et al., 2020; Jabbour et al., 2018; Müller and Voigt, 2018).

Nevertheless, this purpose requires a multidisciplinary and interdisciplinary approach, not always available (Hauseberg et al., 2019). Indeed, when placing humans at the heart of innovation, the environmental implications often remain unclear (Beier et al., 2020).

In the pursuit of a people-centred digitalisation, the concept of “Society 5.0” emerged gaining recognition across the world. “Society 5.0” was coined by the Japanese Cabinet in 2016 (Ferreira and Serpa, 2018; Salgues, 2018), as part of the Japan Strategy for Growth, to reorient economic and technological development towards a human-centric society (Fukuyama, 2018).

Digital transformation permeates all domains of society, seeking well-being, responsibility, and sustainability (Onday, 2019; Ferreira and Sherpa, 2018), and this perspective is soundly integrated within the Society 5.0 concept. Indeed, this novel paradigm proposed a “super, smart, society,” where technology is used for the people (Fukuyama, 2018). This is articulated by connecting people and digital systems (Onday, 2019; Carayannis et al., 2020) and merging the virtual (cyberspace) and the real physical space. In this regard, Bartolini et al. (2021) stressed that considering the social focus, the implementation of Society 5.0 needs to integrate entrepreneurship from civil society and institutions.

Carayannis et al. (2021) and Nambisan et al. (2019) suggested that the paths of Industry 5.0 and Society 5.0 are parallel. Žižek et al. (2021) advocated for a more inclusive vision that further integrated sustainability considerations and extended this concept into an evolved “Society 6.0” vision. Yet, thus far, empirical studies tackling Society 6.0 are scarce due to the novelty of the approach which remains poorly substantiated. Thus, further research is required to solidify its foundation and demonstrate its real-world applications.

Indeed, Carayannis argued that previous discussions have been reductionist envisaging two opposite extremes: a dystopian future where digital technologies hamper humanity and a “naïve” horizon where only benevolent impacts are recognized. Instead, multiple futures are possible (Pashek et al., 2019; Pereira et al., 2020). Nonetheless, social reality has multiple facets which cannot be translated to cyberspace and Society 5.0 does not fully depict contemporary complexity and eco-social transformations. In this regard, technology is not a silver bullet and techno-utopianism should be avoided when advocating for sustainable approaches.

A Society 6.0 vision represents better the intersection of societal, ecological, and digital subsystems for a sustainable digital transformation. However, at present, achieving this vision remains an aspiration for the future rather than an imminent reality. Therefore, transitional models and narratives are necessary in the interim to bridge the gap between current practices and the desired sustainable future.

3.7. Categorisation of the Digital Paradigms for Addressing the SDGs Challenges

This section presents the key findings derived from the systematic literature review and subsequent critical analysis conducted on the realm of the SDG challenges and the potential role of digital paradigms in tackling them.

Despite the importance of pioneering studies and institutional initiatives in this field, a comprehensive analysis of how emerging digital paradigms, such as Big Data and Artificial Intelligence, can be responsibly leveraged to address the caveats of the SDGs has been absent from the literature until this study.

Therefore, this research fills a relevant gap in the literature by exploring the potential of digital technologies to contribute meaningfully and sustainably to the achievement of the SDGs.

Digital Paradigms for Addressing SDG Research Gaps

Drawing on the insights gained, the following section presents the exploration of digital paradigms to address the existing research gaps within the SDG framework.

A growing, but still incipient, body of literature proved how digital paradigms, predominantly Big Data Analytics and Artificial Intelligence, are being applied to measure or advance many SDGs (ITU, 2021; Malhotra et al., 2018; Vinuesa et al., 2020; Walker et al., 2019).

Despite these studies, the scientific literature remains underdeveloped and highly fragmented, with most studies originating from grey literature. Particularly, there exists a lack of focused examination of the research gaps within the SDGs, and the potential for digital paradigms to address them.

Based on the analysis conducted, this research suggests that digital paradigms could contribute to bridging the SDG gaps in three ways:

- (1) First, by overcoming existing data limitations which can be done by harnessing non-traditional data sources, while ensuring ground validation, quality, and interoperability.
- (2) Second, by providing enhanced data-driven analytical capacities for scientific research, monitoring, assessment, decision-making, and governance.
- (3) Third, by expanding collaboration and knowledge-sharing opportunities through the development of highly connected digital ecosystems and data partnerships and stewardship.

The first contribution, related to the data deluge from novel sources, is widely recognized in recent literature. Certainly, the digital technologies, and especially IoT, EO, and Big Data Analytics, have proven to be crucial for compiling vast amounts of data and distil them into actionable knowledge (Guo, 2020; Andries et al., 2019; Fukuda-Parr and McNeill, 2019; Letouzé et al., 2019; Williams et al., 2019; Konduri et al., 2018; Malhotra et al., 2018; Van den Homberg and Sussha, 2018; Chandy et al., 2017; Jacob, 2017).

Prior research corroborated that the data deluge brought by the digital era, offers innovative and cost-effective pathways to overcoming the existing limitations of conventional SDG databases and metrics, by integrating small-scale traditional data sources with emerging Big Data platforms.

However, the literature also unveiled critical capacity constraints, along with methodological and market barriers that need to be addressed to fully leverage new data sources and data-driven technologies (ITU, 2019b; Letouzé et al., 2019; Walker et al., 2019; Yayboke et al., 2017).

Furthermore, relevant social and ethical concerns are underscored around novel data-driven solutions, which deserve specific research and interventions (Campolo et al., 2017; Herschel and Miori, 2017; Lepri et al., 2017; Letouzé and Pentland, 2018; Smith and Neupane, 2018; Vinuesa et al., 2020). On these grounds, this research claims a context-aware, bias-free, trustworthy, and ethically guided approach to avoid risks that could undermine sustainability or inclusion.

Besides, to truly embed a regenerative approach, digital technologies must be encouraged to bring a net-positive impact concerning existing societal and ecological challenges.

The second significant contribution of digital technologies lies not only in the sheer volume of data but also in the capacity to interpret it meaningfully for sustainability purposes. Indeed, prior studies illustrated that the genuine added value of digitalisation goes beyond data, which is worthless without interpretation, especially in the complex and multidimensional domain of sustainability.

The synergistic combination of digital paradigms, particularly the fusion of Big Data Analytics with Artificial Intelligence (AI), unlocks extraordinary computational, analytical, and predictive capabilities (Letouzé, 2015; Vinuesa et al., 2020), that can significantly enhance human decision-making processes in an unprecedented fashion.

Thus, digital technologies push the boundaries of knowledge, enabling a novel research stream that has revolutionized social and behavioural sciences (Bright, 2017; Fazekas, 2014; Paulus et al., 2014). It has also transformed governance frameworks allowing them to address wicked sustainability challenges (Lepri et al., 2017; Athey, 2017; Lowman, 2017).

Stemming from these insights, this research argues that these advancements in digital technologies and capacities could be transformative in addressing many of the implementation and governance hurdles currently faced by the SDG framework.

In this regard, by augmenting analytical capacities and improving data-driven decision-making, digital paradigms can tackle pressing issues. Nevertheless, research in this area remains in its infancy, thus further exploration is essential to fully understand the contribution of digital paradigms to the SDGs and address potential trade-offs.

The third significant contribution of digital paradigms is focused on the role of digital ecosystems in fostering collaboration and expanding knowledge creation and sharing in the pursuit of sustainable development.

Despite the relevance of the digital ecosystems for enabling collaboration, trust and knowledge brokering in the sustainability domain (Jensen and Campbell, 2019; Pappas et al., 2018; Stuermer et al., 2017), their role towards bridging the SDGs gaps remains poorly explored. Previous studies indicated that digital paradigms can significantly enhance connectivity (Fernández-Portillo et al., 2019; ITU, 2017a), facilitate knowledge sharing (Stafford-Smith et al., 2017), and support collaboration across geographical boundaries (ITU, 2017a; Zheng et al., 2020).

Furthermore, the creation of interconnected data partnerships (Rasche et al., 2019; Sussha, 2020; Yayboke et al., 2017) could unite diverse data sources, capabilities, and expertise, thereby overcoming many of the existing limitations of the SDGs related to collaboration and knowledge management (Pappas et al., 2018; Smith and Neupane, 2018).

Indeed, digital ecosystems have the potential to promote digital literacy (Bhargava et al., 2015; Letouzé and Pentland, 2018) and enable multidisciplinary collaboration (Bibri, 2019; ITU, 2017a; Smith and Neupane, 2018), both of which are essential for addressing the complex challenges of sustainable development.

Hence, further examination of the contribution of digital ecosystems to overcome the SDGs would significantly enrich current studies and debates. Providing in-depth insights into how to harness digital paradigms, capacities, and ecosystems for a more effective and integrated approach to the 2030 Agenda results critical for advancing sustainable development. In this regard, the role of digital innovation ecosystems in tackling the sustainability and SDGs challenges, while driving the regenerative triple transition, is further explored in the next Chapter.

The research findings are summarised in Figure 3.2., which presents an outline of how digital paradigms could contribute to addressing the aforementioned research gaps within the SDG framework.

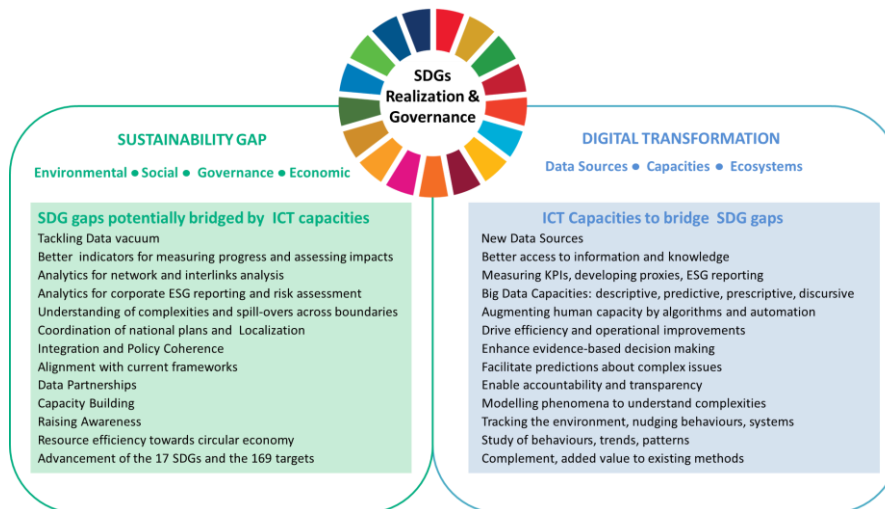


Figure 3.2. The Contribution of the Digital Paradigms to Addressing the SDG Research Gaps
(Own elaboration)

Following the categorization of the digital capabilities for tackling the SDG research gaps, an overview of the limitations inherent to data-driven technologies in addressing these caveats is presented next.

Limitations of Data-driven Technologies for the SDG Challenges

As described in previous sections, the implementation of data-driven or digital technologies in the sustainability realm remains incipient. The current literature primarily emphasized the positive contributions, while often overlooking potential negative aspects and risks. Thus, this field requires enhancement across multiple areas to address the existing uncertainties and unlock the full benefits of digital transformation sustainably.

First, the current understanding of the interlinkages among the SDGs is limited, while being essential for achieving systemic transformation toward regenerative sustainability. The complexity of this network of goals and targets, the related narrow indicators, alongside the data lack and lags in this domain, suggest that a data-driven quantitative approach to analyse the synergies and trade-offs may not be feasible shortly (Gupta et al., 2023b).

In addition, there is limited knowledge about the potential benefits and negative impacts of digital transformation on the social and environmental dimensions, which adds uncertainty to this already complex field. This reality contradicts the generalized claims of positive contributions across the 2030 Agenda, often made by practitioners and governmental institutions.

Furthermore, isolating the specific impact of one technology on the SDGs is challenging, especially considering the multifaceted nature of the goals and the intertwined use of digital solutions. Additionally, the interdisciplinary scope of the SDG metrics makes interpretation ambiguous and frequently leads to contradictory findings across different studies. Second, another key challenge relies on the lack of suitable and pertinent metrics and data, alongside context considerations, which often results in superficial interpretations of the impacts. Contextual factors play a crucial role in determining whether an intervention genuinely contributes to sustainable development and in assessing specific goals.

Furthermore, the difficult balance between global and local perspectives and different paces of development also poses a dilemma, as assessing indicators from a global viewpoint can conflict with local priorities and perspectives. Differing reporting systems, throw inconsistent results across various studies, which further complicate the assessment interpretation.

The insufficient localization in current indicators limits their practical effectiveness of assessments, calling for a holistic, quality-based approach. Indeed, navigating boundaries at micro, meso, and macro levels is vital to capture the impacts in specific settings and this requires close cooperation with stakeholders (Gupta et al., 2023b).

The data limitations may reduce the accuracy of digital technologies such as AI and BDA, decreasing their ability to generalize to other contexts, their potential to identify patterns, and increasing the risks of biases. Considering the data and metrics limitations, expert input is critical to properly interpret the wide range of impacts accurately, ensuring that assessments capture both short-term and long-term effects across different disciplines, scales, and contexts. This means that Big Data, for instance, should be complemented with Small Data and qualitative insights from experts, to provide a suitable interpretation.

While the research landscape around digital technologies and the SDGs is growing, it still faces severe caveats and a limited body of robust literature. Existing metrics and data sources need to be updated and adapted to the evolving digital context. Many underrepresented countries, particularly those in the Global South, are currently missing from the conversation, uncovering the need for more inclusive research.

Given that digital technologies shape the sustainability and well-being of communities, organizations, and society at large, aligning these practices with sustainable principles and SDG objectives is critical. Hence, a fundamental shift in understanding how digital transformation paradigms impact specific contexts is required.

In summary, digital technologies present outstanding opportunities for tackling the SDG challenges but also face some limitations that require further exploration. Addressing these challenges will require comprehensive evaluation frameworks combining quantitative and qualitative approaches, context-sensitive metrics and interpretation, and an emphasis on both positive and negative impacts, alongside the net outcome, thereby supporting a more balanced approach.

The Need for a Holistic Approach to Align Digital Transformation with Sustainability

Beyond prospects, a closer look into the literature revealed that digital disruptions also bring an untamed dark side that needs to be acknowledged and tackled to ensure a positive contribution to the SDGs. In this regard, ongoing debates, controversies, and a lack of systemic perspectives persist regarding the genuine contribution of digital transformation to sustainability (Letouzé and Pentland, 2018; Niño et al., 2017).

Previous studies confirm that digital paradigms, particularly AI, face unresolved challenges and capacity constraints themselves, in part because they lack well-developed theoretical, implementation, and regulatory frameworks (BDVA, 2017; Smith and Neupane, 2018).

Furthermore, intense ongoing debates about the ethical threats and social divides have dominated recent research (Campolo et al., 2018; Herschel and Miori, 2017; Hilbert, 2016; Khakurel et al., 2018; Lepri et al., 2018; Smith and Neupane, 2018). A lack of consensus remains about the notion of ethics, responsibility, or the so-called “social good” movement (Berendt, 2019; Fjeld et al., 2020).

Moreover, environmental sustainability has been either marginally addressed (Khakurel et al., 2018; Vinuesa et al., 2020), or entirely overlooked in both research and policy agendas (Villani, 2018). This has often resulted in cosmetic and superficial approaches to sustainable development or even misleading green claims that dominate the digital landscape.

Critical scholars argued that the caveats of digitalisation often outweigh its opportunities, and even conflict with sustainability goals (Gebhardt, 2017; Unwin, 2017; MacFeely, 2019). Some experts even predict potential dystopian futures potentially brought about by digital paradigms such as AI (Fukuda-Parr and McNeil, 2019; Goralski and Tan, 2020; Metcalf et al., 2016; O'Neill, 2016; Smith and Neupane, 2018).

Additionally, this disconnection between digital transformation and environmental sustainability is also evident in the 2030 Agenda. In this regard, some studies have highlighted the weak and fragmented integration of innovation, technology, and digital advancements within the SDG framework (Novak and Tjoa, 2018). This raises the question of whether it might be beneficial to explore the establishment of dedicated clusters for digital transformation, as suggested by Sachs et al. (2019b), or even the creation of a new SDG18 specifically devoted to the governance of sustainable digital transformation, as argued by Clarks (2022).

Therefore, as Tjoa and Tjoa (2016) asserted, a holistic approach is essential to assess and mitigate the sustainability impacts, which has been lacking so far. Even more, a reorientation of digital transformation is needed (D4S, 2023; CODES, 2022) towards overcoming these challenges and fully unleashing its value for sustainable development and the SDGs.

In this regard, it is important to recognize the specific complexities that arise when digital paradigms are applied to the realm of sustainable development. On one hand, this can be explained by the fact that sustainability issues are inherently wicked, characterized by tensions between different dimensions, and achieving net benefits is highly challenging (Tura et al., 2018).

On the other hand, sustainability and digital transformation must be pursued from a systemic and ethical perspective, moving beyond current techno-centric approaches (Hilbert, 2016; Kane et al., 2019; Leonhard and Graf-von-Kospor, 2017). A closer examination of the literature revealed a gap between science and practice, along with siloed disciplinary approaches (ITU, 2019b; ITU, 2017a) and insufficient diffusion of innovations. These factors may hinder mutual understanding, alignment, and the multidisciplinary approach needed to merge sustainability and digital transformation.

Additionally, some sustainable development gaps are rooted in structural, cultural, financial, or human factors (ITU, 2017a; Smith and Neupane, 2018; Yayboke et al., 2017; Walker et al., 2019) that cannot be resolved through technological innovations alone. While ICTs can add value and enhance human capacity, other enabling elements are necessary, requiring further research, but also policy development.

Despite the remarkable opportunities on the horizon, prior and current research uncovered that progress in harnessing digital paradigms to pursue the SDGs is very slow-paced, incremental, and highly context-dependent. As a result, this domain remains in an embryonic stage.

Hence, this confluence of barriers has led to a pronounced gap between the potential of digital transformation in the realm of sustainable development, and its actual realization (Chandy et al., 2017; Janowski, 2016). This intention-action gap remains a significant challenge in pursuing sustainability efforts, especially in technology-focused sectors.

The predominant school of thought acknowledged that unlocking the potential opportunities that digitalisation presents for sustainable development and curbing its risks, relies on providing responsible, ethics-driven, context-aware governance, alongside enabling frameworks (Kostoska and Kocarev, 2019; Smith and Neupane, 2018; Townsend and Coroama, 2018; Van der Velden, 2018a; Campolo et al., 2017; Fjeld et al., 2020; Hesse et al., 2018; Khakurel et al., 2018; Letouzé and Pentland, 2018).

Aspects such as fairness, accountability, and transparency are particularly relevant (Lepri et al., 2018). Nevertheless, the unintended social, ethical, and environmental risks of digital transformation remain insufficiently reflected in current policies, strategies, and regulations (Wu et al., 2018). Moreover, building digital literacy and awareness, as well as promoting dialogue and collaboration across diverse actors, disciplines, and nations (Bhargava et al., 2015; Letouzé and Pentland, 2018), are also crucial factors for ensuring the sustainable scaling of digital paradigms for the SDGs (Hofstetter et al., 2020; Zheng et al., 2020; ITU, 2019a; Walker et al., 2019; Valencia et al., 2019; Bibri, 2019; Campolo et al., 2018; Smith and Neupane, 2018; Smith and Neupane, 2018; Janowski, 2016).

Humanity stands at a crossroads, because devoid of a sustainable approach, the rapid and widespread development of digital technologies could lead to dire, unsustainable outcomes. Additionally, without suitable interventions and enhancements within the 2030 Agenda, the inherent gaps in the SDG framework may persist, undermining their realization. Thus, the challenge is dual, as both digitalisation and sustainability are unavoidable transformations that must be aligned.

Incremental technological improvements, like those seen at present, are insufficient to address sustainability challenges. A disruptive change is needed to unleash sustainable digital transformation, as argued by Köhler et al. (2019). Thus, identifying the social and environmental value of digitalisation for sustainability and sustainable digitalisation is essential to scale up and mainstream this crucial nexus.

While digital transformation has demonstrated significant potential to support the SDGs and even more ambitious regenerative goals, it is evident that enhancements to both the 2030 Agenda framework and the current trajectories of digital transformation and innovation are necessary to responsibly scale and harness the digital revolution for a truly sustainable and regenerative future.

In response to these caveats, this research seeks to offer a comprehensive approach to reorienting digital transformation towards sustainable and regenerative development. This holistic approach is expected to inform consistent policy interventions and practical strategies within the digital and sustainability domains, while also raising awareness among stakeholders, to ensure that digital transformation is steered towards sustainability and contributes meaningfully to the SDGs.

Considering that current frameworks are insufficient to support the foundations of a sustainable digital transformation, this research advocates for novel constructs that provide a more comprehensive integration and alignment of digital transformation with all dimensions of sustainability and the SDGs, with a particular emphasis on ecological concerns, and regenerative practices. This approach emphasizes that sustainability efforts must proactively bring net-positive impacts, for restoring and regenerating natural, social, and governance ecosystems.

In conclusion, the convergence of digital transformation and the SDGs unfolds a remarkable space for further multidisciplinary research, policy development, and practice in dialogue and close collaboration with key stakeholders. This dissertation is an initial step towards a deeper understanding of the challenges and key tenets of this research field.

3.8. Concluding Reflections on the Interplay between Digital Transformation and Sustainability

This Chapter presents a comprehensive analysis of the research field and the rationale behind the interplay between digital transformation and sustainability, uncovering the key research streams and gaps that require further exploration and policy development.

Furthermore, it sheds light on whether, how, and to what extent digital paradigms and innovations can be responsibly harnessed to bridge existing SDG gaps and leapfrog sustainable and regenerative development. The findings offer a foundational reference point, contributing to a deeper understanding of the convergence between these two critical domains, while also identifying and introducing the following research directions of the dissertation.

Despite the growing interest and the expanding body of literature on the potential of digital transformation for advancing sustainability and the SDGs, digital paradigms remain largely untapped in this realm, exposing numerous controversial aspects that still require in-depth research.

Limited attention has been given to the role of digital paradigms and digital innovations in addressing the complexities, limitations, and research gaps within the SDG framework, as identified in Chapter 2, along with the resulting policy and practice implications.

A holistic categorization of the SDGs challenges (Chapter 2), alongside a comprehensive exploration and categorization of the contribution of digital paradigms to overcome these obstacles sustainably (Chapter 3), has not been produced elsewhere, representing a relevant contribution to the field.

Considering that the interplay between digital transformation and sustainability remains insufficiently understood and poorly articulated, the holistic approach proposed in this research is, to the best of current knowledge, the first of its kind. Therefore, it offers valuable insights for identifying current research foci and potential future directions.

About the role of digital paradigms in addressing the SDGs gaps and advancing the 2030 Agenda, they present both promises and threats. On one hand, digital paradigms and ICTs provide outstanding opportunities, in terms of novel data sources, unprecedented computational power and analytics, novel collaborative ecosystems, and enhanced capabilities to cope with wicked societal problems.

Notably, the integration of IoT and EO data with Big Data Analytics, and Artificial Intelligence, can provide descriptive, predictive, prescriptive, and discursive capacities that surpass traditional methods by augmenting human abilities. Additionally, Blockchain can enhance traceability and accountability, while advanced connectivity provides unprecedented interconnectedness. Collectively, digital solutions can be leveraged to improve decision-making in sustainability governance, alongside social and environmental regeneration.

However, the findings also reveal that digital technologies are not a universal and one-size-fits-all solution and come with substantial, yet unknown caveats, including ethical issues, social divides, and environmental concerns that could undermine the achievement of the SDGs.

Furthermore, the application of digital paradigms to sustainability remains nascent, and highly fragmented, marked by controversies and unexplored issues. In addition, it has been often limited to isolated projects that lack scalability and integration. Both sustainability and digital transformation are complex and multi-dimensional, and their intersection lacks theoretical cohesion, clear definitions, and cohesive research boundaries. This has been mainly driven by the rapid and disordered evolution of digital transformation, with theoretical development and scientific literature struggling to keep pace with the phenomena under study.

The findings also unveiled that environmental sustainability is insufficiently embedded within digital strategies, policies, and research agendas, posing a threat to achieving genuine sustainability and meaningful contributions to the SDGs. Considering the multidisciplinary nature of this domain, integrating all relevant perspectives is essential to capture the phenomenon in its entire magnitude. The ecological and social dimensions must be strongly embedded at the core of the digital and technological agendas, avoiding cosmetic or “ethic-washing” approaches.

For that purpose, the implementation of enabling frameworks and novel incentives for enhanced sustainability accountability and integration would be highly beneficial, thereby transforming them into net-positive regenerative engines. Policymakers should adopt flexible and responsible regulatory and financial frameworks, supporting knowledge transfer, digital innovation, and the co-evolution of digital transformation, innovation, and regenerative sustainability.

In this context, the main problem lies in the absence of a holistic framework that encompasses all the determinant factors of sustainable digitalisation for and with regenerative sustainability, including environmental, social, governance, economic dimensions, and cooperation.

Without a comprehensive understanding of these factors, it becomes challenging for researchers, policymakers, or practitioners to hold the necessary knowledge to align their policies and practices with the triple transition.

Therefore, it is critical to develop a structured framework that fills this gap and provides to the digital, innovation, and sustainability realms and their actors, with a comprehensive overview of the challenges and opportunities of the triple transition.

Moreover, further efforts are needed to strengthen science-policy interfaces to facilitate the integration of digital paradigms into sustainable development strategies. This would require developing novel frameworks that bridge gaps between research findings and their application in policymaking, ensuring a more effective alignment of the SDGs with digital innovations.

Another relevant consideration lies in that not all sustainability challenges can be addressed through data-driven solutions or technology-enabled capacities, as some obstacles are structural in nature and require solutions beyond technological interventions. Direct policy interventions are also required to level the playing field and should be guided by ethical and inclusive approaches while offering regulatory, financial, and capacity-building support. Behavioural change is also an area of utmost relevance in this context.

Consequently, given the current limitations, the emerging and evolving nature of these topics, and the reliance on qualitative analysis within an expanding body of literature, further in-depth research is essential to categorise the full potential of digital technologies, capacities and ecosystems in supporting the SDGs with regenerative sustainability approaches, particularly those linked to Big Data Analytics, AI and advance computing paradigms.

This includes addressing current capacity constraints, ecological and ethical concerns, and context-specific challenges to maximize the transformative impact of digital ecosystems on sustainable development, regeneration, and long-term resilience. Additionally, research should adopt a portfolio and mission-based approach, and promote inter- and intra-disciplinary knowledge transfer, rather than being siloed, to ensure scalability and replicability beyond pilot actions.

Future studies should explore deeper the capacities, interrelations among actors, and the role of digital innovation ecosystems and multistakeholder partnerships in driving the regenerative triple transition.

This should examine ways to leverage digital ecosystems to foster collaboration, knowledge-sharing, and the integration of digital and sustainability literacy among policymakers and practitioners, for enhancing their mutual understanding and cooperation. In addition, the engagement of civil society, bottom-up governance and grassroots movements are important and deserve further exploration.

The findings within this section can be regarded as a foundational reference, which illustrates and categorises the available knowledge on the vast opportunities and challenges within the interplay between digital transformation and sustainability, and research directions to address them. This multifaceted nexus offers promising avenues for multidisciplinary research towards leveraging the responsible and inclusive convergence of these powerful fields for addressing SDG challenges, and further promoting the regenerative triple transition. Overall, humanity is witnessing a critical moment in shaping the future of digital transformation, innovation, and sustainable development strategies.

There are clear windows of opportunity to steer the convergence of the digital, environmental, and socially just transitions, ensuring that digitalisation for the SDGs is ethically mainstreamed by mitigating potential risks. Also, an extraordinary opportunity is emerging to adopt regenerative approaches with the support of digital tools, which contribute to revitalising a harmonious development among social, ecological, and economic systems.

Following this overview, the reflections on the implications of the findings and their relevance to the broader context of sustainable digital transformation are provided below, to guide the next directions of the dissertation.

Considering the insights gained, this research advocates for more ambitious approaches by embedding a regenerative perspective and promoting the co-evolution of innovation, sustainability, and digital transformation towards the vision of the triple transition. Notably, these realms must be also effectively integrated into the 2030 Agenda, as their synergistic alignment is crucial for addressing the complex challenges and seizing the opportunities offered by the regenerative triple transition.

Furthermore, digital paradigms, when managed responsibly, possess outstanding potential to enhance sustainable development and the SDGs by leveraging novel data, augmented capacities, and forging new ecosystems and communities. Yet, a recalibration of digital transformation is essential to address its inherent social and environmental challenges that demand careful consideration and mitigation.

The exploration of the research challenges has yielded valuable insights for guiding the next steps of the research toward three key areas:

First, this research underscores the pressing need to enhance and strengthen the role of innovation and knowledge transfer for advancing the SDGs, supported by digital paradigms. For that purpose, novel models and ecosystems are needed to adapt to the contemporary landscape and the emergence of the regenerative triple transition.

By integrating digital transformation and regenerative sustainability perspectives into innovation models and communities, collaboration, knowledge creation and transfer can be expanded to better contribute to sustainability purposes. Moreover, innovation itself must evolve to meet the intricate challenges of contemporary reality. This research priority is further examined in Chapter 4.

Second, the current trajectory of digital transformation requires a recalibration and reorientation towards a regenerative sustainability perspective, by addressing its inherent and unresolved challenges responsibly.

Considering the current misalignment between digital transformation and sustainability, the inadequacy of current governance frameworks, and the numerous uncertainties in this field, there is a pressing need to provide novel constructs that offer deeper insights about how to better align this interplay between digital transformation and regenerative sustainability.

At present, there is no comprehensive approach that captures all the relevant factors that play a role in driving a sustainable digital transformation. In addition, existing frameworks fail to integrate regenerative perspectives. This absence is hindering the ability to inform policy, practice, and research about how to steer this interplay.

Therefore, it is necessary to develop a unified framework that defines the priorities of a sustainable and regenerative digital transformation that helps the stakeholders to better align both domains toward the triple transition.

For this matter, a comprehensive taxonomy that clarifies and organizes the dimensions of sustainable digital transformation with a regenerative perspective (SRDT) is needed. A Taxonomy for SRDT can provide a structured approach for enabling decision-making, and better aligning digital transformation and regenerative sustainability. This research priority is further examined in Chapter 5.

Third, the alignment and co-evolution of digital transformation, sustainable development, and innovation agendas toward the regenerative triple transition is also imperative.

This can help to leverage their synergies and capacities, overcome the limitations and inherent challenges, and expand the opportunities for realizing the triple transition with regenerative and resilience perspectives.

Achieving this requires strategic recommendations for revisiting current policy frameworks and agendas, along with further collaborative efforts among stakeholders. These strategic recommendations are further analysed in Chapter 8.

In summary, the examination conducted within this Chapter on the interplay between digital transformation and sustainability has provided the foundational insights and the directions for more in-depth research presented in the next Chapters.

Such research directions advocate for a comprehensive integration of digital transformation, and innovation with regenerative sustainability to address the challenges and opportunities of the ongoing digital, environmental, and social transition.

It is important to note that part of the findings of this chapter have been included in the following articles, published in the subsequent indexed journals:

- Del Río Castro, G., González Fernández, M. C., Uruburu Colsa, Á. (2021). *Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review*. Journal of Cleaner Production, 280(Part 1), 122204. <https://doi.org/10.1016/j.jclepro.2020.122204>.
- Gupta, S., Campos Zeballos, J., Del Río Castro, G., et al. (2023). *Operationalizing Digitainability: Encouraging Mindfulness to Harness the Power of Digitalization for Sustainable Development*. Sustainability, 15(6844). <https://doi.org/10.3390/su15086844>.

The next chapter focuses on the assessment of the interplay between innovation, digital transformation, and sustainability. It also proposes a novel helix innovation model aimed at evolving R&I to address contemporary challenges and advance the regenerative triple transition.

4. The Interplay between Innovation, Sustainability and Digital Transformation

4.1. Science, Technology, and Innovation in the 2030 Agenda

The current world is characterized by unprecedented interconnectedness, globalization, digitalization, and technological disruption, resulting in "volatility, uncertainty, complexity, and ambiguity (VUCA)" at an astonishing pace (UNDP, 2019). Addressing the challenges posed by this rapidly changing landscape requires collaborative and responsible innovation (EC, 2022b).

Certainly, sustainability and digital transformations have disrupted and catalysed advancements, not only in the economy and society realms but also it has strongly impacted the way of science and innovation. Digital paradigms are supercharging all disciplines and blurring their borders, reshaping, and revolutionizing every facet of life and society, and merging physical and digital worlds (EC, 2023a), not without challenges and risks.

Science, technology, and innovation (STI) play a crucial role in achieving the SDGs (Walsh et al., 2020; Sachs et al., 2019a) and the Paris Agreement to face the climate crisis (Centobelli et al., 2020; Walz et al., 2017). Indeed, they are recognized as key requirements to promote transitions (Köhler et al., 2019; UN, 2023d) to sustainable development (European Commission, 2015; Köhler et al., 2019; Perez, 2019; Sachs et al., 2019a; Vatananan-Thesenvitz et al., 2019). Therefore, STI should be central to the SDGs implementation (Colglazier, 2015; Walsh et al., 2020).

The UN Global Sustainable Development Report (UN, 2023d) advocated for inclusive, multidisciplinary, openly shared approaches and equitable access to scientific knowledge relevant to society along with context-specific solutions. Nevertheless, science-policy interfaces have been historically dominated by experts from the Global North and relevant stakeholders such as the civil society are often excluded.

Addressing such global imbalance is crucial for SDG achievement. Yet, challenges like misinformation and policy implementation gaps persist, particularly in areas like climate change mitigation. Moreover, the UN (2023d) recognized the importance of narrowing gaps in STI and promoting their responsible use for sustainable development by facilitating the transfer of eco-friendly technologies, promoting open science and stronger partnerships.

Furthermore, relevant literature about the relationship between STI and sustainable transitions exists, underlining the need for novel paradigms (Köhler et al., 2019). For instance, the role of STI in enabling carbon neutrality (Labanca et al., 2020) and improving the efficiency and effectiveness of SD (Berawi, 2017) is widely acknowledged.

Also, eco-innovation is considered a driver for the SDGs (Cordova and Celone, 2019). Indeed, the Agenda and the Paris Climate Agreement rely on the diffusion of green innovative technologies (Centobelli et al., 2020; Walz et al., 2017). However, sustainability issues cannot be solved just by technology (Kane et al., 2019; Soderholm et al., 2019 cited in Secundo et al., 2020) and an extant narrow view of STI along with techno-utopian mindsets are hindering progress.

Walsh et al. (2020) denounced a narrow consideration of STI in framing the SDGs through the UN Technology Facilitation Mechanism (UN, 2018b) since it features a disproportionate focus on technology transfer and little on eco-innovation, wanting planetary boundary awareness (Imaz and Sheinbaum, 2017).

Moreover, social innovation is poorly understood and considered (Eichler and Schwarz, 2019). Knowledge gaps among social and ecological systems remain (Mastrángelo et al., 2019), together with tensions between technological progress and environmental conservation.

Indeed, SDG12 (target 12. a) and SDG17 (17.7.1) support, respectively, technology capacity and transfer in developing countries, as well as diffusion of “environmentally sound technologies”. However, they do not set truly actionable objectives (Gasper et al., 2019) and lack measurement methodologies. Thus, they are unable to overcome market-induced tensions which limits the diffusion of green technologies such as Intellectual Property Rights (IPR). Furthermore, access to technology depends on multiple dynamics and environmental performance is context-dependent.

Thus, literature evidence that policy, along with reinforced means of implementation and finance, are crucial elements to mediate those tensions (Sinha et al., 2020; Walsh et al., 2020). The diffusion and integration of the SDGs within the heart of STI policy is essential (Walsh et al., 2020).

According to the literature, STI narratives should be enhanced by knowledge-sharing and collaboration across geographies and actors (Berawi, 2017), promoting co-creation (Stafford-Smith et al., 2017). Indeed, a knowledge-based society is imperative for realizing the 2030 Agenda (Colglazier, 2015), since knowledge plays a vital role in the international development realm by bridging local and global insights amidst research, policy, and practice.

The goals act like vehicles that arrange and disseminate norms, value creation and policy improvement (Fukuda-Parr and McNeill, 2019), constituting a relevant frame for knowledge brokering among societal actors (Cummings et al., 2019).

However, literature pays little attention to this subject (Barrantes-Briceño and Almada-Santos, 2019). Intellectual capital and creativity function as enablers for transitions towards an innovative, knowledge-based, smart, and sustainable society (Herman and Suciu, 2019; Secundo et al., 2020; Suciu and Nășulea, 2019). Moreover, the interlink amidst human, structural and relational capital is essential to create societal value (Secundo et al., 2020), although rests little explored (Gouvea et al., 2018; Secundo et al., 2020), evidencing inclusiveness gaps.

Enhancing the interfaces between policy and science is also pivotal. Policy diffusion of ecologically aware innovation and green technologies are critical tools for cleaner production and SD (Crespi et al., 2015; Centobelli et al., 2020) since it facilitates knowledge spillovers (Aldieri et al., 2019) leading to a virtuous cycle of eco-innovation.

Hence, policies should promote knowledge transfer between different sources to allow eco-innovation and SD (Aldieri et al., 2020). Yet, derived negative externalities, “free riding” incentives and potential tensions amid genuine sustainability and productivity maximization should be acknowledged by appropriate policy mix and knowledge absorption (Aldieri et al., 2019). Further research is required on breakthrough and diffusion Köhler et al. (2019).

The SDGs diffusion could collide at a global scale due to persistent silos but could be possible close to the implementation level (Kanie et al., 2014). Top-down diffusion of innovations can be difficult in specific contexts, where informal networks can be suitable enablers for dissemination (Henry, 2018; Masuda et al., 2018). Indeed, innovation strategies are context-dependent (Eichler and Schwarz, 2019), while sharing common factors to succeed such as an “enabling environment, absorptive capacity, learning and diffusion”. Thus, policy should balance diffusion and absorptive capacity depending on the maturity of the innovation system (UNCTAD, 2017b).

Research on diffusion dynamics of sustainable innovation is thus far limited (Clausen and Fichter, 2016), particularly concerning bottom-up grassroots innovations (Feola and Butt, 2017). Patnaik and Bhowmick (2020) underscore the relevance of fostering inclusive innovation and native knowledge for SD, overcoming extant asymmetries and ensuring ownership, transformative learning, and psychological nuances.

Hötte (2020) contended that the slow diffusion of green technologies could be partially caused by path dependence of technological change and cumulative knowledge. Pradhan et al. (2020) argue that innovation diffusion and investments impact the economic growth in Europe, the direction of the causality is dependent on the specific measures utilized for that purpose.

Current green growth and innovation perspectives are narrowly techno-centric, mainly focused on economic development, which overlooks environmental concerns (Capasso et al., 2019) and neglects complexity, and social and systemic interactions (Labanca et al., 2020). The social impacts of technological innovations and technology transfer have been disregarded in the literature (Corsi et al., 2020) and should be diffused to guarantee genuine sustainability.

Zhou et al. (2020) explored the partial influence of fairness appreciation, embedders, and knowledge-sharing in enhancing green innovation, as essential factors towards the SDGs.

Schot and Steinmueller (2018) suggested that ecosystems and socio-technical system change should be integrated, to overcome the current lack of knowledge provision from the private sector.

Building up competencies for tackling complexities and social issues seems crucial (Labanca et al., 2020), along with reorientation of technology considering market, structural and transformational failures at different scales (Capasso et al., 2019).

Stimulating a Responsible Research and Innovation (RRI) approach to understanding the complexities (Thapa et al., 2019; Van der Leeuw, 2018) along with facilitating inclusive innovation among low-income segments are priority facets which should be embedded in policies (Foster and Heeks, 2013; Hanlin and Kaplinsky, 2016; Zanello et al., 2013).

However, the RRI concept and related policies persist ambiguous and should be well formulated considering: “inclusion, anticipation, responsiveness, reflexivity, as well as sustainability and care” (Burget et al., 2017). For instance, Responsible Innovation in Health (RIH) represents a promising approach for supporting numerous SDGs, demanding novel business models and social finance (Lehoux et al., 2018). Novel approaches, technologies, and capacities, including design thinking (Maher et al., 2018), and innovative business models (Arnold, 2018; Dressler and Bucher, 2018) are also desirable.

Several authors devote research to the domain of digital technologies. Fukuda-Parr and McNeill (2019) underscore the role of Big Data and digital technologies in shaping knowledge (epistemology) for SD and the SDGs in particular. Pappas et al. (2018) argue that digitalization, specifically Big Data and analytic ecosystems, could speed up a transition to sustainability, provided that the interrelations among actors are well understood, leading to value and knowledge creation.

Stuermer et al. (2017) underline that literature has considered digital artefacts as the means towards SD, although they should comply with several prerequisites for sustainability. Tasic and Zivkovic (2019) claim that a correlation between knowledge and innovation can be found, compatible with the preserving sustainability approach.

Knowledge-sharing policies in smart cities focused on merging green and smart concepts are an emerging, yet untapped, field (Israilidis et al., 2019).

The World Economic Forum (WEF, 2020a) suggested increasing the technological intensity of the strategic and implementation actions within the SDG framework, aligning the 2030 Agenda with the 4th Industrial and Digital Revolution.

Nevertheless, excessive “Techno politics of Development” led by private philanthropists that use developing contexts as living labs for experimentation, could challenge participation and trigger undesirable consequences (Fejerskov, 2017).

Reframing the STI policy agendas to promote and disseminate green technological innovations seems essential (Centobelli et al., 2020). Extant frames should be reoriented to encourage transformation towards SD (Walsh et al., 2020), based on context-savvy solutions (Centobelli et al., 2020), multi-scale and inclusive perspectives (Leach et al., 2012), novel technologies and principles, and suitable mix of strategic actions, policy and finance (Rogge and Reichardt, 2016; Edmondson et al., 2018; Walsh et al., 2020).

Hence, technological innovation is crucial for achieving the goals, but it should be guided by a consistent policy and systemic governance able to overcome persistent barriers and market failures. A profound understanding of potential STI contribution is needed (Colglazier, 2015).

Further understanding of the role, drivers, and dynamics of technological innovation for sustainable development and knowledge flows is needed, together with specific enabling regulations, and effective, and inclusive policies to bridge barriers while reinforcing social good (Vatananan-Thesenvitz et al., 2019).

4.2. The Rise of Non-Conventional Innovation Paradigms

Innovation responds not only to economic expectations but also to social demands, and it is strongly influenced by cultural and human values. Therefore, it should contribute to tackling eco-social challenges (EC, 1995). Rethinking current models of innovation is needed to adapt to the digital age (Skoric, 2014). Indeed, innovation ecosystems may be perceived as collaborative networks, that co-create value by aligning multiple partners and value propositions (Benitez et al., 2020).

Facing the digital era, the global challenges and dilemmas demand a more responsible approach to innovation, giving birth to the Responsible Research and Innovation (RRI) paradigm (EC, 2012; Edwards-Schachter, 2018), whose implementation has raised controversies.

A concise overview of the most novel innovation concepts related to sustainability values and digital perspectives within this research domain is presented as follows.

Eco-Innovation

In the context of digital transformation, eco-innovation is considered essential for enhancing the environmental sustainability of ICTs. As argued by Rupeika-Apoga et al. (2022) and Munodawafa and Johl (2022), eco-innovation is relevant for driving the technological, social, institutional, and cultural changes needed for sustainable development. This approach goes beyond technological advancements and also promotes new business models and practices that support the circular economy and can contribute to broader sustainability efforts within the digital sector.

Furthermore, Faucheux and Nicolai (2011) identified eco-innovation as a key driver for Green ICT, by promoting the multifaceted shifts that sustainable development requires in the digital age. For instance, the benefits of sustainable smart solutions, such as smart buildings, smart energy grids, and smart transport systems, are similarly underlined as part of the eco-innovation landscape.

Frugal Innovation

Regarding frugal innovation, as described by Bound and Thornton (2012), it refers to creating high-quality, while affordable and accessible solutions with utilized minimal resources. This approach is aligned with the concepts of voluntary simplicity, circular economy (Abert, 2019) and sufficiency, all highly valuable for sustainable digitalisation. Certainly, according to Yousaf et al. (2021), frugal innovation is considered a relevant component of sustainable digital innovation, as it enables the reduction of resource consumption and waste while providing competitive advantages.

Nevertheless, some researchers caution that not all frugal innovations are inherently environmentally sustainable. Therefore, according to Albert (2019) who explored the relationship between frugal innovation and sustainability, using the term "ecological frugal innovation" is most appropriate when environmental benefits are explicitly included among the key advantages, to ensure that such innovations contribute to both social and environmental sustainability.

Therefore, ecological frugal innovation is aligned with eco-innovation, along with the sufficiency and eco-design principles, which offers significant opportunities for promoting the triple transition. It represents an opportunity for promoting the triple transition, since it is available at a large scale, with low costs and promotes durable goods and eco-social values (Winkler et al., 2020; Hossain, 2018).

This approach is scalable, and inclusive, and encourages the production of more durable and sustainable goods which create eco-social value. As reasoned by Winkler et al. (2020), this perspective also aligns with the "slow growth" and "conscious" lifestyles, thereby prioritizing resource efficiency, sufficiency, and socio-environmental benefits.

Moreover, Aanestad (2023) further underscored the importance of alternative paradigms such as frugal innovation for achieving a sustainable digital future, particularly concerning the novel degrowth (Albert, 2019) and sufficiency-oriented approaches which are gaining traction.

Frugal innovation is closely intertwined with other non-conventional, and socially oriented innovation paradigms, which also emphasize sustainability and inclusivity.

Additionally, social innovation serves as a complementary force that addresses the societal dimension of the triple transition, ensuring that technological and ecological shifts are aligned with societal needs. These key paradigms are outlined as follows.

Socially Oriented Innovation Paradigms

Certainly, social innovation is a critical component of regenerative solutions since the regenerative paradigm extends beyond ecological and economic concerns to also encompass social transformation and the harmonious integration of human and natural systems. Innovation should respond to society's demands and contribute to tackling societal challenges (Benitez et al., 2020).

Concerning socially oriented innovation in the digital realm, Dionisio et al., (2023) argued that the COVID-19 pandemic accelerated the search for solutions to social problems linked to the SDGs, leading to a renewed focus on "Digital Social Innovations" (DSIs).

These collaborative innovations leverage digital technologies to address social challenges at scale and speed, aligning with the 2030 Agenda (Dionisio et al., 2023; Qureshi et al., 2021), and thereby revolutionizing sectors like healthcare, smart cities, agriculture, and poverty alleviation.

As Qureshi et al. (2021) argued, DSIs are less about technological advancements and more focused on fostering social innovations and they often involve cross-sector collaboration.

However, despite its potential, research has yet to address caveats, such as ethical concerns and power dynamics within marginalized communities. Addressing these gaps is essential to ensure that these innovations lead to meaningful and positive social impact (Dionisio et al., 2023; Qureshi et al., 2021).

Concerning the regenerative paradigm, Avelino et al. (2017) conceptualized the role of social innovation as a “theory of social change”, with transformative potential to reshape communities and spaces. Yet, the literature suggests that social-based regenerative innovations are often context-specific and have not yet evolved the strategic and adaptive qualities needed for broader influence and long-term impact. This stresses the importance of developing robust frameworks and strategies that can support the scaling and long-term sustainability of regenerative innovations.

This aligns with Mehmood et al. (2019), who proposed a holistic framework that integrates regeneration to tackle complex sustainability challenges, rooted in an interdisciplinary, place-based conceptualization of social innovation involving diverse actors. This approach highlights regeneration's potential not only to reverse negative impacts and revitalize, both human and natural systems but also to cultivate a strong sense of place stewardship and community engagement.

Similarly, Toner et al. (2023) underlined that while regenerative design is emerging, the integration of local community ecological knowledge remains inconsistent and context-specific. Therefore, standardized methods with a focus on co-evolving ecological stewardship are needed to ensure more consistent and effective integration of place-based knowledge in regenerative design practices.

Furthermore, Webster and Terzic (2021) explored how innovation intersects with sociological aspects, emphasizing the importance of combining technological and institutional readiness in adopting new disruptive technologies to support regenerative solutions.

Dealing with innovation disruptions, Kivimaa et al. (2021) expanded the concept in socio-technical systems beyond technological changes, by emphasizing non-technical factors like behaviour change, cultural models, markets, policies, and regulations. They concluded that for sustainability transitions to be truly transformative and regenerative, disruptions must be approached from a multi-dimensional perspective.

According to Avelino and Wittmayer (2015), social innovation can be initiated by any type of actor, at any level of society. Actors may participate in initiatives or partnerships that contribute, either deliberately or unintentionally, to social innovation. Additionally, the evolving relationships between actors and the changing boundaries between institutional logic are key indicators of transformative social innovation.

Social regenerative innovation involves a multi-actor approach, since in the pursuit of sustainable development and community regeneration, bringing diverse perspectives, collaboration and co-creation efforts with key stakeholders can lead to more effective and inclusive outcomes. Regenerative design must acknowledge the deep interconnectedness and interdependence between stakeholders and living systems, which is essential for promoting resilience and adaptability, particularly in urban settings (East, 2020).

Central to social innovation is the active engagement of local communities and stakeholders, as their involvement is key to the success of regeneration efforts. In this sense, community-driven approaches can promote regeneration, as evidenced by grassroots initiatives in the urban environment (Alonso et al., 2020). As MacLean et al. (2023) underlined, local actors bring domain-specific knowledge for tailoring solutions to the unique needs of their communities, enhancing the sustainability of these initiatives.

Social innovation, therefore, seeks primarily social inclusion and the economic redistribution of wealth by systemic change (Thompson, 2018). However, to fully realize the potential of social innovation, the concept of innovation ecosystems must also evolve to effectively address the challenges posed by the regenerative triple transition.

In this regard, Granstrand and Holgersson (2020) critically reviewed the concept and evolution of innovation ecosystems underlining its lack of conceptual clarity and consistency. Existing literature placed an excessive emphasis on collaboration and complementarities, while the competition, “substitute relations,” and artefacts are often overlooked.

In response, a more comprehensive definition which integrates these disregarded components is proposed by these scholars, by defining innovation ecosystems as “an evolving set of actors, activities, artefacts, institutions, and relationships (complementary and substitute), that are important for the innovative performance of an actor or a population of actors.” They also argued that a balanced consideration of competition and collaboration is needed, together with the integration of the role of artefacts, echoing the dynamics found in natural ecosystems.

Concerning the contribution of social innovation to the SDGs, according to Eichler and Schwarz (2019), it predominantly targets health and well-being-related goals, although it is often cross-sectoral (Qureshi et al., 2021). The key drivers of social innovation are typically social entrepreneurs and social enterprises, NGOs, non-profits, public institutions, and civil society organizations (Eichler and Schwarz, 2019; Qureshi et al., 2021).

Social innovation has the potential to reshape communities by addressing regenerative sustainability. However, as DoAdro and Fernandes (2020) noted, the field remains fragmented and underutilised in practice, and the knowledge necessary for understanding the long-term impacts and scalability of systemic change is still underdeveloped. Furthermore, it faces challenges such as the lack of strategic frameworks for widespread impact.

Moreover, alternative approaches to innovation, particularly catalytic innovation (Christensen et al., 2006) and grassroots movements could play a relevant role in driving systemic and regenerative eco-social transformations, by fostering more collaborative, open, democratic, and multistakeholder perspectives in research and innovation.

These non-conventional innovations are often driven by alternative players, including civil society. In this sense, the policy drive is fostering public participation (Schütz et al., 2019), thereby igniting a debate to redefine the interaction between science and the public, in a turbulent context submerged in deep social, digital, and ecological transformations. Nevertheless, collaborative innovation and non-conventional approaches also have their challenges, as described as follows.

Grassroots Innovation

SD requires system-wide transformations (Seyfang and Haxaltine, 2012). Civil-society or community-based innovations, known as “grassroots innovations,” have the potential to influence and change socio-technical systems, with bottom-up inclusive solutions adapted to local needs and eco-social concerns (Parnaik and Bhowmick, 2019), bringing value for n-helix contexts. Yet, this domain remains poorly explored, since innovations stemming from civil society have been largely ignored in developed economies (Williams and Woodson, 2012).

Catalytic Innovation

In this dynamic context, non-conventional concepts such as “catalytic innovation” have emerged as transformative forces driving change. Catalytic innovations, as defined by Christensen et al. (2006), are groundbreaking, scalable, and sustainable solutions tackling eco-social problems, which challenge the status quo and address unmet needs in society. These innovations are driven by alternative players who approach problems with fresh perspectives, leading to disruptive changes and systemic transformations. Thus, catalytic innovations pursue eco-social benefits, generate systemic social change, address unmet needs, and are driven by non-conventional players.

In the frenetic race for innovation, the innovation cycle has shortened, which leads to insufficient attention to eco-social risks (Pavie and Egal, 2010) for instance in recent AI development.

To address the unpredictable adoption of disruptive innovations and anticipate potential negative eco-social impacts, a broad-scope responsibility should be integrated into the early stages of the innovation processes (Pavie and Egal, 2010, citing Hans, 1979) to overcome the current disconnecting between technological advancements and moral responsibility.

Open and Collaborative Innovation

Open innovation dynamics, driven by “inbound and outbound knowledge flows” (Chesbrough and Brunswicker, 2014), involve the active participation of customers, users, and civil society, leading to accelerated innovation and reduced time-to-market (Wilson et al., 2018), as well as promoting sustainability (Yun and Liu, 2019).

Crowdsourcing is a usual form of involvement from customers/users and civil society within frameworks led by industry (e.g., open calls) or governments (e.g., e-participation), particularly in the platform economy (Cohen et al., 2016), in which social media has become a critical tool in the innovation funnel (Mount and Martinez, 2014), empowering collaborative and sustainable practices, not without eco-social challenges.

Certainly, innovation ecosystems (Benitez et al., 2020) are defined as collaborative networks pursuing the co-creation of value (Russell and Smorodinskaya, 2018).

Another key aspect of the evolution of innovation relies on the rise of collaborative, open and democratic, participatory, interdisciplinary and multistakeholder approaches. Indeed, civil society actors have been increasingly involved in innovation to better consider societal needs and impacts (Köning et al., 2020; Arnkill et al., 2010; Miller et al., 2018).

Therefore, innovation dynamics became complex due to novel values such as cooperation, co-evolution, and cross-fertilization, distinctive of the “mode 3” of knowledge creation (Carayannis and Campbell, 2009).

Furthermore, the participation of citizens, communities, and novel actors such as prosumers is legitimized (von Hippel 2005) to include non-technological or “hidden” knowledge (Miller et al. 2018). Multistakeholder and bottom-up innovation empowers resilient citizens and communities to deliver sustainable development (Bonsu et al., 2020).

Civil society participation in STI is characterized by multilayer, multidirectional interactions (Schütz et al., 2019). Societal actors have been traditionally overlooked in the R&I landscape, but a more democratised ecosystem has emerged in which society as a whole, has become a full-fledged actor in innovation-enhancing cooperation and collaboration (Cavallini et al., 2016; McAdam and Debackere, 2018).

Nevertheless, the motivations for public involvement need to be further understood (Miller, 2016) and operationalized to reach successful collaborations. The interactions among actors and the approach to reach a fertile implementation have not been yet elucidated (Miller, 2016) and civic engagement remains limited (Sturgis, 2014).

Moreover, strong barriers and resistance to change remain. Public engagement demands additional inter/trans-disciplinarity processes ensuring transient knowledge flows and synergies beyond “glocal” innovation. We argue that this contradiction between the “aspirational” innovation and the actual traditional conceptions, is hampering the public involvement along with the trans-disciplinarity.

The involvement of the public in innovation processes, incorporating societal needs and facilitating democratic participation is underlined by several experts (Carayannis and Campbell 2019). Other scholars argue that innovation can be perceived as a continuum of models (Arnkil et al., 2010) or private-public-people partnerships (MacGregor et al., 2010).

Notably, co-creation (Prahalad and Ramaswamy, 2000) and openness (Chesbrough, 2003) are considered key drivers of innovation (Galvao et al., 2019; Afonso et al., 2012; Mehari et al., 2022). They are influenced by symbiotic relationships, and promote sustainable and responsible development (Ketikidis et al., 2016; Vasconcellos Oliveira, 2021), as well as networking across geographies (Cai et al., 2019; Cai and Etzkowitz, 2020).

Also, co-creation with citizens, users and societal stakeholders is relevant for smart specialization strategies and service effectiveness (Linders, 2012; McAdam and Debackere, 2018). Bauer et al. (2021) claimed inclusiveness and a balanced view of all the innovation actors.

However, a few scholars undervalued the role of societal actors in innovation, arguing difficulties of engagement, diverging interests, unclear goals, or complexities (Borghys et al., 2020). Despite the rise of co-creation in the past decade, very few institutions have adopted it to scale innovation.

Business interest in participatory projects is usually linked to potential market value with limited societal contributions. On the other hand, the complexity of current social and environmental challenges requires firms to undertake collaborative endeavours (Bertello et al., 2021).

Most of these barriers are usually associated with resistance to change and a lack of incentives. The understanding of complex and novel technologies for the public is usually limited, hampering co-creation. The extant innovation models suffer unbalanced power dynamics and asymmetries of information among actors from non-specialized backgrounds, but this also represents an opportunity for creativity and cross-fertilization.

Schütz et al. (2019) argued that European R&I policies and funding have been pushing a re-orientation towards tackling major societal challenges by fostering public participation and further stakeholders' involvement. This policy drive has ignited a debate to redefine the interaction between science and the public (Scrasse et al., 2009) in a turbulent context submerged in deep social, digital and suitability transformations.

Open science and democratic innovation should be reinforced in complex realms such as digital transformation. STI breakthroughs with disruptive impacts on society should be framed to guarantee social good (e.g., Artificial Intelligence). However, the impact is not easy to predict until its development, after which it is difficult to mitigate (Collingridge Dilemma, Schütz et al., 2019 citing Collingridge, 1982).

Sustainable development requires novel ways of collaboration, cooperation, convening and co-facilitation to drive structural change by collective agency, for instance in open platforms following the network governance concept (UNDP, 2019). Certainly, a critical element for the success of social innovation is having an encouraging eco-system.

Carayannis et al. (2021b) suggested an “ecosystem” approach enabling triple-bottom-line entrepreneurial processes for knowledge discovery and bringing understanding of the dynamics of “co-opetitive” (balancing cooperation and competition) ecosystems underpinning civil society, sustainability, and policy.

Del Giudice et al. (2017) argued that complexities arise when knowledge-intensive enterprises collaborate pursuing co-creation and structural change (Carayannis and Rakhmatullin, 2014).

Technology transfer should involve user-focused innovation and cross-fertilisation. Campanella et al., (2017) underlined that all relevant governance systems should be considered to achieve legitimacy.

Vasconcellos Oliveira (2021) claimed that intergenerational justice should be integrated within innovation systems to meet future generations' well-being by tackling the so-called "irreplaceable goods" (e.g., water, biodiversity). Innovation is essential for global competitiveness and further understanding is needed about the levers that influence leadership and demographics (Newman et al., 2020).

Interactive governance and participatory approaches with multiple stakeholders enhance long-term sustainability in complex global value chains (Evans and Vermeulen, 2021) such as the electronic industry. Multi-stakeholder, multi-level collaboration increases governance effectiveness, while lack of supply chain transparency undermines multi-stakeholder interaction.

Huttunen et al. (2022) and Schütz et al. (2019) concluded that the role of citizens and society in innovation and sustainability transitions is still unclear and uncommon, and its participatory means and dynamics should be better defined.

In the transition toward a more advanced innovation, transition brokers emerged. The so-called "Knowledge brokers" and "science shops" (Wachelder, 2003) serve as intermediaries, facilitating interstitial knowledge circulation across and within organizational boundaries, connecting innovation actors, building capacities, and generating "brokered knowledge" tailored to local needs (Meyer, 2010; Wachelder, 2003). These systemic mediators are linked to incubators (e.g., ESA-BICs), innovation hubs, and technology transfer offices (TTO), among others.

Rowan and Casey (2021) argued that a just transition scheme towards a lower carbon future is still missing and advocated for the creation of multi-actor innovation hubs to facilitate such ambition. They proposed the "Empower-Eco sustainability hub" as a living lab, supporting green innovation. However, challenges like distrust and resistance to change must be addressed. Transition brokers are instrumental in implementing circular economy strategies, orchestrating change, building partnerships, and fostering impact in multistakeholder contexts (Cramer, 2020; Barrie et al., 2017).

In essence, considering the contemporary needs and the urgent shift toward sustainability and digital transformation, the integration of non-conventional innovation concepts is crucial. These novel approaches are essential for promoting systemic change and eco-social transformations. They rely on promoting further collaboration across stakeholders and embedding the values of circularity, inclusivity, and regeneration to transform innovation into a more resilient, equitable, and sustainable landscape.

The future of innovation relies on balancing technological advancements with ecological stewardship and social responsibility, towards regeneration, as described below.

4.3. Evolving Innovation towards the Regenerative Triple Transition

The advent of digital disruption has radically changed the nature and landscape of innovation and accelerated its pace. Concurrently, new economies aligned with sustainable development (UNEN, 2020) have emerged, such as the green economy, attention economy, and frugal economy, which must be integrated into innovation systems. Additionally, the disruptions and innovations stemming from the so-called "Gig" and sharing economies require attention to mitigate potential risks to sustainable development. Hence, there is clear evidence that innovation must adapt to better reflect the dynamics of the 21st century, deeply entrenched in the digital era, and facing complex eco-social transformations.

In this matter, undertaking “wicked” sustainability problems and pursuing the 2030 Agenda, demands novel strategies focused on integration (recognition of externalities, consistency across scales, alignment with policy), acceleration (capturing effectiveness gains, quality, positive impacts, resilience) and collective action able to merge social, capital and capacities through alliances or networks (UNDP, 2019). Certainly, innovation is founded on learning and interaction (Lundvall, 2013).

However, extant innovation models and policies have become obsolete in light of the rapidly evolving world landscape, shaped by poly-crisis and novel dynamics driven by STI, digitalization, and sustainability (UN, 2023). Current conceptualization and operationalization of innovation are “rooted in the past” (Edwards-Schachter, 2018; Fagerberg et al., 2013).

Edwards-Schachter (2018) argued that traditional innovation classification is outdated due to globalization, digitalization, the evolution of knowledge production and the integration of “hidden innovation” (Miles and Green, 2008) or “dark innovation” (Martin, 2013), meaning non-technological innovation. According to Prahalad et al. (2009), the new nature of innovation is featured by a variety of agents, partnerships, communities, novel policies, global co-creation with stakeholders, and collaborative networks.

Regarding the relationship between innovation and sustainability, a relevant strand of literature evidenced the outstanding potential of innovative solutions for this domain (Fagerberg, 2018). However, the current focus relies on techno-centric solutions instead of the needed transformation of eco-social practices (Edwards-Schachter, 2018). Moreover, sustainability is often considered a mere “add-on” in research and innovation (R&I) programmes or policies (EC, 2024a).

Certainly, the European Commission (EC, 2024a) acknowledged numerous barriers in R&I policies hindering ambitious transformations, such as achieving climate neutrality and sustainable digitalization. Existing programs operate within silos, lacking systemic perspectives and evaluation tools on interconnected eco-social dynamics. Stakeholder misalignment and disciplinary disconnects exacerbate these challenges.

Additionally, as argued by Joblin et al. (2023), there is a dearth of capacity for systemic transformations and awareness of digitalisation's environmental and societal impacts. The rapid globalization and cascading crises have exceeded the adaptability of governance mechanisms, in addition, the lack of technological sovereignty intensifies these issues. Hence, evolving R&I programs are imperative to address these shortcomings and embrace systemic change, regeneration, sustainability, and resilience in the innovation landscape.

In this regard, beyond the influence of the “twin digital and green transition” paradigm (Muench et al., 2022) on recent R&I policy developments such as the EU’s Green Deal, there is a growing need to also achieve a socially fair and just digital transformation.

As previously mentioned, the convergence of the digital, ecological, and just transitions has led to the emergence of the triple transition (3T) paradigm (EC, 2022c; Caro-González et al., 2023; OECD, 2023a). This paradigm significantly imposes the need to reshape innovation processes by integrating sustainability, digital transformation, and social equity. This approach will ensure that innovations not only drive technological and economic progress but also address environmental sustainability and social justice, aligning with broader global objectives such as the SDGs.

Thus, undergoing an evolution of innovation models to mirror the current dynamics of digitalisation and sustainability is urgently needed to embrace the future of innovation. To achieve this, transformative, and adaptable models aligned with the challenges of the current ever-changing world need to be created.

The focus should go beyond technology, markets, and silo-based economies, towards multidimensional, systemic, and eco-societal transformations with a regenerative lens. Moreover, it also becomes commanding to undertake reforms and enhancements within the 2030 Agenda, to effectively integrate restorative and sustainable digital innovation as a foundational pillar for a regenerative triple transition.

Despite its increasing importance, the interplay between innovation and the triple transition remains underexplored in the literature. Moreover, the triple transition paradigm has not yet permeated into policies and R&I programmes.

The implementation of both regenerative sustainability and regenerative innovation remains limited and faces complexities that require further conceptualization and empirical research and practice. Additionally, to advance regeneration and achieve long-term sustainability and resilience goals, it is essential to establish robust policies and regulations that foster the necessary frameworks for regenerative practices. Currently, there is a significant gap in effective policymaking in this regard.

The regenerative triple transition imperative imposes the integration and alignment of digital and sustainable innovation within current R&I agendas, while simultaneously reorientating them to adapt to the emerging complexities and challenges posed by such a multifaceted transformation.

As Silva and Di Serio (2016) argued, historical waves of innovation have been crucial in driving profound shifts across scientific, technological, business, and competitive landscapes, also redefining global dynamics. While the first five waves encompassed industrial revolutions and the rise of ICTs, a sixth wave is now emerging, driven by sustainability concerns and the need for regenerative solutions.

This recent wave calls for innovation that balances economic, social, and environmental factors, enabling organizations to achieve competitive advantages by aligning their values and strategies with sustainability goals. Further discussion is needed on how sustainability drives innovation and business transformations in the digital age, fostering long-term societal and environmental benefits. This is especially relevant concerning the rapid development and widespread permeation of digital innovations, which accelerate transformative changes across industries and society at an unprecedented pace.

In this matter, Hund et al. (2021) explored the concept of digital innovation across eight disciplines and proposed a new definition and framework for understanding this realm, emphasizing its multi-layered nature. They also argued that there is a lack of systematic research on digital innovation paradoxes, the interplay of different types of knowledge, and the role of AI in knowledge recombination.

The study emphasized the importance of including sociotechnical perspectives within digital innovation, distinguishing it from traditional innovation approaches. In this realm, key themes included the redefinition of boundaries, the role of digital platforms and ecosystems, along the novel strategic approaches needed in digital environments.

Furthermore, Hund et al. (2021) suggested that further research is needed to explore how individuals and organizations manage paradoxes, advance democratized innovation through digital technologies, and examine the potential of AI technologies in enhancing innovation processes.

In conclusion, the emergence of the triple transition and regenerative sustainability has underscored the need to rethink innovation in line with these transformative goals, giving rise to regenerative innovation. This innovation concept is closely related to the non-conventional approaches such as eco-innovation, frugal innovation, socially oriented and collaborative innovation.

Considering its importance for this research field, a concise review of the emerging concept of regenerative innovation is provided as follows.

4.4. Regenerative Innovation

The concept of regenerative innovation represents a transformative shift that emphasizes restoring, revitalizing, and enhancing the interdependent ecological, social, and economic systems, to foster a more harmonious relationship between human activities and nature well-being. Regenerative innovation, closely linked to regenerative sustainability, builds upon the principles of regenerative design, which focuses on creating systems that not only sustain themselves but actively improve their environments.

This requires a paradigm shift from linear, growth-oriented models to circular, self-sustaining approaches that support the resilience and well-being of both natural and social systems (Hayes et al., 2020; Ryan et al., 2023).

Notably, innovators are reimagining the economy through the lens of living systems, fostering circularity, mutualism, and continuous learning, aiming for a balance between efficiency, resilience, and social equity (Fullerton, 2015; Gibbons, 2020; Buckton et al., 2023).

The core principles of regenerative innovation are outlined as follows, drawing from the emerging and nascent body of literature in this field.

Yeh et al. (2020) provided a foundational understanding of regenerative innovation, particularly in the industrial waste industry. They argued that regenerative innovation is a transformative approach that focuses on restoring and revitalizing natural, social, and economic systems, creating positive impacts that regenerate ecosystems, strengthen communities, and support resilient economies. Their findings suggested that, by fostering relationship trust, and environmental awareness among stakeholders, this can drive regenerative innovation, leading to improved environmental management outcomes.

However, they also noted that while regenerative innovation enhances environmental management performance, it does not significantly affect environmental operational performance in this specific industry. This distinction underscored the importance of addressing not only technological advancements but also building trust and awareness to achieve broader sustainability goals.

Building on this matter, Cegarra-Navarro et al. (2024) introduced the concept of “regenerative unlearning”, demonstrating its direct impact on green process innovation performance and its indirect effect through the “breadth and depth of knowledge”.

Their study, rooted in a knowledge-based approach, suggested that regenerative unlearning can be a crucial component of knowledge management strategies, particularly in the manufacturing industry. Therefore, by enhancing ecological efficiency, regenerative unlearning could contribute to the development of innovative processes that align with the principles of regeneration.

Hofstra and Huisingh (2014) developed a taxonomic classification of eco-innovations that emphasizes the evolving relationships between humans and nature. They advocated for a shift from an anthropocentric worldview, which prioritizes human needs, to an eco-centric perspective that places nature at the core of innovation processes.

This shift requires a deep understanding of the principles of biology and thermodynamics, as well as the integration of biomimicry, circular design, and regenerative innovation. Indeed, Hofstra and Huisingh argued that such a “dialogical approach,” which balances ecological, social, and economic perspectives, is essential for the long-term sustainability of both society and nature.

Furthermore, Mehmood et al. (2019) explored the concept of regenerative innovation through a holistic framework that integrates learning, experiencing, and regenerative action. Their study emphasized the transformative roles of both individuals and the environments they inhabit, advocating for the inclusion of diverse actors and perspectives in driving social innovation.

The proposed framework combined transformative learning, sense-making through personal experiences, and regenerative actions aimed at reversing environmental degradation and promoting stewardship. Hence, by intertwining these processes, this approach could foster new forms of socially innovative agency, which are crucial for reshaping places towards sustainability.

Nevertheless, despite its promising potential, regenerative innovation faces significant challenges, particularly in terms of scalability and alignment with existing systems.

Regeneration requires a profound understanding of the interrelations between people and their environments, within their specific contexts (Mehmood et al., 2019). However, these practices remain limited in impact, primarily because they have not yet achieved the critical mass needed for widespread adoption. Additionally, these practices rely on participatory and co-creation processes, which have also faced limitations in scaling effectively.

In this regard, Felcis (2019) examined the potential of the permaculture movement to drive regenerative transformations through organic agriculture, ecological building, and sustainable lifestyles. While permaculture aims to educate and empower individuals to become self-sufficient and environmentally conscious, its impact remains constrained by the same challenges of scaling and achieving long-term durability. Thus, the need for systemic approaches capable of integrating regenerative practices into broader societal frameworks is underscored.

Furthermore, Dewick et al. (2019) analysed the critical role of regulatory frameworks and contextual conditions in facilitating or hindering regenerative eco-innovations, particularly in the built environment sector. Considering that this sector is highly regulated and slow to innovate, the authors argued that effective regulation and supportive settings are essential for closing material cycles and reducing waste.

They suggested that regenerative eco-innovation demands radical changes to restore and revitalize natural ecosystems, making it the most relevant, but also the most challenging type of eco-innovation for tackling complex sustainability challenges.

Hofstra and Huisingh (2014) also emphasized the need for more empirical studies on regenerative eco-innovation to further develop both theory and implementation. They also argued that regulatory support is crucial for the successful adoption of these innovations, particularly given the complex interactions between technological, social, and ecological systems.

Thus, regenerative innovation remains a nascent and evolving field, gaining increasing momentum, particularly in sectors such as agriculture (e.g., permaculture), medicine, manufacturing, and the built environment. For instance, Banda et al. (2018) examined how regenerative medicine innovations are disrupting traditional “serving” industries such as pharmaceuticals.

This transformative shift requires innovative business models and value chains to navigate the intricate ecosystem influences in response to novel market dynamics, including regulatory and financial support systems. Hence, regenerative medicine represents an emerging field poised to revolutionize healthcare, yet it underlines the need for systemic analyses to characterize the potential of disruptive innovation and the subsequent necessary regulatory enhancements.

Moreover, Hayes et al. (2020) discussed the role of biomimicry in supporting sustainability and resilience in innovative infrastructures. They reasoned that regenerative development relies on design, development, and operational approaches that regenerate social and ecological systems, bringing net positive outcomes.

While current industrial and infrastructure practices focus mainly on reducing negative impacts, shifting to regenerative approaches requires innovation inspired by natural systems.

However, the integration of regenerative approaches based on biomimicry is still in its early stages, requiring further research to fully understand their benefits and barriers.

The confluence of regenerative sustainability and regenerative innovation, underscores the rise of novel business frameworks, while also evidencing the need for enhanced preparedness and institutional readiness to support this transformative shift.

In this regard, Ryan et al. (2023) introduced a framework for regenerative business, positioning it as a concept that could drive the imperative transformation needed to shift from a paradigm of “doing less bad” to one that creates positive impacts for both the planet and people. Yet, they acknowledged that the corporate and industrial sectors are still struggling with traditional sustainability requirements, thus regenerative approaches remain underdeveloped.

Their study emphasised that regenerative business relies on “empathetic leadership” and intertwines six principles: empowered relationships with stakeholders, connection to context, circularity, trust and transparency, innovation and adaptability, and capacity for systems resilience. Therefore, the connection between sustainability, innovation, and resilience is fully embodied in the concept of regeneration.

Webster and Terzic (2021) explored the concept of “regenerative readiness” to understand how innovation intersects with sociological aspects. This aligns with McKelvey et al. (2021), who suggested the term “innovation governance readiness” to address the complex relationships between different actors within regulatory frameworks, particularly in the field of regenerative medicine. They underlined the importance of considering both technological and institutional readiness to effectively manage innovation and its adoption in real-world contexts.

Regenerative innovation represents a forward-looking and transformative approach that seeks to go beyond traditional sustainability, by focusing on restoring, revitalizing, and harmonizing natural, social, and economic systems through innovative practices. While the potential of regenerative innovation is outstanding, its implementation faces significant challenges, including scalability, alignment with existing systems, commitment from society, and the need for effective regulation and institutional readiness and support.

As research continues to advance allowing the refinement of the principles of regenerative innovation, it becomes evident that a holistic approach is essential for achieving long-term sustainability and resilience of global systems, particularly in the context of the triple transition.

In light of the aforementioned and considering the relevance of both social and ecological aspects for providing regenerative solutions, this research proposes a greater focus on socio-ecological systems to better address the interconnectedness of social and ecological domains in pursuing the triple transition.

Rethinking current innovation models and systems is essential for adapting them to both the digital age (Skoric, 2014) and the regenerative opportunities of the triple transition. The n-helix models, for instance, offer the ideal framework for repositioning the role of society and nature as central actors in the innovation landscape, fostering deeper collaboration across stakeholders and sectors (Cavallini et al., 2016; McAdam and Debackere, 2018). This will ensure a more inclusive and systemic approach to regenerative innovation in response to contemporary challenges.

An unexplored approach in the literature is to conceive digital and ecological transformations as key actors in SD through a helix innovation approach. The n-helix innovation models emerged as implementation frameworks, fostering optimal knowledge exchange and innovation flows aligned with socio-ecologic transformations. Nevertheless, the helix-based approach offers untapped potential but requires refinement to address contemporary systemic complexities.

The following section outlines the evolution of the n-helix innovation models over time, which represent a dynamic approach that involves multiple stakeholders, offering outstanding potential for adapting the innovation landscape to the regenerative triple transition requirements.

4.5. Evolution of the n-Helix Innovation Models

Undergoing an evolution of innovation models to mirror the current dynamics of digitalization and sustainability is urgently needed to embrace the future of society. Therefore, transformative, and adaptable innovation models align with the challenges and opportunities of our ever-changing world need to be created.

The n-helix innovation model represents a shift toward knowledge societies (Carayannis et al., 2012) where cumulative sources of knowledge (helices) which conform to societal subsystems, are twisted together to propel innovation, in equivalence with how DNA creates living cells in biology. The intertwined dynamics amid the variety of societal subsystems/helices spark innovation beyond technology. König et al. (2020) argue that the n-helix models are levers for framing research policies towards SD and the SDGs. The body of literature on this approach is extensive (Cai and Lattu, 2020).

The second helix of knowledge was formed in the Industrial Revolution era by bringing together the academia and economic subsystems towards knowledge development (Carayannis et al., 2012).

Originally introduced by Etzkowitz and Leydesdorff (1995), the triple helix model builds on the “mode 2” of knowledge production, as well as the Information Society concept (Carayannis et al., 2012) and integrates the three traditional innovation subsystems and interactions: the government, leading STI policies and funding; academia devoted to education, research and the third mission of university; and the economic subsystem led by enterprises and market dynamics. Besides, novel hybrid institutions emerged such as the entrepreneur universities, the corporate universities, or the public venture capital.

This paradigm further evolved with the proposal of the quadruple helix model (4H) envisaged by (Carayannis and Campbell, 2009) which includes a fourth helix focused on civil society, users or the culture and media subsystem (Marcovich and Shinn 2011) promoting more creative and social-focused innovations. Alternative fourth spirals have been also proposed: globalization (Yawson, 2009); and user-led innovation (Arnkil et al., 2010).

Most scholars agree that collaboration is not complete without the involvement of society (Hock et al., 2012), while cooperation amid the diverse helices is of the utmost relevance. Societal engagement is crucial for ethical innovation. However, the inclusion of the civil society subsystem has been a subject of heated controversies.

Moreover, the literature on the 4H model does not sufficiently cover the community as a sphere even when is essential for social innovation (Etzioni, 2017). Still, even the earliest pioneers of innovation (e.g., Schumpeter, 1954) emphasized the “creative destruction” and transformational nature of innovation and its social implications beyond the economy, along with the interdependency between society and economy (Amartya Sen, 2000).

Amid such ongoing debates, the quintuple helix model emerged, proposing a fifth spiral representing the natural environment to embed socio-ecological transitions (Carayannis and Campbell, 2010). Afterwards, Leydesdorff (2012) argued against constraining the helix model when explaining complex development phenomena, proposing the possibility of envisioning potential n-helix configurations.

The n-helix model seeks the benefit of the system, instead of the benefit of each sphere. Subsystems/actors are related by “multi-layered, dynamic and multidirectional interactions” rather than traditional push-pull unidirectional dynamics (Yu and Liu, 2019).

When it comes to integrating sustainability within the n-helix models, several proposals coexist including the following: the “Sustainability Triple Helix” proposed by Etzkowitz and Zhou (2006); the 5H model by Carayannis and Campbell (2010) which highlights eco-social impacts while integrating responsibility (Suwala and Albers, 2020); the quadruple green helix by Gouvea et al. (2013) integrating the third sector; and the 4H model with open innovation by Yun and Liu (2019), which integrates a holistic concept of sustainability, not as a subsystem, but as “dorsal spine” of innovation.

However, the latest conceptual framework has some flaws since sustainability appears to be treated as a subsystem within a quintuple (5H) model rather than an independent system. Additionally, the significance of industrial entrepreneurship, alliances, partnerships, and networks has been disregarded. Approaches that merge the helix model and the SDGs are gaining relevance (e.g., Carayannis and Campbell 2010; Maldonado Mendes 2010; Gouvea et al. 2013). Carayannis and Campbell (2021) advocate integrating democracy and ecological sensitivity into knowledge creation and innovation. The 5H supports socio-ecological transitions, acknowledging the role of culture and art in innovation settings.

The added value of the additional helices for knowledge generation, diffusion, and innovation, has been an object of controversies and debates and divergent opinions coexist. Campanella et al. (2016) underline that innovation needs society since it goes beyond technology. The empirical cases evidence that the 4H model involving civil society could lead to the creation of novel sources of knowledge through crowdsourcing and user-focused innovation.

Moreover, the 5H model encourages cross-fertilization to tackle eco-social concerns and transform them into opportunities through eco-innovation or eco-entrepreneurship (Carayannis et al. 2012). Borkowska and Osborne (2018) underline the mutual benefits of engaging citizens (4H) in the decision-making of urban infrastructures, facilitating social inclusion and learning. On the contrary, Kolehmainen et al. (2016) claim that the involvement of civil society in triggering social innovation is still unclear.

The most criticized model is the 4H, arguing that is highly complex (Hasche et al., 2020), fragmented, lacks conceptualization of the dynamics at the micro level and technology transfer (Miller et al., 2018; Cunningham et al., 2018) and its impact on innovation hubs is unclear (Malik et al. 2021).

On the contrary, De Oliveira and Carayannis (2017) underlined the “irreplaceable role” of the four helices. Other scholars claimed that further openness in R&I policies to overcome barriers that hamper adoption such as capacities and funding (Santos and Mendonça, 2017).

Indeed, engaging civil society in the long term remains a challenge due to declining interest and lack of resources. Collaboration from all stakeholders can enhance innovation impact and sustainability, but barriers between diverse actors persist (capacity constraints, unclear collaboration, and the need for incentives, and assessment methodologies). These barriers are typical in innovation and can be addressed as civil participation gains further support from policy.

The key novelty of the triple-helix model lies in the “hybridization”, meaning the juxtaposition of interrelations across the helices (Etzkowitz and Leydesdorff, 2000), which becomes crucial for knowledge capitalization. This is possible due to the co-evolution and the contribution of each strand (Leydesdorff and Etzkowitz, 2003). This phenomenon fosters multidisciplinary and co-responsible communities, driving transformative processes at all scales (Etzkowitz, 2003; Leydesdorff and Etzkowitz 2000), while reshaping social capital.

The n-helix dynamics, relying on the “cognitization of capital” and “capitalization of knowledge,” reinforce cross-border cooperation and globalization, fuelling both innovation and economic development (Etzkowitz and Leydesdorff, 2000). Hybridization leads to the emergence of novel hybrid entities and roles (e.g., incubators, living labs, innovation hubs, innovation communities), and transforming traditional innovation actors.

Yet, tensions and diverging expectations exist among the helices. The helix framework facilitates a virtuous cycle of knowledge creation, transfer, and multidisciplinary innovation (Urra, 2017), enhancing globalization through transnational interactions via networks.

The practical implementation of the n-helix models and innovation in general, is highly context-dependent (McAdam and Debackere, 2018). The n-helix has been widely applied across Europe (e.g., Smart Specialization Strategies), the USA, South Korea (Park, 2013) and other geographies (Galvao et al., 2019), gaining increasing influence in the policy realm (De Oliveira Monteiro and Carayannis, 2017; Etzkowitz, 2012; Brinkhoff et al. 2015).

However, there is an uneven research landscape, with underrepresented stakeholders and geographies, since most studies addressed developed economies (De Oliveira Monteiro and Carayannis 2017). Yun and Liu (2019) argue that the triple helix (3H) is preferred in Western countries with top-down policy push, while the quadruple helix (4H) blends top-down and bottom-up voices, and the 5H adds ecological sustainability, therefore both are useful for all contexts. Galvao et al. (2019) concluded that the triple helix dominates the landscape at the expense of the society and natural environment helices which remain poorly researched.

Yet, smart specialization strategies in regional innovation systems in Europe have been dominated by a 4H model (Höglund and Linton, 2018; EC, 2016) involving users or civil society. Yet, Balland et al. (2019) argue that the smart specialization policies have not been entirely operationalized.

Novel and non-traditional agents, such as incubators, Science and Technology Parks (STPs) emerge as pivotal mechanisms for the 4H model implementation (Schoonmaker and Carayannis, 2013; Mulyaningsih, 2015; Pascoal and Cabrita, 2016; McAdam et al., 2016; Bikse et al., 2016; Laguna and Durán-Romero, 2017; Machado et al., 2018). Yet, they face challenges balancing interactions and conflicting interests (Machado et al., 2018; Hasche et al., 2019). They could also promote sustainability due to spillovers across helices, but this remains poorly explored (Laguna and Durán-Romero, 2017).

Also, civil society actors, such as associations and communities are considered potential enablers of innovation (Arnkil et al., 2010; Carayannis & Rakhmatullin, 2014).

The 4H model has been widely applied to smart cities under the influence of digital platform disruptions and subsequent social concerns (Borghys et al., 2020). The pervasive use of ICT in the digital era has intensified collaboration between local government, “gig economy” businesses and citizens (Anthopoulos et al., 2016). Schütz et al. (2019) claim that “technological determinism” dominates the urban sustainability and innovation landscapes and legitimization of the 4H approach is relevant to ensure sustainable solutions with societal impact.

Thus, the advent of the digital era, the rising economic and societal concerns, together with the spiralling environmental consciousness and the urgency for tackling climate change and SD, have made the triple helix model obsolete, demanding its evolution (Pascoal and Cabrita, 2016; Laguna and Durán-Romero, 2017; Aranguren, Magro, Navarro, & Wilson, 2018) towards the actual needs of humanity in the 21st century.

The integration of the fifth helix pursuing sustainability has the potential to profoundly impact the entire innovation system (Laguna and Durán-Romero, 2017), facilitating SD (Machado et al., 2018). The interaction with sustainable universities, entrepreneurs, and eco-innovators generates "sustainable knowledge spillovers" (Bikse et al., 2016). However, limitations exist due to the novelty of the topic and the lack of research in relevant environments.

The 5H model offers a capabilities-based perspective for exploring SD, and analysing system interactions (De la Vega Hernández et al., 2020). It emphasizes the importance of society as a valid actor in decision-making for SD (Barcellos-Paula et al. (2021). Nevertheless, the complexity arising from numerous variables can pose challenges in identifying cause-effect relationships and achieving system harmony, particularly when considering inequalities and varying circumstances across countries.

Taratori et al. (2021) emphasize the need for sound governance models in smart city implementation and propose 5H collaboration across European case studies as potential solutions. They identify public participation, multidisciplinary synergies, and long-term political commitment as crucial drivers for urban innovation, fostering trust and behavioural change towards smart, sustainable, and socio-ecological transitions.

Smart cities offer promising ecosystems, but their underlying dynamics remain unclear, often treating smartness as a "magic tool" without always materializing societal impact. On the other hand, Galan et al. (2017) explore the role of ICTs in energy access governance, advocating for novel frames to tackle global demand for clean energies and democratizing the energy system transition. However, the convergence of energy and digitalization faces challenges, such as neo-colonial influences, human rights controversies, and environmental impacts along value chains, which need to be addressed.

Only a few scholars have proposed a sextuple helix innovation model. Lopez-Rubio et al. (2021a, b) suggested a sixth strand focused on entrepreneurship. Knowledge-intensive entrepreneurship activities require continuous exchanges of knowledge across and beyond organisational boundaries (Malerba and McKelvey, 2020).

Yet, entrepreneurship forms part of the economic system and is already well-integrated within the triple and quintuple helix models, making it appear more as a micro-dynamic embedded within the n-helix rather than a standalone subsystem. The boundaries between the different types of entrepreneurship are blurring and a profound understanding of the dynamics amid the diverse actors is required.

However, the current systems do not fully reflect the complexity and multidimensional nature of digital transition and its impact on the economy, society, and the environment.

The helix model should be downscaled for implementation where the creation of knowledge is influenced not only by infrastructures and data availability but also by digital ecosystems and the dynamics emerging around the triple transition. Besides, digital access and skills play a vital role in facilitating co-creation and fuelling n-helix innovation.

Regarding the relationship between n-helix models and the 2030 Agenda and the context of digital transformation, the literature acknowledges this interplay. According to König et al. (2020) all n-helix models integrating the SD imperative are built on how knowledge creation, diffusion and innovation and evolve influenced by openness, democratic processes, and mutual learning, thus they could support the 2030 Agenda or specific goals like SDG5 on gender equality (Lindberg et al. 2012) or SDG 13 "climate action" (Carayannis and Campbell, 2010).

Indeed, current research underlines that policy should ensure that all innovation subsystems interact synergistically for mutual benefit, promoting cooperation and knowledge circulation which generates capital and sustainable innovation. Working together, the subsystems create further cumulative knowledge. Nevertheless, it remains unclear to what extent, and through which process, diverse entities bring their knowledge for this purpose.

Leydesdorff (2012) underscored that innovation processes are continually evolving with diverging forces amid societal and knowledge systems, leading to the extension to n-tuple helices. The integration of wealth creation, knowledge production, and normative control occurs at the interfaces. In the digital society driven by Big Data, n-tuple helices with more dimensions may be needed to understand the complex dynamics (Park and Leydesdorff, 2013).

Indeed, the widespread digitalization leads to an increasing interrelation of knowledge production which needs to adapt to contemporary grassroots and eco-social priorities (Park, 2014). Sautter (2021) emphasizes multi-actor participatory approaches and collective actions for shaping digital ecosystems aligned with sustainability, circularity, and the SDGs. Appio et al. (2019) underscore the paybacks of n-helix innovation models for economic development and environmental concerns.

Scholars also recognize the role of n-helix models in enhancing the implementation and governance of smart cities and digital contexts, but challenges like conflicting views and limited interfaces persist. Smart cities are nurseries of technology hubs enabling knowledge sharing, incubators, accelerators, and innovation parks (Leydesdorff and Deakin, 2011). Overall, n-tuple helix models provide valuable insights into the interactions among subsystems and components of the innovation spectrum (McAdam and Debackere, 2018).

Borghys et al. (2020) highlight the unprecedented disruptive impact of digital platforms on society and the rise of complex ecosystems involving private, public, and citizen stakeholders. The platforms offer multi-sided markets, enabling user participation and co-creation. However, uncertainties remain regarding their value to local contexts and citizen collaboration, along with concerns about regulation gaps, ethics, and environmental impact.

While some smart city projects have successfully engaged civil society, challenges persist. Cavallini et al. (2016) claim that very few cases have shown a positive impact on citizens. Digital platforms promised to propel the “democratization of innovation” (Von Hippel, 2005). Certainly, peer-to-peer and prosumer models are disrupting markets, but by luring the collaboration and democratization paradox.

The evolution of the platform paradigm requires critical review to mitigate social threats and power asymmetries. Pioneer governmental initiatives, like “Decide Madrid,” or programmes such as Horizon Europe have demonstrated successful public participation and innovation with a sustainability focus. Disbelievers of collaboration and co-creation may cite barriers, but collaboration and co-opetition can better manage conflicts and power imbalances.

In the current and future landscape, innovation, digitalization, and sustainability are essential for success, universities integrate entrepreneurship, enterprises embrace corporate social responsibility (CSR), and innovative communities thrive across various technological fields (e.g., smart energy communities, smart cities). Hence, to balance innovation impacts and address negative disruptions, novel innovation models for shaping a more inclusive and sustainable digital innovation are required.

This research addresses the pressing need for holistic frameworks that adapt innovation to contemporary challenges, and for that purpose, it proposes a novel helix innovation model that is fully adapted to the regenerative triple transition demands.

4.6. Proposal of a Sextuple Helix Innovation Model

Based on the insights gained from the thorough analysis conducted, the Sextuple Helix Innovation Model (6HIM) was developed, which is specifically designed to align with the novel configurations and evolving landscape of innovation and support a regenerative triple transition for sustainable development. An outline of the model is presented in Figure 4.1.

The proposed 6HIM encompasses six interrelated subsystems or helices, each contributing with unique forms of knowledge and capital creation to various dimensions of regenerative development:

- (i) Open Academia (H1), which encompasses science, culture and RRI conducted with and for society. It primarily generates human and intellectual capital, fosters responsible R&I, and smart education in close collaboration with society.
- (ii) Whole-of-Government (H2), which mainly promotes social capital and smart governance through the action of public bodies and international organisations.
- (iii) Conscious Economy (H3), which creates financial capital (economic and manufactured) and intellectual capital, thereby driving economic growth through mindful, sustainable, and smart industries, enterprises, and entrepreneurship for a smart economy.
- (iv) Empowered “Whole-of-Society” (H4), which encourages a just transition, by fostering human and social capital. It promotes “smart living” through the active participation of citizens, users, communities, civic alliances, and Non-Governmental Organisations (NGOs).
- (v) Regenerated Planet and Healthy Ecosphere (H5), which advances the ecological transition by creating natural capital and promoting regenerative sustainability to ensure thriving living ecosystems. It also supports the development of smart environments.
- (vi) Mindful and Green Digital Sphere (H6), which facilitates digital transformation by generating mainly digital capital while enabling the “smart everything” paradigm (Langley et al., 2021; Streitz, 2018) to drive sustainable digital innovation.

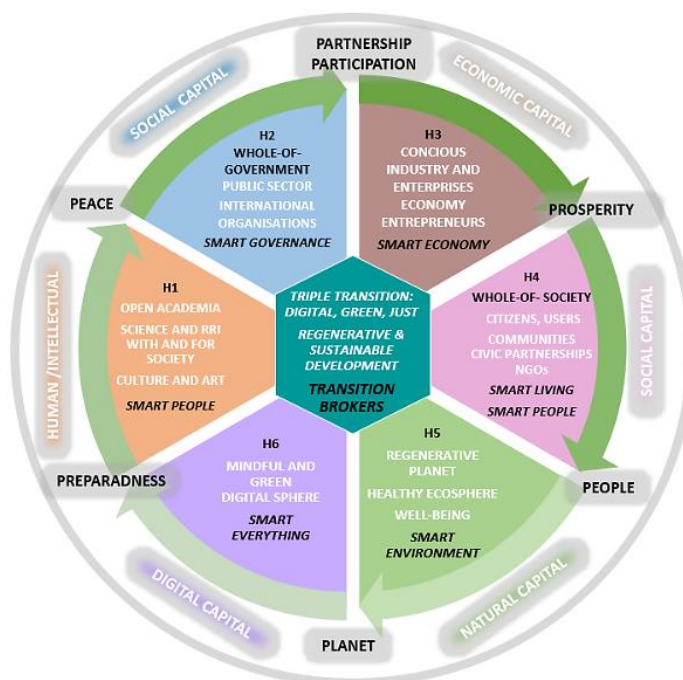


Figure 4.1. Scheme of the proposed Sextuple Helix Innovation Model (6HIM)
(Own elaboration)

The six-strand and six-capital 6HIM model builds upon and extends previous helix approaches and the IIRC's Six Capitals Framework, by reorienting them towards the regenerative triple transition.

Hence, the proposed 6HIM model represents a forward-thinking evolution towards a "knowledgeable humanity", by promoting pluriversal, multidisciplinary, sustainable, and regenerative innovation in the digital era.

Furthermore, it is aligned with the 2030 Agenda's five pillars (people, planet, prosperity, peace, and partnerships), while introducing a new pillar on preparedness, which is essential for navigating complex transformations (Pingali et al., 2023), and for supporting regenerative innovations and institutions (Webster and Terzic, 2021).

Preparedness is also crucial for advancing regenerative digital innovation and the triple transition by fostering readiness, resilience, and adaptability in response to disruptions. It is related to being ready and equipped to adapt to unforeseen crises while building resilience and promoting sustainability in the long term.

It lies at the core of digital transformation and the triple transition since it plays an essential role in ensuring that technological advancements and innovations in all their forms and across all sectors, contribute meaningfully to broader ecological and social objectives.

Both the integration of technological and institutional readiness are needed to adopt disruptive technologies for regenerative solutions (Webster & Terzic, 2021). Thus, a comprehensive approach to preparedness includes infrastructures, skills, a supportive environment, agile leadership, and a culture of innovation, enabling organizations and societies to withstand disruptions and ensure long-term resilience.

Ultimately, preparedness is key to aligning innovation, digital transformation, and sustainability agendas, but for that purpose, the reorientation of innovation frameworks and policies is needed, thereby supporting the regenerative triple transition.

Concerning the evolution of the IIRC's "Six Capitals Framework" (Adams et al., 2013), this research proposes that it must be updated to meet the novel requirements and trends of the digital age, and better align with the demands of the regenerative triple transition.

The IIRC framework incorporates the "Multi-Capital Theory", which represents a leading trend in assessing sustainable value creation by balancing different forms of capital, similar to how organizations manage trade-offs to achieve the SDGs (Adams et al., 2017). This research suggests that the integration of digital capital is needed to reflect the unique impacts of digital transformation on value creation.

In this regard, digital capital encompasses digital assets, capacities, and networks, thereby capturing the unique transformative influence of the digital era on the economy, governance, environment, and society. This ensures that the multi-capital framework remains reflective of the ongoing transitions and guides sustainable value creation in the rapidly evolving digital landscape.

Therefore, the expanded Six Capitals framework should include digital capital, economic capital (combining financial and manufactured capital), intellectual capital (collective and organisation-focused knowledge), human capital (individual-focused capabilities), social capital (relationships), and natural capital (environmental resources and ecosystem services). This revised framework provides a more comprehensive reflection of value creation in the modern digital and regenerative context.

In essence, the expanded framework is aligned with the Sextuple Helix Innovation Model (6HIM), which integrates the revised forms of capital, enabling a holistic assessment of value creation, which is crucial for navigating the triple transition and fostering regenerative development.

Furthermore, this dynamic structure facilitates collaboration, coopetition, co-creation, cross-fertilisation, and cooperation across the six helices, giving rise to novel hybrid entities and sparking trailblazing solutions.

The 6HIM model also integrates transition brokers (Cramer, 2020), as the intermediaries who play a crucial role in overcoming barriers and catalysing change, promoting the integration and synergies within the helices, thereby fostering open dialogue and cooperation across all societal subsystems. In that way, interconnected ecosystems are created where knowledge is multiplied and circulated.

Indeed, the foundational principles of the proposed 6HIM model are grounded in conscious, community-driven, crowdsourced knowledge exchange across diverse disciplines, geographies, generations, cultures, and stakeholders, ultimately reinforcing its capacity to address global challenges through regenerative innovation.

Hence, the key novelties of the proposed 6HIM are described as follows: (i) the evolution of the six societal subsystems towards contributing to the regenerative triple transition for sustainable and revitalizing development; (ii) the cohesive integration of these six subsystems, to foster the creation and sharing of knowledge and multi-capitals for regenerative development; this encompasses both traditional actors (state, academy and market), along with novel actors, driving the digital, ecological and socially just transitions (digital sphere, ecosphere and whole-of-society); (iii) the integration of transition brokers as catalysers to facilitate the implementation of the model, addressing potential barriers while promoting collaboration and coopetition.

In conclusion, the evolution of helix innovation models is outlined in Figure 4.2. and Table 4.1, showcases the progression from the triple to the sextuple helix, along with their unique characteristics. Each iteration expands the scope to address emerging contemporary challenges and opportunities.

Overall, the 6HIM model represents a holistic approach to regenerative innovation and the triple transition, aiming to foster synergies and transformative change towards regenerative sustainable development in the digital era.

Figure 4.2. Scheme of the Evolution of the Helix Innovation Models
(Own Elaboration)

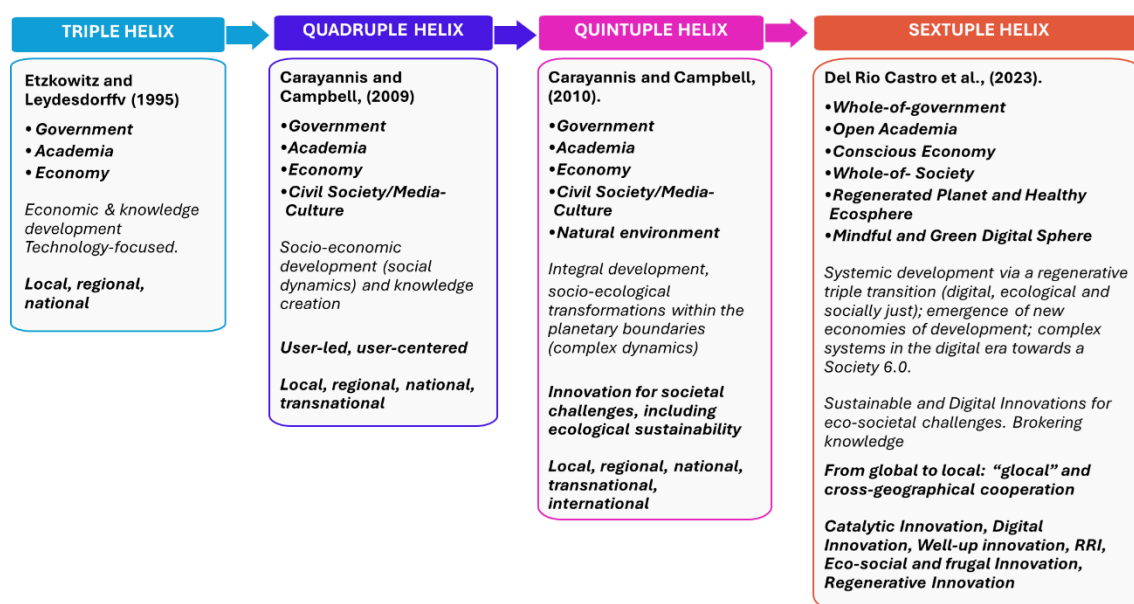


Table 4.1. Outline of the Evolution and Characteristics of the Helix Innovation Models
(Own elaboration)

DESCRIPTION	Triple Helix	Quadruple Helix	Quintuple Helix	Sextuple Helix
SUBSYSTEMS	Government Academia Economy	Government Academia Economy Civil Society/Media/Culture	Government Academia Economy Civil Society/Media/ Culture Natural environment	Whole-of-government Open Academia Conscious Economy Whole-of-society Regenerated Planet/Healthy Ecosphere Mindful and Green Digital Sphere Transition Brokers
FOCUS	Technology-focused Economic and knowledge development	User-led, user-centred products and services Socio-economic development and knowledge creation	Innovation for societal challenges, including ecological sustainability. Integral development through socio- ecological transformations within the planetary boundaries	Regenerative and Sustainable Digital Innovation for eco-societal transformation and revitalization Regenerative development via the regenerative triple transition (digital, ecological, and socially just) New economies of development Brokering knowledge
SCALE	Local, regional, and national	Local, regional, national, and transnational	Local, regional, national, transnational, and international	From global to local: “glocal” Cross-geographical interlinkages
DOMINANT CAPITAL GENERATION	Economic, Human, and Intellectual capital	Economic, Human, Intellectual, and social capital	Economic, Human, Intellectual, Social and Natural Capital	Economic, Human, Intellectual, Social, Natural and Digital Capital
DOMINANT INNOVATION STYLE	Technological and business-focused Innovation	Social Innovation Grassroots Innovation Open Innovation User-led Innovation Technological and Business Innovation	Eco-innovation Frugal Innovation Well-up Innovation Biomimetic Innovation Social and Open Innovation Technological and Business Innovation	Regenerative Innovation Catalytic Innovation Digital Innovation Well-up innovation Eco-social innovation Frugal Innovation Technological and business innovation
DOMINANT DYNAMICS	Economic dynamics Knowledge generation/ diffusion	Social Dynamics Participation and Collaboration Openness Knowledge generation/diffusion	Socio-ecological dynamics within planetary and social boundaries Cooperation for sustainability Knowledge generation/diffusion	Multidimensional dynamics within the triple transition Global cooperation, co-creation, co-evolution, cross-fertilisation, co-opetition, collaboration. Knowledge expansion across and within boundaries (cross- generational, cross-geographical, cross-cultural, cross-disciplinary, cross-sectoral, cross-stakeholder, cross-scale). Conscious, communitarian, crowdsourced, co-networked knowledge

NOVEL HYBRID ENTITIES OR INITIATIVES	Science and Technology Parks	Living Labs	Energy Communities	Sustainable and Regenerative
	EU EIT Communities	Innovation	Eco-villages	Digital Innovation Hubs
	ERA-NET Networks	Communities/Cooperatives	Eco-innovation communities, hubs	Digital Alliances/Partnerships for Sustainability
	Entrepreneur University	Citizen Science Alliances	Citizen-led Environmental	Smart and Sustainable Communities
	Corporate University	Innovation Hubs	Platforms	Crowdsourcing Digital Platforms for Sustainability
	Industrial	Social Movements, Participatory Budgets	Green Science and Technology Parks	Digital education platforms
	Doctorates	Innovation Valleys	Ecology Movements	Digital government platforms
	Clusters	Smart Specialization Strategies		Data collaboratives for sustainability
	Angel Networks	Incubators/accelerators		Virtual Assemblies/Activism
	Venture Capital			Sharing economy platforms

4.7. Alignment Assessment of Relevant R&I Initiatives against the 6HIM Model

The results of the alignment assessment conducted are presented as follows, starting with the Horizon Europe Programme, followed by an analysis of the European Digital Innovation Hubs, and concluding with the CODES Coalition.

4.7.1. Alignment Assessment of the Horizon Europe Programme

The Horizon Europe Programme (HE) signifies the 9th European Framework Programme (FP) for R&I during the period 2021-2027. With a budget of €95.5 billion (EC, 2021a), HE is considered the most advanced public STI initiative ever (Annete, 2021). Ideally, HE expects to transcend boundaries, fostering collaboration among disciplines from fundamental research to groundbreaking innovations. Besides, HE holds a commitment to open science and RRI (Cozzoni et al., 2021), to generate ethical, sustainable, and socially desirable breakthroughs and ecosystems.

Hence, HE represents a commitment to tackling global challenges and nurturing the R&I community toward the digital and green transition. Nonetheless, despite this outstanding public support, the continent is trailing behind global R&I leaders (Annete, 2021).

Structured into three main pillars, HE covers all relevant models of knowledge, and R&I. Pillar I focuses on excellent science and basic research; Pillar II supports applied R&I, addressing societal challenges through six clusters and partnerships; and Pillar III enhances innovation and entrepreneurship. HE marks a significant evolution from earlier FP frameworks, promoting transformative missions, groundbreaking innovation, and international cooperation through partnerships (Steeman et al., 2023).

Moreover, HE integrates RRI more strongly than its predecessors. However, improved integration of societal impacts, co-creation dynamics, and interrelations are required (Cozzoni et al., 2021; Robinson et al., 2020), along with better incorporation of inclusion and sustainable growth within planetary and social boundaries (Albertson et al., 2021).

Criticism of HE also addresses the limited understanding and missing methodology to evaluate helix impacts in co-creation efforts and the failure to fully democratize science in line with societal expectations.

Besides, impact-driven research has become a priority, emphasizing the need for deeper engagement with Social Sciences and Humanities and multistakeholder collaborations. Yet, challenges remain in integrating environmental concerns and achieving genuine societal impacts (EC, 2024a; Stier and Smit, 2021).

Nonetheless, even high-level documents remain supported by “innovation-for-growth” and “extractive” economies, demanding a more advanced and comprehensive approach to acknowledge interdependencies, and equality, along with “well-up” economics (Albertson et al., 2021).

In addition, the envisioned “twin digital and green transition” lacks cohesive implementation, with sustainability inadequately integrated (Stier and Smit, 2021), and a missing regenerative approach. Moreover, concerns arise about declining R&I impacts due to the focus on complementary activities, impeding genuine scientific endeavours and bottom-up voices.

Hence, despite advancements, the regenerative triple transition is overlooked in HE. Further efforts are necessary to genuinely integrate sustainability, and regenerative principles, along with broadening stakeholder involvement to enhance R&I responsiveness to eco-social needs (Albertson et al., 2021).

This research proposed the 6HIM model as a conceptual framework for addressing these challenges and preparing R&I ecosystems for the triple transition, thereby promoting holistic, responsible, inclusive, and regenerative innovation.

For shedding light on the alignment of the HE programme with the 6HIM, a comprehensive examination of the HE’s Work Programmes (WPs) for 2022-2023 (EC, 2023d) was conducted, by employing qualitative analysis, supported by text exploration and visualization with “Voyant tools”.

This approach enabled an in-depth exploration of key themes such as digitalization, environmental sustainability, and regeneration, along with social aspects like inclusiveness, justice, participatory approaches, collaboration, co-creation, openness, citizen involvement, and ethics.

Therefore, the analysis unveiled valuable insights into how these themes are integrated within the HE programme. The key findings from this analysis are summarized in Figure 4.3. and further described below.

WORK PROGRAMME 2022-2023	INTEGRATION OF N-HELIX DIMENSIONS		
	DIGITALIZATION H6	ENVIRONMENTAL SUSTAINABILITY H5	SOCIETAL ASPECTS AND INCLUSIVENESS H4
WP1 - General Introduction	Very strong	Very Strong	Moderate
WP2 - MSCA actions	Very weak	Moderate-weak	Weak
WP3 - Research Infrastructures	Strong	Moderate	Very weak
WP4 - Health	Moderate	Moderate-weak	Weak
WP5 - Culture, Creativity, and Inclusive Society	Strong	Moderate-weak	Strong
WP6 - Civil Security	Moderate	Very weak	Moderate-weak
WP7 - Digital, Industry and Space	Very strong	Moderate	Very weak
WP8 - Climate, Energy and Mobility	Moderate	Strong	Very weak
WP9 - Food, bioeconomy, natural resources, agriculture, environment	Moderate	Very strong	Weak
WP10 - European Innovation Ecosystems	Moderate	Weak	Weak
WP11 - Widening participation and Strengthening the EU Research Area	Moderate	Moderate-weak	Weak
WP12 - Missions	Moderate	Moderate	Moderate-weak

Figure 4.3. Alignment Assessment of Horizon Europe’s WP 2022-2023
(Own elaboration)

The analysis reveals that digitalization stands as a dominant aspect in the WPs, particularly, is prominently present in the general description and within the Digital Cluster (WP7), but is less emphasized in the Missions, Infrastructures, and Health programmes. Conversely, environmental considerations are poorly integrated beyond the Clusters on Climate and Environment (WP8 and WP9), suggesting a limited focus on resilience, ecology, and regeneration throughout the HE programme.

Furthermore, social inclusion and other societal factors are also weakly represented, with few exceptions in specific clusters (WP5).

Concerning the alignment with cross-cutting themes, co-creation, and citizen involvement are well integrated, and collaboration is also prominently included in specific clusters. However, cooperation and participative approaches are generally underrepresented, except in a few areas. Besides, community integration remains weak outside of certain clusters.

While open approaches are broadly recognized, the helix innovation model finds relevance only in the “Widening” WP. Lastly, ethics and responsibility also received limited attention, appearing in only a few WPs.

Overall, these insights underscore the need for enhancing HE’s alignment with critical eco-societal challenges and the triple transition, embedded within the 6HIM framework.

4.7.2. Alignment Assessment of the European Digital Innovation Hubs

The Digital Europe Programme (DEP) fosters key digital technologies in line with EU policies such as the Green Deal and the Digital Agenda (EC, 2023b; 2024b). Central to DEP is the European Digital Innovation Hubs (EDIHs), supported by the EU and regional governments to assist in the digital and green transitions. These hubs aim to become extensive international networks, facilitating collaboration and acting as innovation intermediaries (Crupi et al., 2020).

Nevertheless, according to Lepore et al. (2023), the EDIHs fail to fully capitalize on the opportunities for community development, civic engagement, and environmental consciousness. Indeed, the sustainability aspects are not deeply integrated into their operations, missing their potential for promoting regenerative sustainability and the triple transition.

The analysis of the EDIH catalogue as of June 2024 (EC, 2024b) reveals a predominant focus on technocentric solutions, with limited emphasis on genuine sustainability practices. Certainly, most hubs operate within a 3-helix (3H) model, primarily engaging government, industry, and academia while lacking broader multistakeholder collaboration and genuine sustainability practices.

This narrow approach often overlooks key eco-societal needs, such as environmental regeneration and social inclusivity. Consequently, there is a noticeable gap in addressing the broader eco-societal challenges essential for a comprehensive, sustainable digital transformation.

Only a minority, specifically five out of 228 hubs, show a credible orientation towards sustainability. In this regard, the sustainable-oriented EDIHs are, namely: GREENEDIH, DATA2SUSTAIN (focused on innovations for circular economy, operations, and sustainability), and DIGIHUB.LI (devoted to innovation and growth with a regenerative purpose), AIR4S (dedicated to Artificial Intelligence and robotics for achieving the SDGs), and DIH4CN (prioritizing climate neutrality initiatives).

Therefore, a shift towards reorienting these hubs to the 6HIM model is required to fully leverage the potential of these hubs in advancing the regenerative sustainability domain.

Despite their current limitations, the EDIHs possess outstanding potential as catalysts of regenerative innovation and the triple transition. As relatively new entities in the digital landscape, EDIHs' contribution to sustainable digital development remains poorly explored. Hence, further research and consolidation of these novel ecosystems are needed to fully harness their contribution to sustainable and regenerative digital development.

The analysis of the three EDIHs with stronger integration of the six-helix and sustainability vision yields the following findings.

In this regard, most EDIHs analysed exhibit limited integration with civil society and weak sustainability practices. Furthermore, collaboration among the six helices is not optimal, subsequently, hybridization efforts are impeded. Additionally, collaboration among the six helices is not optimal, hindering hybridization efforts.

Assessment of the “AIR4S” Hub

The “AIR4S” European Digital Innovation Hub, led by Universidad Politécnica de Madrid (UPM), promotes AI, robotics and digital solutions aligned with the SDGs for regional development and competitiveness. It offers services such as capacity building, financing, and entrepreneurship support, emphasizing social, legal, and ethical balance for sustainability competitiveness. Key findings of the respective alignment assessment are summarised in Figure 4.4.

AIR4S (SPAIN)		
SUBSYSTEM	INTEGRATION	ANALYSIS OF THE INTEGRATION OF 6HIM SUBSYSTEMS
Governance	Strong	Relevant participation of regional and local public institutions
Academia	Very strong	Universities, research institutions, and collaboration with other R&I initiatives
Business	Very strong	High participation of enterprises (including) SMEs, start-ups, and business associations.
Civil Society	Weak	Low co-creation with users, limited workshops with civil society stakeholders
Digital Sphere	Very Strong	AI, robotics, and synergic digital technologies
Nature	Moderate	Services are aligned with SDGs, but sustainability impacts are not properly considered
Seamless collaboration and hybridization	Moderate	Limited collaboration with novel subsystems like civil society and weak integration of sustainability aspects. It follows a 3H model with digital and SDGs spheres as added on. It presents high potential for evolution towards the 6H model.

Figure 4.4. Alignment Assessment of the “AIR4S” Hub
(Own elaboration)

Assessment of the “GreeneDIH” Hub

The “GreeneDIH” European Digital Innovation Hub aims to bridge the evolving digitalization needs with sustainable solutions. Through collaboration networks, policy alignment, project origination, test-before-invest activities, technology transfer, and knowledge dissemination, this hub also aims to foster synergies with other initiatives (e.g., “SmartAgriHubs,” “Green Technology Cluster”) and promotes cross-industry efforts to reduce GHG emissions and protect the environment.

Key findings of the respective assessment are summarised in Figure 4.5.

GREENEDIH (Romania)		
SUBSYSTEM	INTEGRATION	ANALYSIS OF THE INTEGRATION OF 6HIM SUBSYSTEMS
Governance	Strong	Participation of public institutions and notable policy alignment
Academia	Very Strong	Robust support from academia partners (universities, research institutes)
Business	Very Strong	Active engage of enterprises and industry (both SMEs and Large)
Civil Society	Weak	While open to participation, civil society and social aspects lack significant presence
Digital Sphere	Strong	Wide spectrum of digital technologies, but with cross-sector focus
Nature	Moderate	Promotion of eco-friendly practices, but with limited evidence and narrow applications
Seamless collaboration and hybridization	Moderate	Limited collaboration with novel subsystems, weak participation of civil society and narrow approach to sustainability. Uncertain application of digital solutions to the environmental domain thus far. It follows a 3H model with digital and nature spheres as added on. It presents high potential for evolution towards the 6H model.

Figure 4.5. Alignment Assessment of the “GREENEDIH” Hub
(Own elaboration)

Assessment of the EDIH DIGIHUB.LI Hub

The DIGIHUB.LI European Digital Innovation Hub is dedicated to social innovation and regeneration, fostering collaboration to address sustainability challenges. It hosts training and communication activities, including regenerative leadership sessions, ultimately promoting a transformative vision for innovation leaders. Additionally, it provides a “Digital Maturity Assessment tool” to guide organizations in their DT and sustainability efforts, emphasizing collaboration and co-creation. While the initiative is committed to sustainability, more evidence of activities directly targeting environmental and social aspects is needed.

The findings of the corresponding analysis are shown in Figure 4.6.

DIGIHUB.LI (Liechtenstein)		
SUBSYSTEM	INTEGRATION	ANALYSIS OF THE INTEGRATION OF 6HIM SUBSYSTEMS
Governance	Moderate	Participation of public institutions is considered limited
Academia	Strong	Relevant support from academia partners
Business	Very Strong	Relevant participation of enterprises, including SMEs and social entrepreneurs
Civil Society	Weak	Civil society lacks relevant presence
Digital Sphere	Strong	It covers a diversity of digital technologies, applications, and ecosystems
Nature	Moderate	It promotes regenerative leadership and sustainability, but limited applications thus far
Seamless collaboration and hybridization	Moderate	Collaboration with novel subsystems and civil society participation is weak, and evidence of sustainability applications beyond awareness is limited. Overall, it follows mainly a 3H model with the addition of the digital sphere and regenerative sustainability components. However, there is high potential for evolution towards the 6H model.

Figure 4.6. Alignment Assessment of the “DIGIHUB.LI” Hub

(Own elaboration)

4.7.3. Alignment Assessment of the Coalition for Digital Environmental Sustainability (CODES)

The UNEP’s Coalition for Digital Environmental Sustainability (CODES, 2022) exemplifies an effective alignment with the 6HIM framework, since it serves as an open global alliance for uniting stakeholders, in advancing digital sustainability efforts. The coalition strategically addresses gaps in digital and sustainability literacy (Jobling et al., 2023), enhancing awareness to prevent exacerbating environmental and social challenges. CODES also promotes sustainability through three shifts: 1) harmonizing the visions and values of both DT and sustainability by proper dialogue; 2) mitigating adverse impacts of digitalization on sustainability; and 3) accelerating digital innovations endeavours by bringing positive change and regeneration potential.

Indeed, CODES demonstrates a robust dedication to promoting sustainable digital transformation aligned with the policy objectives of the 6HIM. It intertwines policymakers, academics, enterprises, and civil society, alongside digital and sustainability considerations. It collaborates closely with academic institutions to foster research and knowledge exchange, together with technology companies to develop innovative solutions for sustainability. Additionally, CODES engage NGOs to align with civil society demands and perspectives. In essence, CODES mirrors consistently most helices of the 6HIM.

Hence, this coalition is strongly aligned with the 6HIM model, as it significantly intertwines essential stakeholders and sustainability considerations for effectively integrating DT with SD practices. Nevertheless, further emphasis on the regenerative triple transition is required.

The respective findings are provided in Figure 4.7.

COALITION FOR DIGITAL ENVIRONMENTAL SUSTAINABILITY (CODES)		
SUBSYSTEM	INTEGRATION	ANALYSIS OF THE INTEGRATION WITH 6HIM SUBSYSTEMS
Governance	Strong	Relevant participation of policy makers and global governance organisations
Academia	Very Strong	Robust participation of Universities and Research Centres
Business	Strong	Significant participation of technology enterprises
Civil Society	Moderate	Notable participation of NGOs, but limited engagement of citizens
Digital	Very Strong	It covers all relevant digital technologies and their impacts on SD
Nature	Very Strong	Both environmental sustainability and social aspects are soundly embedded
Seamless collaboration and hybridization	Strong	Collaboration among the six subsystems is properly achieved, exemplifying a robust 6H model. However, further integration of the civil society subsystem would be beneficial to enhance the impact. Additionally, advancing practical applications and influencing domestic policies would bolster its effectiveness.

Figure 4.7. Alignment Assessment of the CODES Coalition

(Own elaboration)

4.8. Regenerative Readiness Levels

Considering the need to evolve innovation towards regenerative sustainability, it is necessary to develop a framework that defines gradual levels of regeneration, in analogy to the already established Technology Readiness Levels (TRLs) and the Innovation Readiness Levels.

Therefore, this section proposes a scheme of progressive “Regenerative Readiness Levels” (RRLs) to systematically assess, monitor and communicate the progress of innovation programmes, policies, practices, and ecosystems in contributing to regenerative innovation for the triple transition.

In addition, this scheme aims to enhance accountability, raise awareness and mitigate the prevalence of greenwashing in the digital and innovation realms.

Nevertheless, as emphasized by several experts, this scheme should be complemented by education and capacity-building incentives and measures for all the stakeholders, to equip them with the skills and insights to support meaningful and genuine sustainability efforts.

Therefore, analogous to the TRLs, widely applied in the R&I domain, six Regenerative Readiness Levels (RRLs) are proposed to evaluate the degree of alignment between innovation practices, programmes, policies or ecosystems with the principles and values embedded within the Sextuple Helix Innovation Model (6HIM).

As Webster and Terzic (2021) suggested, while the traditional TRLs framework is useful, it requires to be complemented to account for “regenerative readiness”, which also relates to both technological and institutional readiness.

The proposed RRLs are inspired by the framework established by the UNDP’s Digital Development Compass (2021, 2023), which defines progressive levels of digital development: from basic, opportunistic, systematic, and differentiating, to transformational.

The resulting framework comprises six distinct levels, each corresponding to varying degrees of commitment and performance concerning regenerative practices.

These six levels are structured to evaluate the integration of regenerative practices and subsequent alignment with the 6HIM across the organisation, from minimal awareness to industry-leading excellence, as outlined in Table 4.2.

Hence, this structured approach provides a clear pathway for assessing and advancing regenerative readiness while ensuring alignment with the principles of the regenerative triple transition and sustainable development.

Table 4.2. Outline of the Regenerative Readiness Levels for Regenerative Innovation
(Own elaboration)

LEVEL	DESCRIPTION	ALIGNMENT WITH THE 6HIM MODEL
RRL1	Minimal or No Alignment: The organization shows no consideration for regenerative sustainability measures or policies, indicating a fundamental disconnect with regenerative principles. Strong misalignment with the 6HIM.	Strongly Misaligned
RRL2	Emerging Awareness: The organization demonstrates initial recognition of the importance of regenerative sustainability. This level includes the implementation of a few pilot and isolated actions without a systemic strategy or policy across the organization. Misalignment with the 6HIM.	Misaligned
RRL3	Moderate Alignment: The organization shows growing awareness and action, and it is beginning to integrate regenerative sustainability measures in some areas, accompanied by preliminary policies or strategies. While there is initial alignment with the 6HIM, significant limitations and areas for improvement remain.	Neutral
RRL4	Good Commitment: The organization shows good awareness of regenerative practices and is actively implementing a growing number of regenerative sustainability measures aligned with the 6HIM. A consistent set of policies and strategies is in place across several levels of the organization. Good alignment with most aspects of the 6HIM, with several limitations requiring enhancement.	Aligned – Bronze Standard
RRL5	Strong Commitment: The organization is fully committed to the 6HIM and the regenerative triple transition. It has established a comprehensive, systemic approach to sustainable regeneration across all levels of the organization, with robust measures in place, including policies and recognised sustainability standards. Alignment with the 6HIM is strong, with only a few minor limitations.	Strongly Aligned – Silver Standard
RRL6	Best in Class: The organization demonstrates an exceptional commitment to the 6HIM and the regenerative triple transition, setting industry benchmarks for regenerative practices and performance. A systematic, organization-wide approach to regenerative sustainability is implemented, with robust policies and measures implemented at all levels and throughout supply chains. The organization leads innovative initiatives that drive transformation and collaborate with other entities on the regenerative journey. Excellent alignment with the 6HIM with no significant limitation.	Champion – Gold Standard

4.9. Reflections on the Interplay between Innovation, Digitalisation, and Sustainability

This research emphasizes the urgent need to address the complex relationship between sustainability, innovation, and digital transformation, particularly through a regenerative lens. Despite efforts to promote collaboration and sustainability, significant gaps remain, especially in integrating eco-social transformations within existing helix innovation models.

Traditional approaches to innovation are often technocentric, failing to address the complex and multifaceted challenges of the digital era and unfolding social and environmental global crises. This limitation significantly hinders progress toward achieving critical global objectives, including the UN 2030 Agenda and the Global Digital Compact.

A crucial aspect underlined by recent literature relies on the imperative alignment of innovation with ecological stewardship and social equity, ensuring that transformative processes support the SDGs. Besides, the regenerative paradigm goes beyond and calls for innovations capable of bringing positive change by balancing living ecosystems in harmony. This challenges the technocentric and growth-oriented mindsets that dominate traditional innovation models.

This scenario calls for novel innovation models and advanced policy support to foster collaboration across disciplines, sectors, and diverse actors within innovation ecosystems. While scaling and operationalising emerging paradigms such as regenerative innovation or ecological frugal innovation remain challenging, these approaches are crucial for unlocking the full potential of R&I in driving progress toward long-term sustainability goals in the digital era.

Thus, this dissertation addresses the identified gaps by proposing a paradigm shift in the innovation landscape through a novel Sextuple Helix Innovation Model (6HIM). This holistic and pluriversal model seeks to recalibrate research and innovation realms by adopting a regenerative and systemic resilience perspective, thereby contributing to the triple transition, in line with global dynamics.

The proposed 6HIM model fosters inclusivity by engaging all relevant stakeholders, societal subsystems, and knowledge bases, facilitating the alignment of innovation with digital transformation, and regenerative sustainability, into a cohesive driving force for supporting the regenerative triple transition.

The evolution of n-helix innovation models toward supporting the regenerative triple transition exemplifies the growing emphasis on multi-stakeholder collaboration. In this context, the active involvement of civil society, the integration of nature and environmental stakeholders as key actors, and the consideration of digital disruptions, emerge as essential components for fostering knowledge generation, multi-capital creation, and sustainable innovation ecosystems.

Therefore, the 6HIM model represents a key contribution of this dissertation, breaking down siloed mindsets and disconnected realms to promote multistakeholder and interdisciplinary collaboration for advancing systemic transformation towards regenerative innovation.

Additionally, the research proposed enabling ecosystems for practical experimentation and scaling of the 6HIM. In this regard, ecosystems such as the European Digital Innovation Hubs can be reoriented into “Regenerative Innovation Hubs” (RegenDIHs), emerging as key enablers of regenerative innovation by embedding the principles of the 6HIM.

These RegenDIHs may function as transition brokers, facilitating agile governance and systemic transformation to navigate the complex interplay between digital transformation, innovation, and regenerative sustainability. Other relevant ecosystems for testing and scaling the 6HIM are the Smart and Sustainable Communities, such as Smart and Sustainable Cities, and Smart Energy Communities, among others.

Furthermore, this research contributes to consolidating the concept of regenerative innovation and the emergence of the seventh wave of innovation, which addresses the complexities of contemporary challenges to promote long-term sustainability and resilience.

This dissertation demonstrates that the proposed 6HIM model and its enabling ecosystems are not merely a conceptual vision but are already materializing through advanced initiatives such as the CODES coalition.

The findings underscore the pressing need to reshape existing R&I programmes, policies, and ecosystems to align with 6HIM principles and embrace regenerative innovation, thereby driving systemic transformation toward the triple transition.

However, novel innovation models, such as the one proposed, often confront significant implementation barriers, and collaboration among diverse stakeholders is particularly challenging, especially in the R&I domain where dominant stakeholders often ignore sustainability values and are reluctant to leave their “ivory towers.”

Additionally, the interrelationships between the helices and the dynamics of transition brokers remain insufficiently understood. Therefore, advancing and reshaping the innovation landscape requires a concerted effort across research, policy, and practice, supported by specific incentives, awareness-raising initiatives, and capacity-building measures.

These findings provide both a conceptual foundation and a practical guide for innovation stakeholders, supporting the adoption of regenerative innovation practices and long-term sustainability, equity, and resilience of future R&I ecosystems.

In conclusion, the findings underscore the pressing need to reshape current innovation models, policies, programmes, and ecosystems to align with the principles of the regenerative triple transition and the multi-stakeholder collaboration exemplified in the 6HIM framework.

Yet, further research, practical experimentation in real-world contexts, and policy alignment are essential to overcome reluctance, resistance to change, and other implementation barriers, thereby unlocking and scaling these transformative approaches.

4.9.1. Opportunities of the 6HIM Model for the Triple Transition

This section provides a reflection on the opportunities and challenges that the 6HIM model opens for advancing regenerative innovation and sustainability, in the pursuit of the triple transition.

Opportunities of the 6HIM Model in Smart and Sustainable Communities and Paradigms

The analysis conducted has revealed intriguing insights and opportunities for advancing the regenerative triple transition by integrating the 6HIM into digital ecosystems and Smart and Sustainable Communities. This section offers a concise discussion of potential opportunities for implementing the 6HIM model in Smart Cities, Smart Energy Communities, and other aspirational visions, such as Society 6.0. It also reflects on the role of transition brokers in catalysing and accelerating systemic changes.

The outstanding opportunities of the Smart Cities³ and Communities (SCC), Smart Energy Communities, and Society 6.0 for advancing the triple transition were already introduced in Chapter 3. This section, therefore, focuses on the specific opportunities for implementing the 6HIM within these communities.

Notably, SCCs have provided a key context for exploring n-helix innovation models, particularly the quadruple helix approach (4H). These communities serve as ideal platforms for eco-social innovation, fostering collaboration among multiple stakeholders to revitalize urban environments.

As highlighted by Ghilic-Micu et al. (2019) and Taratori et al. (2021), SCCs exemplify how digitalization and innovation can function as eco-societal changers, integrating technological advancements, public purpose, resource efficiency, and citizen participation to address urban and societal challenges. However, as Borghys et al. (2020) and Schütz et al. (2019) argued, SCCs have often failed to contribute to genuine sustainability and their effectiveness has often been undermined by the techno-centric focus of dominant models such as the triple and quadruple helix.

³ In this research, *Smart City* is understood as “a system that enhances human and social capital wisely, by using and interacting with natural and economic resources via technology-based solutions to address public issues and efficiently achieve sustainable development and quality of life, based on multi-stakeholder and partnerships” (Fernandez-Anez, 2016).

Furthermore, the underlying dynamics of these ecosystems remain unclear, limiting their capacity to balance ecological, economic, and social goals.

Understanding the lessons learned from implementing n-helix models in SCCs is crucial for informing more effective applications in other contexts. Achieving successful implementation requires addressing asymmetries in power and influence among stakeholders while aligning innovation efforts with sustainability and inclusivity.

Also, the Smart Energy Communities (SECs) represent a promising context for applying n-helix innovation models, though they have received both praise and criticism, similar to many other “smart solutions.” SECs aim to drive eco-social innovation by fostering citizen participation and ownership in the pursuit of the energy transition.

These communities have enabled the creation of hybrid actors, such as “prosumers” (individuals who are both consumers and producers of energy), promoting self-consumption through renewable energy adoption, addressing energy poverty, and mitigating climate change. Consequently, SECs can contribute to eco-social transformation by addressing both ecological and just transition priorities, as argued by Geels et al. (2017) and the EC (2020).

According to Galan et al. (2017), the n-helix innovation models served as critical enablers for energy communities, by facilitating collaboration, and co-creation, as well as the integration of top-down and bottom-up approaches to address gaps and uncertainties (Darja et al., 2022; Otamendi-Irizar et al., 2022).

However, despite their potential, few initiatives have effectively leveraged digital transformation to enhance their impact (Ghiani et al., 2019; Barone et al., 2020; Reis et al., 2021). This highlights the need for better integration of digital technologies into SECs to maximize their role in advancing sustainability transitions while empowering society and encouraging participation.

Although SECs offer a collaborative and sustainable framework well-suited to n-helix models and regenerative innovation, they face significant challenges in translating these objectives into scalable solutions, limiting their broader adoption.

As such, SECs provide an excellent research context for implementing the 6HIM model and advancing the vision of the triple transition, unlocking their full potential (Loock, 2020; Otamendi-Irizar et al., 2022). Nevertheless, beyond technology and digitalization, additional efforts are required in capacity building, governance, regulation, and collaboration.

Other ecosystems, such as those focused on “Smart Agriculture” or “AgriTech” communities, offer valuable opportunities to experiment with the 6HIM model. These contexts are well-suited for exploring underlying dynamics and interrelations among actors, identifying potential implementation barriers, and advancing the triple transition through innovative and sustainable practices. Thus, these communities represent a highly relevant setting for applying and refining the 6HIM model.

Additionally, another innovative paradigm related to the triple transition and with potential opportunities to benefit from the implementation of the 6HIM is Society 6.0. Certainly, the Society 6.0 paradigm is well-aligned with the 6HIM model and presents opportunities for its joint application. However, its potential remains untapped due to conceptual uncertainties and a lack of empirical research.

Building on Japan's Society 5.0 strategy (Ferreira and Serpa, 2018; Salgues, 2018), which emphasizes a “super-smart society” where technology benefits humanity (Fukuyama, 2018; Onda, 2019), Society 6.0 expands this vision to integrate sustainability considerations (Žižek et al., 2021). While Society 5.0 aligns with helix models such as the quintuple helix (Carayannis et al., 2019 a, b, c; Bartolini et al. 2021) it is still an aspirational concept with a weak consideration of environmental sustainability.

Similarly, Society 6.0, while conceptually aligned with the 6HIM model and the vision of the triple transition, requires further conceptual elaboration and real-world experimentation to assess its viability for advancing regenerative innovation and the triple transition.

In conclusion, Society 6.0 holds promise as a representation of a “smart and sustainable society”, providing a relevant context for 6HIM experimentation. However, its realization depends on bridging conceptual gaps and conducting empirical research to confirm its potential.

The Role of Transition Brokers as Catalysts of the Triple Transition

Transition brokers often function as innovation intermediaries, facilitating knowledge circulation across organisational boundaries by connecting diverse innovation actors and generating “brokered knowledge” tailored to local needs (Meyer, 2010). They also serve as validators and disseminators of novel ideas within innovation networks (Winch and Courtney, 2007).

In helix models, transition brokers play a crucial role by forging alliances, facilitating knowledge exchange, and promoting systemic change, particularly in complex sustainability transitions.

As argued by Nakwa and Zawdie (2015), these intermediaries have bridged gaps, channelled resources, and spanned boundaries within triple helix ecosystems.

In this regard, Cramer (2020) underlined the relevance of transition brokers in implementing circular economy initiatives, since they inspire change, empower stakeholders, build alliances, address externalities, and create conditions for sustainable innovation through a “stretch-and-transform” approach.

Similarly, Barrie et al. (2019) emphasized that these kinds of intermediaries enhanced network cohesion and fostered collaborative learning among triple helix actors, thereby supporting niche innovations for sustainability transitions. These scholars also argued that the quadruple helix model is more effective for capitalizing on brokers, as it involves a broader range of stakeholders. Therefore, the 6HIM is even more suitable for these dynamic transition brokers.

Furthermore, Rowan and Casey (2021) argued that multi-actor innovation hubs, acting as transition brokers, have the potential to address the missing just transition approach in the shift toward a low-carbon future. Similarly, MacGregor et al. (2010) suggested that innovation should be understood as a collaborative effort among public, private, and community partnerships, underscoring the significance of cross-sector collaboration catalysed by knowledge and innovation brokers, to drive socio-ecological transformations.

In the digital sphere, Lepore et al. (2023) argued that intermediaries, such as digital hubs, may serve as transformation leaders by facilitating the use of advanced technologies for inclusive urban development. However, Kivimaa et al. (2019) pointed out that despite the critical role of transition brokers in enabling sustainability transitions, significant gaps remain in understanding the full scope of their functions, long-term impacts, and policy influence.

Also, further research is needed to understand how intermediaries operate across various socio-technical regimes, including underrepresented sectors, to leverage their potential for driving broader eco-social transformations (Barrie et al., 2019).

Therefore, the value of the transition brokers for enabling the 6HIM in regenerative innovation ecosystems is promising, but further research is needed to deepen empirical and theoretical understanding of their role and dynamics in advanced helix models and sustainability transitions.

In conclusion, there are significant opportunities for implementing the 6HIM in diverse digital ecosystems, innovative concepts like Society 6.0, and various Smart and Sustainable Communities (SSC). These ecosystems and communities are closely aligned with the principles of the 6HIM model and the vision of achieving a regenerative triple transition.

Therefore, they provide fertile grounds for experimentation, addressing collaboration and sustainability gaps, and refining the model to foster regenerative innovation and advance the triple transition. However, further research is necessary to fully understand the underlying dynamics and overcome existing barriers.

4.9.2. Challenges of the 6HIM Model

Despite the policy expectations about the n-helix models, their practical implementation has faced difficulties and controversies (Etzkowitz and Zhou 2006; Leydesdorff, 2012; König et al., 2020). According to the comprehensive analysis conducted in this research on the n-helix innovation models and the interplay between innovation, sustainability and DT, the following caveats have been uncovered.

Caveats and Misconceptions about the n-Helix Models

First, the practicality of the n-helix models has been questioned, due to unclear conceptual aspects (Etzkowitz 2002; Leydesdorff and Meyer, 2003), insufficient definition of novel subsystems (e.g., civil society), along with scarce empirical support, making the implementation complex and uncertain.

There is a limited understanding of the intricate interrelationships and dynamics between the helices, which jeopardizes holistic and integrated outcomes (Cunningham et al., 2018; Galvao et al., 2019; Borghys et al., 2020; Köning, 2020). Novel dynamics from the digital disruption have changed the interlinkages across all spirals, and their adaptation is neither fully explored in literature nor understood.

The absence of standardized methodologies for effective collaboration among stakeholders, along with the limited means of measuring social impact have raised concerns about the overall effectiveness of digitalisation and innovation efforts. This may lead to fragmented collaboration and unclear outcomes.

Additionally, balancing conflicts of interest and power imbalances among stakeholders has posed significant challenges (Machado et al., 2018; Hasche, Höglund, and Linton, 2019). Indeed, an uneven distribution of influence can hinder the realization of sustainable and society-centric outcomes.

Also, insufficient support from policymakers and risk-aversion funding for multistakeholder and collaborative structures often hampers the scalability and long-term viability of novel approaches. In this regard, MacGregor et al. (2010) concluded that this lack of public involvement is prevalent in regions without strong science-based industries.

Another relevant barrier is the frequent resistance to change that arises when a novel approach is proposed, together with the marginalization or undervaluation of new actors from established subsystems. This reticence hampers the creation and circulation of innovative ideas and impedes inclusivity (Borghys et al., 2020), therefore is a strong barrier to regenerative innovation.

Furthermore, the idea of participatory democracy (Calzada, 2020) evokes concerns among dominant stakeholders, due to apprehensions surrounding a potential loss of control, trust, or governance challenges in a more decentralized decision-making process. This is a typical barrier in most collaborative environments that confront the status quo.

While helix approaches claim to support sustainability, the integration of both ecological and social sustainability values into innovation processes remains underdeveloped and is poorly embraced by traditional actors.

The triple helix approach, encompassing industry, academia, and government, still dominates the innovation landscape. Even the most advanced R&I programmes continue to treat sustainability as a peripheral aspect rather than the imperative priority that it should be.

Lastly, the adoption of helix models varies significantly across regions and sectors, uncovering underrepresented geographies and actors. This disparity poses challenges to achieving a truly pluriversal and inclusive approach.

In addition to these caveats, some criticisms of the helix model stem not from genuine barriers but rather from misconceptions and biased opinions. This dissertation argues that many of these critical voices are questioning broader traditional dilemmas of innovation, such as the "Ivory Tower Syndrome", the need for greater emphasis on applied science, the importance of trans-disciplinarity, enhanced cooperation, and meaningful participation from civil society.

These challenges reflect long-standing issues in innovation ecosystems that require careful consideration but are not a limitation of helix models but stem from narrow mindsets and resistance to change prevalent in the whole R&I landscape.

Confronting these misconceptions, studies have demonstrated the value of integrating these elements, showing that combining diverse knowledge streams from academia, industry, government, and civil society are not only compatible but also complementary. Indeed, this integration fosters better, more inclusive, and representative outcomes.

Therefore, these specific criticisms lack substantiation, as it has been proven that all modes of knowledge production can work together harmoniously to enhance innovation, and thereby, they can address more efficiently complex socio-ecological challenges than traditional conceptions.

Despite the controversies and critics, most scholars and studies claim that the triple helix model is not able to cope with the complexity of contemporary sustainable development and the disruptions of digitalisation, and further helices are needed to ensure the participation of all relevant actors and types of knowledge, such as civil society, the natural environment represented by environmental stakeholders and the digital sphere represented by digital players.

Nevertheless, the integration of novel actors and the hybridization dynamics is also overly complex and has not been fully addressed in the literature thus far. Therefore, all helix innovation models, face limitations in dealing with poorly understood interlinkages and dynamics among helices. This can be solved by further research and policy development.

Regarding the criticisms about the complexity of helix innovation models, particularly the six-helix model, this dissertation argues that the triple transition is not simple and cannot be represented through oversimplified approaches designed merely to make actors feel more comfortable.

Implementation barriers can be addressed through strategic, practical measures and further research. However, a simplistic, unrealistic, and unambitious approach, such as the triple helix, condemns the triple transition and regenerative innovation to remain mere concepts within academic papers.

Moreover, the challenges humanity faces are not simple, and natural ecosystems are inherently complex, requiring thousands of years to evolve. Therefore, while it is essential to provide lean approaches for facilitating gradual implementation, these must avoid inert oversimplification, disconnect from reality, and destined to fail. Innovation is rooted in change, in generating new ideas, and in transferring them to society.

Hence, innovation models must reflect and align with social dynamics to truly drive transformative progress. This requires a balanced approach between reality and lean implementation, as well as gradual and transitional approaches to translate innovative concepts into practice.

Helix models in general, and the 6HIM in particular, face both implementation barriers stemming from the inherent dynamics of collaboration among actors with differing priorities and the "valley of death" challenge in translating new ideas into practice.

Additionally, these models confront misconceptions and resistance to change from traditional actors and disciplines with siloed mindsets unwilling to embrace innovation's transformative nature. However, innovation inherently evolves alongside societal shifts, and the need for adaptive, inclusive approaches is gaining traction and is expected to keep permeating all realms.

Hence, to overcome these barriers and misconceptions, further research, education, stakeholder dialogue, and policy development are essential. Sandbox environments, pilot programmes and initiatives can serve as test beds for testing and scaling the 6HIM model and offer more tangible evidence of its potential.

These efforts can bridge gaps, address resistance, and build the empirical evidence needed to demonstrate the feasibility of the proposed model in real-world contexts. Both theoretical exploration and empirical development are critical to unlocking the 6HIM's capacity to drive regenerative innovation and align with the broader goals of the triple transition.

Unlocking the Potential of the 6HIM model

Considering the insights gained and their implications regarding previous literature, the 6HIM model represents a fresh paradigm, closely aligned with a digitally empowered and regenerative society. It captures the multifaceted contemporary complexities and dynamics of innovation and addresses the unprecedented regenerative triple transition.

Therefore, it is well-positioned to address the "seventh wave of innovation," which emphasizes sustainability, progressing beyond the sixth wave centred on digitalisation, as suggested by Silva and Di Serio (2016). Nevertheless, several controversies identified in the literature deserve further discussion.

While the helix innovation models represent a paradigm shift, holding great expectations for unleashing the power of R&I for positive eco-societal impact, their implementation meets with controversies and barriers as argued by König et al. (2020). Indeed, the practicality of helix models has been questioned due to insufficient definition of novel subsystems and limited empirical support.

The findings align with Galvao et al. (2019) and Borhgys et al. (2020) about the current limited understanding of interrelationships between helices, jeopardizing the subsequent outcomes, especially those related to digital disruptions.

Nevertheless, most barriers are not unique to helix models but are typical of collaborative, groundbreaking environments. Challenges include the lack of methodologies for fostering collaboration and measuring social impact, conflicts of interest, and power imbalances (Machado et al., 2018; Hasche et al., 2020), insufficient support from policymakers (MacGregor et al., 2010), and risk-averse funding models that limit scalability (EC, 2024a).

These challenges could be effectively mitigated through further research, practical innovations, and the implementation of supportive policies and incentives that encourage risk-taking and foster cross-sector collaboration.

Additionally, existing misconceptions can be addressed through stakeholder dialogue, education, awareness-raising, and the introduction of appropriate incentives. For instance, resistance to change, the marginalization of emerging actors (Borghys et al., 2020), and concerns about participatory democracy (Calzada, 2020). Moreover, the undervaluation of trans-disciplinarity and cooperation frequently arises when innovative approaches challenge the status quo, underscoring the need for a shift in both mindset and governance.

Critics of collaboration and co-creation can be contested, as the literature consistently demonstrates that these approaches not only foster innovation but also provide effective mechanisms for managing conflicts and addressing power imbalances. Certainly, collaborative, and “multidimensional” innovation are gaining momentum in programmes such as Horizon Europe.

Further empirical research on the interrelations among the different helices, as well as the role of intermediaries, is essential to achieve better implementation outcomes and gain a clearer understanding of the hybridization dynamics within helix models and their transformative potential.

In addition, policy alignment is critical for further testing and scaling the helix model and securing the necessary support for its implementation. Therefore, it is evidenced that policies must integrate and prioritize the active participation of multiple stakeholders and regenerative sustainability to ensure that regenerative and inclusiveness objectives are met, and the triple transition is considered, to unlock the full potential of the 6HIM.

Notwithstanding the controversies, this research aligns with other scholars about the imperative to integrate further helices to address the complexities of contemporary digital and sustainability challenges. However, this research underscores that the dynamics within the traditional triple helix model (academia, industry, government) also remain opaque, and the interactions between conventional actors, such as university-enterprise collaborations, remain limited in many contexts.

The limitations regarding the participation of civil society agents are multivariate and not solely attributable to the caveats of the helix models but are also influenced by power inertias, lack of local capacities, resistance to change and fear of democracy, similar to the issues encountered during the transition from Mode 1 to Mode 3 of knowledge production (Gibbons, 1994).

Gibbons described the Modes of Knowledge et al. (1994) as follows: mode one was focused on basic research and traditional disciplines (19th and 20th centuries). Mode 2 was devoted to applied research to tackling societal challenges, trans-disciplinarity, and collaboration (20th and 21st centuries). Mode 3 was driven by blended knowledge created from global innovation networks and diverse sources (21st century).

Furthermore, systemic transformations are always complex to implement and demand policy and societal support for being successful. The quadruple and quintuple helix models are relatively new frameworks in innovation systems and, as such, require time to challenge established norms and consolidate their role. Overall, to be able to pursue a regenerative triple transition, all relevant helices should be properly integrated and understood, and this task is potentially as complex as the SDGs themselves (König et al., 2020).

Mainstream R&I and respective initiatives are still driven by triple helix approaches, easier to implement due to their lower complexity and longer legacy. Nonetheless, in the long term, a sextuple helix model will bring further societal, environmental, and economic value, promoting regenerative sustainability, and social cohesion and reinforcing legitimization and trust. Winds of change are evident as innovation processes evolve, increasingly integrating partnerships, living labs, open data, and digital-based citizen applications such as crowdsourcing. The rise of co-creation on digital platforms, user-focused agile management, eco-innovation, and social innovation further emphasizes the growing complexity of innovation ecosystems.

Hence, it is evidenced that the proposed 6HIM holds the potential for greater societal, environmental, and economic value in the long term, promoting equitable and regenerative development adapted to the digital era and the unfolding eco-social transitions. The participation of the community and the convening of all actors, including the natural environment and the digital sphere, strengthens a realistic approach to the common good, allows synergies and cooperation to tackle wicked challenges, and drives equitable growth, envisioning an innovation model oriented to people and the planet.

Therefore, it is imperative to rethink current innovation models and evolve existing policies and programmes, along with obsolete mindsets, to align with the regenerative triple transition materialised within the 6HIM.

Moreover, these findings not only address the existing controversies but also underscore the opportunities presented by the seventh wave of innovation, driven by the regenerative vision.

In this light, this research emphasizes the role of non-traditional, catalytic, frugal, and grassroots innovations (Christensen et al., 2006) for their value in driving co-created value and systemic eco-social transformations (Benitez et al., 2020). Besides, non-conventional innovations are driven by alternative players who approach problems with fresh perspectives, leading to disruptive changes and systemic transformations in line with the ambition of the 6HIM model.

Furthermore, as previously described, Smart Sustainable Cities (SCC), and Smart Energy Communities (SEC) exemplify the 6HIM principles, in which digitalisation can serve as an eco-social changer, empowering communities to drive regenerative transformations.

Therefore, this research argues that the legitimization of a more systemic helix approach is relevant to ensure regenerative solutions with positive eco-societal impact. Understanding lessons learned in these communities will be crucial for the implementation of the 6HIM in other contexts. It also underlines that digital ecosystems and communities of practice, such as the DIHs, Eco-hubs, and Living Labs, could play the role of transition brokers of the triple transition by embracing the 6HIM principles. They offer exceptional opportunities to enable ecosystems to test and scale the 6HIM and foster regenerative innovation.

Additionally, this research suggests that the transition brokers (Cramer, 2020), as key intermediaries facilitating interstitial knowledge circulation and collaboration across organizational boundaries, are crucial to overcoming current misconceptions and implementation barriers, towards promoting regenerative eco-social transitions by the 6HIM. The proposed model is also aligned with the vision of a Society 6.0 “smart and sustainable” and offers a transitional pathway to bridge current conceptual and empirical gaps and move this intriguing vision forward.

Hence, the 6HIM represents a transformative opportunity to align innovation ecosystems with the regenerative triple transition, addressing complex societal, environmental, and digital challenges. Nevertheless, further research, particularly empirical experimentation, is essential to refine the understanding of dynamics among helices and transition brokers, facilitating more efficient implementation.

The 6HIM model and the paradigm of regenerative innovation must confront barriers, misconceptions, and dilemmas inherent in challenging traditional mindsets. Overcoming these obstacles requires ambitious policy development and alignment, strategic incentives, inclusive dialogue, and concerted efforts from all stakeholders, to unlock the full potential of this transformative framework.

It is important to note that part of the findings presented in this chapter have been included in an article that was presented at the ICSD 2023 Conference: Del Río Castro, G., Uruburu Colso, Á., González Fernández, M. C. (2023). *A digital, green, and socially fair future: Unravelling the triple transition with a pluriversal sextuple helix model of innovation for sustainable development in the age of digitalization*. International Conference on ICT for Sustainability. 11th International Conference on Sustainable Development (ICSD) 2023, 19th–20th September 2024, New York, United States.

The next chapter addresses one of the key contributions of the dissertation, the proposal of Taxonomy for promoting a Sustainable and Regenerative Digital Transformation.

5. Proposal of Taxonomy for Sustainable and Regenerative Digital Transformation

This chapter establishes the context for substantiating a proposal of Taxonomy for Sustainable and Regenerative Digital Transformation (SRDT). It begins with an overview of the relevance of the taxonomies in the fields of sustainability and digital transformation, followed by a review of existing frameworks for assessing these realms, and a gap analysis regarding their alignment with the research objectives. Subsequently, the primary dimensions and elements of the proposed Taxonomy are examined in detail. The resulting taxonomy is then proposed and further explained, underlining its contributions, and added value to the research field. Lastly, a reflection and concluding remarks are provided.

5.1. Introduction to the Research Context of the Taxonomy for SRDT

As described in previous sections, it is necessary to clarify the key domains and determinant factors that characterize a sustainable and regenerative digital transformation. Considering the significant misalignment between the sustainability and digital agendas and governance frameworks, along with the insufficient reflection of environmental and social aspects in current digital development, it is imperative to fill this gap with a structured and holistic construct.

The current lack of clarity regarding what constitutes a sustainable digital transformation creates gaps in the understanding of how digital paradigms are impacting sustainability goals for good and bad. This hinders the development and implementation of effective strategies and interventions to seize digital opportunities while mitigating the inherent social and environmental risks.

The proposed Taxonomy for SRDT aims to bridge existing gaps, fragmented views, and misaligned agendas that hinder the understanding and governance of the interplay between regenerative sustainability and digital transformation. It provides a structured and comprehensive framework to categorise the determinant factors and domains that must be considered when approaching this promising nexus. Thus, it ensures a holistic approach that integrates environmental, social, governance, and economic dimensions which are crucial for driving the regenerative triple transition.

In terms of novelty and contribution to the research field, as far as is known, there is no similar framework documented in the existing literature, and the proposed Taxonomy for SRDT represents the first structured and comprehensive approach in providing the determinant factors of the triple transition - digital, environmental and socially just - with regenerative perspective.

From a practical viewpoint, the proposed Taxonomy for SRDT serves as an actionable tool since it facilitates more informed decision-making by providing a comprehensive and structured framework that categorises the critical factors for the triple transition. It enables policymakers, practitioners, and researchers to identify key factors necessary for aligning their interventions with the vision of a sustainable and regenerative digital transformation.

Furthermore, the proposed Taxonomy would support the alignment of the strategies and interventions with the priorities outlined in the 2030 Agenda and the digital initiatives like the Global Digital Compact. It ensures a more holistic, inclusive, and effective approach, by explicitly integrating the environmental and social dimensions with regenerative perspectives, which are currently overlooked or inconsistently represented in dominant frameworks for both digital transformation and sustainability.

The proposed Taxonomy also provides a foundation for better informing targeted policies, supporting policymakers and researchers to better evaluate and measure progress toward a truly sustainable digital transformation aligned with the SDGs and regenerative principles.

In the following sections, the state of the art on existing taxonomies and measuring frameworks for both sustainability and digital transformation is presented. This background is followed by an overview of the gap analysis conducted, which served as the foundation for the development of the Taxonomy for SRDT.

5.1.1. The Role of Taxonomies in the Sustainability and Digital Realms

A concise introduction to the role of taxonomies in the environmental sustainability and digital realms is provided as follows, to illustrate their relevance and underline the added value of the proposed contribution of this dissertation in relation to the research field.

Taxonomies have served as essential tools in sustainability, by providing structured frameworks for classifying and organizing complex concepts, thereby facilitating more informed decision-making and governance.

However, in the context of the interplay between digital transformation and sustainability, there is no taxonomy or similar framework that systematically structures and integrates the environmental, social, governance, and economic dimensions relevant to this domain.

A taxonomy is defined as a scientific process of classifying things based on shared qualities. It serves as a hierarchical scheme for organizing entities. Initially exclusive to classified organisms in biology, taxonomies now extend to categorizing various concepts and phenomena, including sustainability indicators and digital innovation projects. These frameworks facilitate information classification, organization, and knowledge diffusion across disciplines.

Certainly, taxonomies have become crucial tools in environmental monitoring, by enhancing the understanding of complex research fields and promoting better-informed decision-making.

In the realm of sustainability, taxonomies play a crucial role in classifying circularity indicators (Saidani et al., 2019), and in assessing the sustainability of economic activities exemplified by the widely recognized “EU Taxonomy for Sustainable Activities”, commonly referred to as the “Green Taxonomy” (EC, 2021c).

Therefore, as argued by Schütze and Stede (2021), taxonomies in the environmental sustainability domain also serve to establish criteria for climate change mitigation or adaptation, minimum social safeguards, and the avoidance of harm to environmental objectives, thereby enhancing the transparency and accountability of sustainability claims.

In the realm of digital transformation and innovation, taxonomies, though more recent, are also supportive in understanding projects (Hermann et al., 2023), classifying AI approaches in Industry 4.0 (Farhan et al., 2023), aligning methods in knowledge organization systems for objects (Mohamad et al., 2023), or in organising open government data and smart mobility services (Cledou et al., 2018).

Notably, Hermann et al. (2023) developed a taxonomy to facilitate digital innovation projects in Small and Medium Enterprises (SMEs), providing a valuable tool for classifying and understanding such initiatives. Similarly, Farhan et al. (2023) proposed a taxonomy for AI in Industry 4.0, classifying approaches of design and quality control, emphasizing the role of Artificial Intelligence in the context of extensive data generated by Industry 4.0. Complementing these studies, Newman (2023) developed a taxonomy focused on AI trustworthiness, while Gill et al. (2020) addressed Quantum Computing.

Furthermore, Reuel et al. (2024) proposed a taxonomy for categorizing technical AI governance into capacities (i.e., assessment, access, verification, security, operationalization, and ecosystem monitoring) and targets (i.e., data, computing, models, and deployment). Their taxonomy aims to guide researchers and policymakers in addressing these challenges and enhancing the governance of AI systems.

The use of taxonomies in the domain of information systems (IS) is also noteworthy and expanding. In this sense, Nickerson et al. (2013) addressed the challenge of classifying objects in IS, suggesting a taxonomy tailored for this domain. Cheng and Xia (2023) conducted a literature review on taxonomy alignment methods, providing methodological guidelines for future research in the field of knowledge organization systems.

Moreover, taxonomies are employed in the classification of research areas, such as open government data (OGD) research (Mohamad et al., 2023), and smart mobility services planning and design (Cledou et al., 2018). Thus, it is evident that taxonomies contribute to a more systematic understanding of intricate and novel complex domains by organizing information, enhancing knowledge dissemination, and aiding decision-making processes.

Overall, the taxonomies represent indispensable tools in the realms of sustainability, digital transformation, and research and innovation. They provide structured frameworks for categorizing, characterizing, and classifying knowledge about intricate domains, ultimately enhancing the understanding and insights about them. This, in turn, supports governance in these areas.

Building on the existing knowledge and the in-depth analysis conducted, this dissertation proposes that the intersection of regenerative sustainability and digital transformation can greatly benefit from the creation of a specific and structured taxonomy. This approach will contribute to a more nuanced and comprehensive understanding of the interplay between both realms, and a more effective and coherent governance of this promising, yet underexplored, nexus.

In conclusion, in light of the state-of-the-art findings, the existing literature reveals that a taxonomy in this specific context has not yet been developed, underscoring the relevance and novelty of the contribution made by this dissertation.

5.1.2. Assessment Frameworks for Digital Transformation and Sustainability

The following section provides a concise overview of the existing frameworks for assessing digital transformation and sustainability, along with their intersection, underlining the challenges and synergies that require attention. First, an overview of the challenges in digital transformation frameworks is presented, with a particular focus on the lack of integration of sustainability considerations. Following this, an overview of sustainability frameworks is provided.

Together, they expose the caveats that motivate the development of more comprehensive and integrative approaches to address the interplay between both realms.

In the context of impact assessment, guiding principles offer strategic direction, frameworks provide structured foundations, standards establish essential guidelines, methodologies support informed decision-making, and indicators serve as quantitative or qualitative tools for assessment.

Furthermore, evaluating impact requires assessing transformative changes in both scalability and depth among the stakeholders and the context in which an intervention takes place. Thus, it is essential to appraise the potential contributions of the interventions within a counterfactual context, understanding the distinctive influence and added value they provide (San Pedro and Ballesteros, 2021).

Assessment Frameworks for Digital Transformation

The existing literature on the assessment of digital transformation (DT) and its societal impact covers a wide range of heterogeneous themes. However, most existing studies tend to focus on very specific aspects, mainly related to technological issues and governance, leaving a fragmented and incomplete literature landscape that lacks cohesion.

For instance, Bruno et al. (2023) proposed a composite indicator for measuring the digital divide. Caro-Gonzalez et al. (2020) underlined the unintended consequences of digital trends on labour, while Pawlowski and Scholta (2023) addressed the lack of conceptual clarity in digital governance.

This fragmentation and lack of consistency are intensified by the absence of coherent definitions and clear boundaries regarding the scope, dimensions, and determinant factors of digital transformation. As argued by Xiaoli and Weiging (2022) and Chawla and Goyal (2022), the lack of a comprehensive definition and depiction of the broad implications of DT is aggravated by the absence of frameworks for assessing the sustainability and ethical impacts.

In this regard, Vial (2019) defined DT as a process driven by disruptive digital technologies, prompting strategic responses from organizations to alter their value creation paths, addressing structural changes with a consideration of dynamic capabilities and ethical concerns. Certainly, the literature described digital technologies as inherently disruptive (Karimi and Walter, 2015), impacting behaviours, and communication capabilities, and reshaping business models by bringing disintermediation, new actors, and networks (Chawla and Goyal, 2022).

Studies addressing the assessment of digital transformation and its disruptions and impacts as a broad phenomenon remain scarce in the scientific literature. Consequently, the literature fails to provide a panoramic view of the DT phenomena that would enable a comprehensive and effective monitoring and impact assessment.

The rapid pace of digital transformation has outshined theoretical development, resulting in frameworks that are insufficient for guiding its effective implementation and governance.

Taylor (2007) also underlined the methodological challenges in measuring digitalisation, particularly in models assessing the “e-society”, digital divide, and “e-readiness”, underscoring the need for robust, multidimensional measurement approaches. In this regard, the intangible nature of certain aspects of digitalisation related to knowledge and information poses challenges due to conceptual ambiguity. International organizations like ITU and OECD have developed integrated models to include some social aspects, but existing indicators exhibit weaknesses, conceptual imprecision, and measurement issues.

Indeed, most assessment frameworks for DT have been developed by governmental bodies, international organisations, and practitioners from the digital realm, lacking multidisciplinary perspectives and holistic approaches.

In addition, these frameworks, such as the European Digital Economy and Society Index (DESI) (EU, 2023a), ITU indices for digital development, and OECD reports (2022; 2019d) for measuring digital transformation, are predominantly focused on technological, economic, and narrow governance aspects, frequently overlooking other relevant sustainability dimensions.

This gap is especially problematic concerning environmental sustainability, as this dimension is frequently overlooked, while the social aspects are receiving only minimal attention. Some scholars caution against the prevailing naive perspective on the impacts associated with sustainability within the digital realm, as presented in existing frameworks (George et al., 2020).

Furthermore, the scarce literature also presents contradictory views. While some researchers suggested that DT promotes sustainable impacts (Feng et al., 2022), others contended that it may hinder them (Ning et al., 2023). Social aspects are also under-researched as argued by Szalkowski and Johansen (2024), who explored the effects of digital technologies on social sustainability.

While recognizing the potential benefits of DT, most scholars stressed the need for more dynamic perspectives in addressing the digital phenomena. Besides some scholars also advocated for a shift from a static perspective to a dynamic vision of the triple transition (Dobrolyubova, 2021).

In conclusion, the existing limitations in the currently available assessment frameworks for digital transformation stem from the insufficient development of both theory and literature in terms of measuring digital phenomena with a systemic perspective. Existing frameworks overlook sustainability aspects, especially the environmental dimension.

This underlines the need for more integrated and comprehensive studies that provide a cohesive and comprehensive perspective on the key factors of digital development across all relevant dimensions of society, including environmental sustainability aspects. Additionally, there is a critical need for robust theoretical approaches and assessment frameworks specifically designed to navigate the complex interplay between digital transformation, sustainability, and societal change.

Frameworks on the Interplay between Digital Transformation and Sustainability

When it comes to assessing the interplay between digital transformation and sustainability, recent research underscores the inadequacy of existing frameworks and metrics, since they typically focus on either the digital aspects or sustainability issues independently, neglecting their interconnected dynamics. The evolving measurement frameworks lag behind the rapid changes in digital and sustainability phenomena, resulting in an incomplete reflection of societal changes driven by the data deluge and increased computational power. Moreover, when sustainability is integrated into digital transformation frameworks, it is often treated superficially, merely as an additional component, rather than as a core element.

In this regard, Fuchs (2006) advocated for indicators that go beyond economic parameters to evaluate the ecological, social, and institutional sustainability of ICTs, providing a more comprehensive understanding of what constitutes a sustainable information society. This scholar emphasized the role of policy interventions to steer digital transformation toward positive societal outcomes, by promoting inclusive participation and risk mitigation. Yet, policy interventions need science-based information to be well-addressed.

Notably, few scientific studies have explored the interrelations between digital and sustainability indicators. For instance, Gallucci et al. (2019) used the Granger Causality Test to understand the interrelationships between ICTs and environmental indicators, aiming to drive green growth and promote environmental services. Popovs and Drinke (2022) argued that sustainability can be effectively assessed by using digital solutions like sustainability analytics. They proposed a reciprocal relationship where sustainability initiatives not only leverage digital transformation but also drive it, creating a mutually reinforcing cycle.

Pérez-Martínez et al. (2023) argued that while digitalisation influences various domains, its impact on sustainability, especially environmental SDGs, remains unclear, presenting severe trade-offs. These scholars underlined non-causal correlations and ongoing controversies, emphasizing the complex nature of this interplay.

Therefore, the expected environmental benefits of digitalisation, particularly in dematerialization, efficiency and decarbonization, have not materialized as anticipated and its net contribution remains enigmatic and requires a critical reassessment, which is not possible with current frameworks. Thus, the persistent illusion of ICTs as magical and immaterial tools necessitates a critical reassessment of their impact on sustainability.

The current lack of scientific studies in this field contradicts recent policy advancements, as some digital strategies are beginning to acknowledge the relevance of social and environmental aspects. However, these advancements are not being translated into practical implementation, and the corresponding measurement frameworks still overlook sustainability metrics. Consequently, the integration of sustainability remains superficial and is not effectively measured.

For instance, the EU's Digital Decade Communication (2021B) emphasized a human-centred, sustainable, and prosperous digital future within a global context. This strategic vision prioritizes human welfare, sustainability, and prosperity in the transformative digital landscape envisioned for the next decade. However, the respective DESI Index (EC, 2023d) does not include any sustainability metric.

The CODES coalition (CODES, 2022) introduced a foundational framework for digital development, stressing the need to consider environmental sustainability in DT. This initiative recognizes various multi-stakeholder initiatives, standards, and regulatory frameworks in the digitalization-sustainability domain, acknowledging the need to bridge existing gaps for a more responsible digital future. CODES underlined the importance of standards for measuring environmental impacts and creating connectivity between digitalisation and sustainability to overcome current fragmentation and caveats.

In essence, the analysis performed identified a significant gap concerning the integration of sustainability aspects and metrics within digital transformation frameworks and vice versa, emphasizing the need for a novel comprehensive and integrated approach. The research also calls for a broader measurement scope, considering the triple transition dynamics, and addressing data gaps in understanding the broader implications of digital transformation.

Hence, it is essential for research institutions, and policy bodies, alongside international organizations to advance assessment frameworks for DT, placing a stronger emphasis on both environmental and social transitions. Furthermore, sustainability frameworks should thoroughly integrate the unique challenges and opportunities of digitalisation.

Assessment Frameworks for Sustainability and Sustainable Development

The sustainability domain has a robust tradition of creating frameworks to assess the triple bottom line, demonstrating a long-standing commitment to comprehensively gauge economic, social, and environmental impacts. Indeed, diverse frameworks contributed to a comprehensive evaluation effort in the sustainability realm. This encompasses principles (e.g., IFC), indices (e.g., SDG Index, EPI Index), standards (e.g., GRI, SASB, EFRAG), methodologies (e.g., IRIS+), and indicators (e.g., Circular Indicators WBCSD, 2023; EAP, 2023).

Notable sustainability frameworks include the Global Sustainable Competitiveness Index (SolAbility, 2023), the Competitive Sustainability Index (Cambridge University-CSIL, 2022), the EPI Index (Yale, 2022), EEA indicators (EEA, 2023), among many others.

The SDG Index (Sachs et al., 2024) is also widely recognized as a benchmark for assessing progress on the SDGs, yet it has also faced criticism as described in Chapter 2.

Nevertheless, none of these frameworks adequately address the scope and dimensions of Sustainable and Regenerative Digital Transformation (SRDT) in an integrated manner, across all scales and relevant dimensions. Additionally, according to Cambridge University (2022), sustainability is often treated as an “add-on” in most assessment frameworks unrelated to this field such as competitiveness, as they were not originally designed with this domain in mind.

Similarly, environmental frameworks often lack a consideration of digital aspects. For instance, the EAP indicators (EEA, 2023) are crucial for assessing environmental sustainability within planetary boundaries, emphasizing circularity and regeneration linked to human well-being, and extending beyond environmental aspects to include socioeconomic factors. They encompass various dimensions, including environmental pressures, enabling conditions, and living well indicators. Yet, these indicators lack coverage of digital dimensions, as they were designed to address ecological aspects.

Cambridge University (2022) examined the relationship between sustainability and competitiveness across various indices, finding that these dimensions remain largely disconnected, with significant gaps hindering their potential synergies. The study also highlighted that the frameworks developed by governmental organisations, such as the European Commission, are generally more robust compared to those created by private entities.

In addition, the “Transitions Performance Index” (EC, 2022b), addresses the transition toward sustainable prosperity with a comprehensive, yet summative approach. Yet, this framework also lacks the “competitiveness” dimension.

The Competitive Sustainability Index (Cambridge University – CSIL, 2022) introduced nuanced metrics for European countries, endorsed by the Joint Research Centre, including a few digital aspects such as broadband, skills, e-government services, and cybersecurity.

However, the ecological dimension in sustainability frameworks, including this advanced index, often lacks depth, since it is overly focused on resource productivity, and overlooks broader ecological aspects.

Another sort of framework is the MSCI Global Environment Index (2023) which serves as a classification tool for investments, recognizing companies generating 50% more revenue within the renewable energy, energy efficiency, water, green building, and pollution prevention domains.

Additionally, the MSCI Sustainable Impact Metrics Taxonomy (2019) covers environmental and social impacts, with the “empowerment dimension” addressing connectivity and the digital divide. The MSCI ACWI IMI Sharing Economy Index (2021) comprises companies fostering a circular transition, spanning the sharing economy, smart mobility, e-commerce, social media, digital payments, and cloud computing. In this regard, the sustainability finance sector, driven by legislative momentum (e.g. EC, 2019), is integrating digitalisation with advancements in analytics, Big Data Analytics and Artificial Intelligence.

The conclusion suggests that sustainability frameworks, while advancing, still face notable gaps in addressing the impacts of the digital age, with environmental frameworks aligning more strongly with social aspects than ecological issues. Additionally, existing frameworks do not consistently integrate regenerative sustainability approaches, underscoring the need for further consideration and development in this area. Furthermore, the environmental frameworks exhibit stronger alignment with social aspects than social frameworks with ecological issues.

The exposed challenges and ongoing controversies emphasize the need for greater accountability through novel comprehensive frameworks that accurately capture and reflect the intricate dynamics between digital transformation and sustainability aspects.

Reflections on the existing frameworks for digital transformation, sustainability, and their interplay

Examining the measuring frameworks addressing the interplay between digital transformation and sustainability, two significant divides among disciplines are observed: A disconnect between social and environmental research fields, and a substantial divide between the environmental and digital realms. Addressing these disparities and disconnections calls for a more integrated approach that harmonizes the interconnections between social, environmental, and digital dimensions, towards creating a sound and coherent articulation to advance the triple transition.

Concerning the disconnection between social and environmental realms, a clear example is the Human Development Index (HDI), which has been criticized for neglecting the environmental dimension, rewarding major polluters based solely on income. Hickel (2020) proposed a Sustainable Development Index (SDI) that incorporates ecological impacts, for addressing the limitations of the HDI, by offering a stronger sustainability approach.

However, both Hickel (2020) and O'Neill (2018) argued that these approaches may still fall short of planetary boundaries, which in the end merely offer a narrow vision of sustainability. Prioritizing development solely with a socioeconomic lens and dismissing the interconnections to biophysical systems, has led to adverse environmental effects, contributing to biodiversity loss, ecosystem damage, and climate change which in the end also hinder human development (Pérez-Martínez et al., 2023; Nicholson et al., 2021; Kroll et al., 2019; Warchold et al., 2021; Zeng et al., 2020).

While some scholars argued that planetary targets are secondary to social justice, an evolving school of thought suggested that integrating biophysical targets by reflecting planetary boundaries is essential for risk management and leads to greater social justice (Hulme, 2020; Gupta et al., 2021).

Gupta et al. (2021) advocated for qualifying environmental targets with justice considerations, aligning them with the SDGs to manage synergies and trade-offs between social and environmental aspirations. These scholars stressed the interconnectedness of social and ecological issues, emphasizing the need for a comprehensive transformation that incorporates justice and ecological criteria.

Collaborative efforts to integrate planetary justice with planetary boundaries are judged crucial for a successful and comprehensive transformation towards a more just and ecologically sustainable future. The research underscored the importance of bridging disciplinary divides and inequalities to avoid overexploitation and promote a harmonious relationship between social and ecological concerns.

Regarding the disconnection between digital transformation and sustainability, thus far, the literature has ignored that DT is not a linear process and entails social changes. Digital advancements did not always lead to a fairer society since they may generate unintended consequences like environmental damage and social exclusion. Governance challenges in digital ecosystems necessitate a comprehensive approach, combining top-down and bottom-up strategies.

Indeed, the digital ecosystems and communities act as transformative and collaborative forces addressing global issues, fostering connections between technological, social, and environmental realms.

Therefore, these digital dynamics that illustrate the intertwined relationship with sustainability must be reflected in the assessment frameworks, in the same way they are beginning to be integrated within high-level strategies.

Another aspect that deserves further exploration in this field is the concept of "Dynamic Materiality". Introduced by CFA (2023), the dynamic materiality notion emphasizes continuous reassessment of material aspects for organisations in the evolving landscape of ESG factors. The notion of "double dynamic materiality" in the digital realm underscores the need for a holistic perspective, considering both internal and external impacts and could be useful to provide a more comprehensive approach to SRDT.

In conclusion, the measurement and impact assessment frameworks for digital transformation and sustainability must evolve to achieve strong alignment towards more inclusive and holistic approaches capable of evaluating progress towards the Sustainable and Regenerative Digital Transformation (SRDT) and the triple transition.

5.1.3. Gap Analysis on Existing Frameworks for Sustainability and Digital Transformation

In this research, a meticulous mapping and examination of the most relevant frameworks available for digital transformation, innovation, and sustainability, as well as their interplay, was conducted, revealing crucial insights. First, a thorough mapping was conducted to identify the most relevant frameworks to examine, followed by their categorization and codification.

This process included a preliminary analysis of their dimensions (primary areas comprised), scope (e.g. global, European, sector-specific), scale (micro, "meso," macro), and components (themes covered). Subsequently, these frameworks were prioritized on a 1–3 scale according to their relevance to the research objectives. This prioritization informed the selection of the most pertinent documents for a more in-depth analysis which later served as the foundation for developing the proposed Taxonomy.

Furthermore, a gap analysis was carried out in parallel on this corpus of documents, unveiling the gaps in this context. The overall results are presented as follows.

The framework selection followed the methodological guidelines suggested by Cambridge University (2022), UNDP (2021; 2023), and Lai and Cole (2022). In this regard, Cambridge University (2022) conducted a comprehensive gap analysis of sustainability and competitiveness indices to identify research gaps and select the most suitable framework for developing a Competitive Sustainability Index (CSI). Their approach focused on understanding the core limitations of existing indices to create a more focused and streamlined framework, resulting in a novel index which included a few indicators related to digital transformation.

Similarly, UNDP (2021; 2023) proposed the Digital Development Compass (DDC) by identifying key pillars and sub-pillars representing the principles of inclusive digital development across countries. Additionally, the DDC incorporates a Theory of Change, outlining progress across five distinct digital maturity levels. Overall, it serves as a valuable tool for understanding the current digital landscape opportunities and challenges.

Lai and Cole (2022) emphasized the importance of a careful selection of themes, levels of measurement, and scope of coverage. These scholars underscored the challenge of ensuring equivalency in frameworks, especially regarding measurement scales and geographical scope.

Their research explored six comparable indices and introduced nine categories for holistic assessment, underlining the need for context-sensitive measurements that accommodate the diverse realities of urban environments. This study proposed a framework integrating both "hard" and "soft" domains for assessing progress in smart cities.

Ultimately, these methodologies underscored the importance of selecting frameworks that balance scalability, contextual relevance, and comprehensive coverage, especially in complex areas like sustainability and digital transformation.

Therefore, in this research, a total of 355 frameworks (i.e., indices, benchmarks, strategic assessment reports, research reports, and standards) were mapped and preliminary analysed. Among these, 292 were predominantly focused on digital transformation, forty-six on environmental sustainability, twelve on social aspects, and five on sustainable development encompassing both the environmental and social dimensions (e.g., approaches focused on the SDGs).

Additionally, 335 scientific articles (peer-reviewed), specifically addressing digital and sustainability-related themes, were also analysed.

Concerning the digital transformation frameworks analysed, 60% of the respective approaches did not address sustainability aspects, 15% mentioned it only as a superficial aspiration or general context, and just 25% explicitly addressed, at least, one relevant aspect of sustainability. As a result, the majority (75%) of these frameworks lack a comprehensive integration of sustainability considerations.

Additionally, when analysing digital frameworks integrating sustainability-related aspects, it was found that approximately 20% focused on climate-related aspects, 40% covered general environmental issues, 8% addressed e-waste, 6% was dedicated to energy issues, and 7% explored circularity measures.

Moreover, specific aspects concerning the sustainability of digital transformation are poorly addressed. Only a few documents touched on other environmental issues, such as electromagnetic impacts or the rebound effects of ICTs, and none incorporated regenerative principles.

It is noteworthy that numerous digital transformation frameworks included a few social aspects, such as inclusiveness, human rights, or literacy. However, most failed to recognize the interconnectedness between digital, social, and environmental aspects.

The summary of the gap analysis of digital transformation frameworks concerning their coverage of sustainability aspects is provided in Table 5.1.

Table 5.1. Summary of the Gap Analysis of Digital Transformation Frameworks
(Own elaboration)

Gap Analysis of Digital Transformation Frameworks	
Sustainability Aspects Coverage	Percentage of Frameworks
A. Did not address sustainability	60 %
B. Addressed sustainability as a general aspiration or context	15%
C. Explicitly address, at least, one relevant aspect of sustainability	25%
Climate-related aspects	20%
General Environmental Aspects	40%
Electronic Waste	8%
Other Aspects	32%

Regarding the environmental sustainability-focused frameworks examined, 28% integrated at least one relevant digital aspect, and 30% also addressed social dimensions. Conversely, social frameworks showed lower integration of digital aspects (27%), and only 9% incorporated environmental considerations.

These findings underlined a significant gap in the literature, reflecting a clear disconnect between social and environmental disciplines, and insufficient integration of key digital aspects for sustainability. Besides, a lack of “pluriversal” perspectives was also found.

While sustainability frameworks are gradually incorporating a few elements of digital transformation such as basic connectivity, along with a few social considerations, they still fall short of supporting a comprehensive triple transition. Additionally, the regenerative perspective is not consistently applied even in the sustainability realm.

The summary of the gap analysis of sustainability and sustainable development frameworks concerning their coverage of digital aspects, alongside environmental and social issues is provided in Table 5.2.

Table 5.2. Summary of the Gap Analysis of Sustainable Development Frameworks
(Own elaboration)

Gap Analysis of Sustainability and Sustainable Development Frameworks			
Framework Focus	Percentage of Frameworks Integrating Digital Transformation	Percentage of Frameworks Integrating Environmental Aspects	Percentage of Frameworks Integrating Social Aspects
Environmental Sustainability	28%	100%	30%
Social Sustainability	27%	9%	100%

Consequently, the findings revealed that the interplay between digital and sustainability transitions, as well as the triple transition paradigm, remain largely overlooked in the research landscape and practice, and invisible in policy agendas.

This underscores the urgent need for a more comprehensive and integrated approach, that fully reflects the environmental and social implications within the broader digital risk and impact assessment landscape, and vice versa.

A more holistic and cohesive framework is also essential to bridge these gaps and align digital transformation and sustainability efforts in the same direction towards achieving a regenerative triple transition.

Turning the attention to the scale of the analysed frameworks the majority focused on the “macro” level (i.e., countries, regions), often targeting global or European contexts. In contrast, the “micro” level (i.e., companies, organizations, individuals) was mainly covered through documents or indices related to ESG standards or circular economy indicators.

Notably, the “meso” level (i.e., sectoral) was the least represented, revealing a significant gap in the literature. This landscape underscored a clear disparity, as most frameworks adopted a macro perspective, even though the primary impacts often occur at the micro and “meso” levels. An overview of this analysis is shown in Table 5.3.

Furthermore, when examining the origin of these frameworks, the prevailing indices are global (94%), with only 6% originating from Europe, and a limited number from other contexts such as the USA. Multilateral and international organizations, along with the European Commission, are the primary developers, revealing a lack of diverse representation, particularly from stakeholders in the Global South.

Table 5.3. Overview of the Gaps of the Existing Assessment Frameworks
(Own elaboration)

SCALE	DIGITAL TRANSFORMATION	SUSTAINABILITY (Environmental and Social Aspects)	SUSTAINABLE DIGITAL TRANSFORMATION
MACRO	STRONG	STRONG	WEAK
MESO	MODERATE	MODERATE	VERY WEAK
MICRO	MODERATE	STRONG	VERY WEAK

In-Depth Analysis

Following the mapping and preliminary analysis, an in-depth analysis was conducted on the most relevant and representative documents in the field. A total of 155 frameworks and articles were identified as the most closely aligned with the research objectives, providing valuable insights into the interplay between digital transformation and sustainability.

Consequently, an in-depth examination of these documents was carried out, by following the methodological guidelines of the Digital Development Compass (UNDP, 2021), and the Competitive Sustainability Index (CSI) from Cambridge University (2022).

In this regard, the selected frameworks were systematically analysed, categorised, and codified based on several criteria, encompassing: their nature (e.g., index, benchmark, report, article), scale (micro, meso, macro), scope or geographical context, recency (publication year), leading developer (e.g., academic, practitioner, international organization, standardization body, government), priority themes, integration of indicators or metrics, contributions to the digital, environmental, social spheres, as well as the degree of alignment and integration of the triple transition paradigm.

Drawing on insights from the analysis conducted, it was evidenced that a Taxonomical framework was necessary to address the identified gaps and offer a comprehensive, structured, and actionable approach to guide the alignment of digital transformation and regenerative sustainability towards achieving the triple transition.

5.1.4. Motivation, Objectives, and Research Approach for Developing a Taxonomy for SRDT

In light of the existing gaps in the literature concerning a comprehensive understanding and assessment of the interplay between digital transformation and regenerative sustainability, as well as the disconnect between both realms, developing a structured approach able to bridge these gaps and articulate this promising field is crucial.

In response to these caveats, this research proposes to develop a Taxonomy, to categorise in a comprehensive and structured manner, the determinant factors for a Sustainable and Regenerative Digital Transformation (SRDT), that contribute to a comprehensive understanding of this phenomenon towards the realization of a regenerative triple transition, digital, environmental and socially just.

The motivations for the development of the Taxonomy for SRDT are the following: a) to raise awareness of relevant aspects that require further research and are currently not considered within digital or sustainability frameworks; b) to improve the organisation of existing knowledge, thereby enabling better decision-making in driving the digital, ecological, and socially just triple transition with regenerative perspectives; c) to offer insights about risks and opportunities that digital transformation may pose for sustainability, thus informing the formulation of political priorities, practical actions, and research agendas.

Therefore, the proposed Taxonomy for SRDT represents a fusion of conceptual depth and existing empirical insights in the extensive literature, aiming to establish the groundwork for future theoretical, practical, and policy advancements in this field. Hence, it offers the foundation to navigate the complexities of the ever-evolving interplay between digital transformation and regenerative sustainability, thereby advancing their alignment towards the triple transition. In essence, the proposed Taxonomy aims to translate knowledge into actionable outcomes by effectively guiding decision-making and governance choices in this research field.

Methodological Approach

The proposed Taxonomy was developed through a systematic literature review and subsequent in-depth qualitative analysis of both scientific and grey literature as proposed by Hermann et al. (2023), and Mohamad et al. (2023). This included the examination of 355 international frameworks and 335 scientific articles related to digital transformation, digital innovation, and sustainability, as well as their intersection. This substantial corpus of documents ensured that the findings accurately reflected existing knowledge, ongoing debates, and priority trends within the research field.

Considering the large volume of available frameworks in this research context, the in-depth analysis, prioritized a selection of digital transformation frameworks that integrate elements of sustainability aspects, and vice versa, since this interplay represents the more nascent and compelling area.

Thus, special attention was given to those frameworks and articles that integrate both digital transformation and sustainability factors. The literature review, however, revealed a significant knowledge gap in this interplay. This challenge was especially pronounced and complex in the environmental dimension of sustainability, which remains underrepresented in the digital transformation literature. After selecting and examining the most relevant frameworks for the research objectives, a thorough qualitative analysis was conducted, supported by text mining and topic modelling techniques, using the RapidMiner and Orange software programmes.

Through these techniques, combined with conventional qualitative analysis, the most relevant domains, and thematic factors of the phenomena under study were identified. Subsequently, building on the insights gained from this exhaustive analysis, and using clustering and visualization techniques, the phenomena were categorised into three levels: six main pillars at the more general level, further divided into thirty-six domains at the intermediate level, and finally dissected into 273 thematic factors at the most detailed level.

This detailed categorization outlines and defines what constitutes a sustainable and regenerative digital transformation based on the available knowledge as of October 2024 (see Figure 5.1).

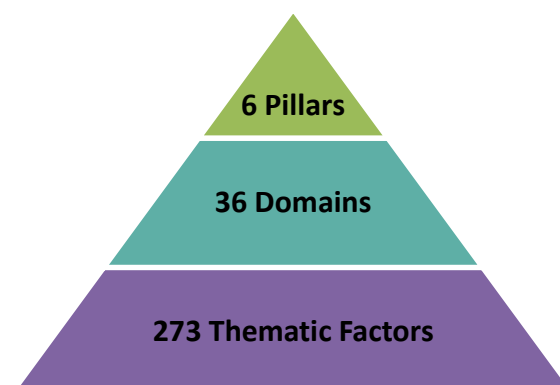


Figure 5.1. Overview Structure of the three levels of the proposed Taxonomy for SRDT
(Own elaboration)

5.1.5. Structure and Research Significance of the Taxonomy for SRDT

Following the introduction of the context and methodological approach, this section provides an overview of the general structure of the proposed Taxonomy for SRDT, along with their significance and novelty to the research field.

General Structure of the Proposed Taxonomy

The six proposed pillars which constitute the high-level category of the Taxonomy were meticulously defined to ensure strong alignment and coherence with globally recognized frameworks, particularly the 2030 Agenda and the leading approaches within the Digital Agenda.

Therefore, five of these pillars are inspired by the corresponding pillars of the 2030 Agenda, namely: people (social dimension), prosperity (socioeconomic dimension), planetary sustainability (environmental dimension), peace (governance dimension), and partnerships (cooperation dimension), thereby reflecting the priorities of the international community on sustainable development.

In addition to these five pillars, this research proposes a sixth pillar centred on preparedness to efficiently and responsibly face the emergence of the digital transformation, the consequent triple transition, as well as ongoing or future global crises and challenges. This novel pillar is crucial for advancing long-term sustainability, resilience, and inclusiveness, all essential components for a regenerative triple transition.

Hence, by integrating this novel pillar and embedding both regenerative sustainability and digital transformation priorities, the proposed Taxonomy for SRDT is fully aligned with key milestone frameworks of the digital agenda realm.

These include the UN's "Our Common Agenda," the "Digital Global Compact" (UN, 2024b), the UN's "Digital Development Compass" (UNDP, 2021), the EU's "2030 Digital Compass 2030" (EC, 2021b). Also, it addresses a crucial gap within the DCC, by thoroughly integrating the environmental sustainability dimension, which is currently overlooked in this framework.

Overall, the six pillars proposed and summarised in Figure 5.2, encompass the key aspects for advancing a sustainable and regenerative digital transformation, while also facilitating the triple transition: digital, environmental, and socially just.

In this context, the realms of planetary sustainability, peace, and preparedness within digital transformation are relatively more recent and less developed, making them innovative and emblematic of the triple transition. In contrast, the pillars concerning peace (mindful governance), prosperity (purposeful socio-economic development), and partnership (cooperation) are more established.

Nevertheless, in the proposed Taxonomy, these pillars are also reoriented to meet the contemporary sustainability requirements of the regenerative triple transition.

While the first group is underrepresented in the literature, policy and practice, the latter, despite being more established, still faces challenges that require intervention to fully align them with regenerative sustainability and the triple transition goals.

Together, these six pillars offer a balanced and comprehensive approach, integrating forward-thinking perspectives with well-established strategies, and ensuring alignment with both digital and sustainability agendas.

The proposed Taxonomy for SRDT is also aligned with the Sextuple Helix Innovation Model, and the reviewed Six Capital Framework, to which it contributes, as explained in Chapter 4. Certainly, the Taxonomy for SRDT aligned with a reviewed adaptation of the IIRC's Six Capitals Framework (Adams, 2013; Adams, 2017).

This framework has been updated, as a proposal to give more prominence to the concept of digital capital, thereby recognizing its potential to create value across both virtual and physical domains.

In this research, “digital capital” refers to the set of digital assets, capacities and ecosystems that jointly create added value and promote an effective and valuable contribution to the digital transformation of the economy and society.

The adapted IIRC framework encompasses in this research the digital capital, along with the other five capitals considered critical to SRDT and the triple transition, namely: economic capital (financial and manufactured), human capital, social (relationships) capital, natural capital, and intellectual capital. This approach ensures a holistic assessment of value creation across the multiple dimensions of the triple transition and reflects more accurately modern sustainability and digital transformation realities.

In conclusion, Figure 5.2 and Table 5.4 provide an overview of the six pillars, the dimensions they represent within the context of Sustainable and Regenerative Digital Transformation (SRDT) and the triple transition, along with the specific domains of each pillar, and the main capitals that they generate.



Figure 5.2. Overview of the six pillars within the proposed taxonomy for SRDT
(Own elaboration)

Overall, the proposed Taxonomy for SRDT has been meticulously elaborated to provide a holistic overview of what constitutes a sustainable and regenerative digital transformation. It is aligned with existing frameworks, and the other contributions proposed within this dissertation, and captures the latest trends in the fields of sustainability, digital transformation, and innovation.

This panoramic perspective and strong alignment with the established frameworks aim to further guide research, policy, and practice, to promote a more sustainable digital transformation with regenerative qualities, capable of driving the triple transition forward.

Table 5.4. Overview of the Components and Dimensions of the Taxonomy for SRDT
(Own elaboration)

PILLAR	REPRESENTED DIMENSION	MAIN CAPITAL	DOMAINS
PLANETARY SUSTAINABILITY	The environmental dimension of sustainability and the triple transition	<i>Natural Capital</i>	Sustainability and Regeneration Principles and Policies; Environmental Direct Impacts; Indirect Impacts; Rebound and Systemic Effects; Environmental Handprints; Green ICT mitigation measures; Awareness-Raising; Digital Opportunities for Regenerative Sustainability.
PEOPLE	The social dimension of sustainability and the triple transition	<i>Human Capital and Social Capital</i>	Equitable, Inclusive, and Safe Digital Development; Empowerment, Ownership, and Human-Centred Digital Development; Protection of Personal Digital Human Rights; Responsible and Accessible Use, and Safe Adoption; Digital Culture, Creativity, and Digital Humanism; Digital Opportunities for Social Resilience and Regeneration; Societal Engagement and e-Participation.
PEACE	The mindful governance dimension (cross-cutting) of sustainability and the triple transition	<i>Social Capital</i>	Responsible Multilevel Oversight, Regulation, and Policies; Digital Ethics Governance for Safeguarding Human Rights, Peace, and Democracy; Digital Responsibility; Openness and Stewardship of Digital Commons; Digital Trust, Transparency, and Accountability; Accessible and Secure e-Government Opportunities.
PROSPERITY	The socioeconomic dimension of sustainability and the triple transition	<i>Economic Capital and Intellectual Capital</i>	Sustainable and Equitable Digital Economy and Competitiveness, Responsible Digital Innovation and Entrepreneurship Ecosystems; Fair Digital Labour, Decent Work, Reskilling and Upskilling; Responsible End-to-End Technology Adoption for Regenerative Development; Inclusive Digital Financing and Taxation.
PARTNERSHIPS	The cooperation dimension (cross-cutting) of sustainability and the triple transition	<i>Social Capital</i>	Global Digital Cooperation and Diplomacy; Multilevel, Multi-Stakeholder Communities and Co-creation Alliances; Multilateral Cooperation Programmes for Sustainable Digital Development and Capacity Building Mechanisms.
PREPAREDNESS	The readiness, resilience, and response to crises dimensions for the triple transition (cross-cutting)	Digital Capital, Human Capital, Social Capital	Universal and Meaningful Connectivity; Resilient, Secure, and Sustainable Infrastructures and Systems; Robust, Secure and Resilient Data Infrastructures; Digital, Sustainability, and Resilience-oriented capacities; Transformational Leadership and Culture of Responsibility; Conducive Enabling Environment and Ecosystems; Crisis Preparedness and Emergency Response Capacities and Supporting Systems.

Research Significance and Novelty

As far as it is known, this is the first-of-its-kind Taxonomy for SRDT, since no similar framework is currently available in the literature. It provides a significant contribution to the research field, as explained below.

While aligned with current literature, the proposed Taxonomy for SRDT offers a holistic, and up-to-date perspective, capturing the essence of the triple transition, and embracing the vision of long-term regenerative sustainability, inclusiveness, and resilience.

Within this context, it advocates for a digital transformation approach that not only supports socioeconomic and technological development but also leverages the digital era to create positive societal and environmental opportunities that regenerate society and the environment.

Hence, its primary aim is to provide guidelines to better integrate the digital, environmental, and socially just transitions systematically and with regenerative perspectives. This comprehensive approach distinguishes the Taxonomy for SRDT from previous frameworks, since regenerative sustainability is embedded across all pillars, domains, and thematic factors, for creating opportunities to restore and revitalize nature and society in a harmonized manner, while aligning currently disconnected and often conflicting dimensions.

Furthermore, it brings together “whole-of-society” and “whole-of-development” approaches, embedding multistakeholder cooperation, and inclusiveness by a “pluriversal” perspective, needed for realizing the regenerative triple transition.

Given the complex and interconnected nature of this realm, certain topics may span multiple dimensions (e.g. leadership, human rights).

Therefore, in the Taxonomy, they have been positioned where they exhibit the greatest affinity, effectiveness, alignment with current frameworks, and impact for the common goal of achieving a sustainable and regenerative digital transformation for the triple transition.

Hence, the proposed Taxonomy for SRDT offers a holistic understanding of the key pillars, domains and detailed thematic factors that can influence the realization of a sustainable and regenerative digital transformation.

This comprehensive perspective is crucial for informing effective decision-making, aligning, and steering research, policy interventions, and practical activities within the digital realm towards regenerative sustainability and the triple transition.

Following the introduction to the research context, the general structure and relevance of the proposed Taxonomy for SRDT, the next sections provide a detailed substantiation of the relevance and the domains within each pillar.

This includes the careful examination of the proposed six pillars, namely: the “planetary sustainability” pillar, reflecting the environmental dimension; the “people pillar”, representing the social dimension and just transition; the “peace pillar”, encompassing the mindful governance dimension; the “prosperity pillar”, reflecting a purposeful socioeconomic dimension; the “partnership pillar”, representing cooperation; and finally, the “preparedness pillar”, which encompasses the sound integration of the readiness, resilience, and response to crises dimensions for advancing the triple transition.

5.2. The Planetary Sustainability Pillar: The Environmental Transition

This section provides the substantiation of the “Planetary Sustainability Pillar,” representing the environmental dimension of the triple transition. It begins with an overview of its structure and significance within the research context. Next, an examination of the various domains classified under this pillar is presented. Finally, the section concludes with a reflection on the insights gained and the respective implications.

The Planetary Sustainability Pillar emphasizes the importance of integrating environmental sustainability and eco-social concerns into digital transformation research, practices, and policies. It focuses not only on reducing the negative environmental impacts of digital solutions but also on harnessing the positive opportunities they offer for restoring and regenerating the environment and enhancing the well-being of society.

Despite the potential of digital technologies to address environmental challenges, their contribution so far has not met the aspired expectations. The perception of digital transformation as a universal green solution is overly simplistic since it ignores the direct, indirect, and rebound effects of digitalisation on the environment and society.

According to Aanestad (2023), digital solutions should be deployed consciously and ethically, serving both nature and society. This requires a dual approach to sustainability: implementing digitalisation in an environmentally responsible manner while using digital solutions to support ecosystem protection, restoration, and resilience. Mitigating risks while maximizing opportunities is crucial for achieving “net positive” contributions.

A critical aspect is moving beyond the current “carbon myopia” in the sustainability discourse, which overly emphasizes the reduction of greenhouse gas (GHG) emissions in the digital sector while overlooking other critical issues. Although the carbon footprint is important, digital transformation impacts the environment in multiple ways, including electronic waste, raw material use, water and soil pollution, land change, electromagnetic fields (EMFs), and biodiversity loss, among other effects.

As justified by UNCTAD (2024), existing frameworks and standards for assessing the environmental impact of digital technologies are obsolete and overly focused on climate impacts, primarily linked to energy consumption. Thus, to steer digital transformation toward sustainable development, there is an urgent need for updated frameworks that encompass these broader ecological concerns.

Additionally, the few existing sustainability frameworks and standards specific to ICTs (e.g., ITU-T L and Y Series, IEC, IEEE, ETSI standards) have not effectively engaged with eco-social communities and remain poorly endorsed. Most of them do not fully reflect the numerous impacts and opportunities of digital transformation for sustainable development.

Moreover, net-positive or regenerative approaches remain largely unexplored in the digital literature, revealing the need to establish cohesive narratives and common terminologies to align digital and sustainability realms effectively.

In light of these considerations, this dissertation introduces several domains, for this crucial pillar of planetary sustainability in the context of the related environmental transition, namely: (i) Planetary sustainability and regeneration principles and policies; (ii) Direct environmental impacts of digital transformation; (iii) Indirect impacts, including positive and negative enabling effects; (iv) Rebound and systemic effects; (v) Transboundary spillovers; (vi) Environmental handprints (net-positive effects within or beyond the ICT sector); (vii) Green ICT mitigation strategies and awareness-raising; and (viii) Digital opportunities for regenerative sustainability and achieving the SDGs.

The following sections provide a detailed justification of the relevance of each domain within the planetary sustainability pillar.

5.2.1. Planetary Sustainability and Regeneration Principles and Policies

Environmental principles are essential for reforming the organisational strategies to ensure sustainability readiness. These strategies should address both potential impacts (footprints) and opportunities (handprints), to adopt a regenerative approach. Traditional principles of environmental sustainability include the precautionary principle (preventive action against threats), responsibility principle (holding those causing harm accountable), equity principle (fair distribution of benefits and burdens), efficiency principle (rational use of resources), solidarity principle (international cooperation), participation principle (stakeholder engagement), and integration principle (considering environmental aspects in decision-making).

The United Nations Environment Management Group (UN EMG, 2023) supported environmental principles that emphasize intergenerational justice and equity, circular economy, science-based decision-making, human rights, health, and access to justice. In line with this, the proposed Taxonomy integrated these traditional principles and, besides, advances a more holistic approach tailored to the digital domain, by focusing on regeneration, ecological resilience, climate neutrality, resource efficiency, digital sufficiency, eco-design, eco-innovation, and education for behaviour change.

The novelty of the proposed approach lies in its comprehensive integration of eco-social dynamics and regenerative strategies within digital transformations, balancing environmental dimensions and promoting both ecological and social well-being.

Furthermore, relevant frameworks in the sustainability realm that inspired the suggested Taxonomy included the Green Growth Index (2023), the Transition Performance Index (EC, 2022a), the Planetary Pressures Adjusted HDI Index (PHDI, 2023), as well as the Global Information Society Watch (Gi swatch, 2020).

In addition, the recently launched “Pact for the Future” and “Global Digital Compact” (UN, 2024a,b) underlined the relevance of embedding environmental sustainability principles within the digital strategy, particularly, for driving net-zero infrastructures by 2050 and for reducing their environmental footprint and mineral consumption through the entire life cycle.

Indeed, promoting eco-social transformations entails integrating eco-social principles into digital advancements, ensuring that technological innovations benefit communities equitably and support ecological and social well-being (Metzner-Szigeth, 2019; OECD, 2023a). Although a global strategy for the “triple transition” (digital, ecological, and social) is still needed (OECD, 2023a), this approach emphasizes pluralism and diversity, avoiding one-size-fits-all solutions.

The proposed Taxonomy also emphasizes regenerative sustainability as a critical principle to integrate across all domains, particularly, within the digital realm. Regenerative sustainability seeks to restore ecosystems and natural resources in harmony with societal needs. In the digital context, it advocates for technologies and infrastructures that contribute positively to environmental, social, economic, and governance regeneration rather than merely minimizing harm.

Notably, resilience is central to this approach, involving adaptability to challenges while preserving ecological integrity. In the digital sector, resilience is related to readiness, maturity, security, and sustainable practices, intricately linked to the notion of “digital sufficiency” (Rugeviciute and Courboulay, 2024; Lobschat et al., 2020).

The principle of digital sufficiency is crucial for the sustainability of the sector and is gaining relevance in the digital community.

It focuses on reducing the overall resource and energy demand from ICTs, by addressing the limitations of efficiency strategies. It requires policies across hardware, software, user, and economic dimensions (Santarius et al., 2022; Gatt and Madon, 2024).

Concerning sufficiency, other related innovative concepts such as ecological ethics, digital degrowth, and “permacomputing” propose radical shifts toward sustainability and ethics in technology development. These novel principles challenge growth-centric models, promoting radical reductions in consumption, and emphasizing ecological values together with enhancing social well-being (De Vank, 2021; Aanestad, 2023; Vetter, 2018). For instance, “digital conviviality” refers to the alignment of digital technologies with ecological cycles and community access, advocating for social equity and environmental sustainability (Selwyn, 2023; Carrigan et al., 2020).

In terms of the principle of climate neutrality, is a crucial aspect in the domain of digital transformation, particularly, for addressing the significant energy consumption and subsequent GHG emissions associated with digital technologies operation. Achieving a climate-neutral digital sector requires transitioning to renewable energy sources, optimizing energy efficiency, promoting sufficiency and circularity approaches, and offsetting residual emissions (Aanestad, 2023; D4S, 2023).

Certainly, circularity in digital processes is another critical principle, providing advantages in closing resource loops, reducing waste, promoting sufficiency, maximizing the lifespan and efficiency of products and infrastructures through strategies such as server virtualization, edge computing, and energy-efficient design, and finally recycling and recovering critical materials (Ranta et al., 2021; Liu et al., 2022).

These values are also integrated within the eco-design principle, critical for achieving sustainable digitalisation, which advocates for the development of products, processes, and services that minimize environmental impact throughout their lifecycle (Martínez-Cámara et al., 2021).

Moreover, another relevant principle for enhancing environmental sustainability in the digital sector relies on education, awareness raising and behavioural change. Notably, raising awareness and promoting education for behavioural change across all stakeholders is essential for making digital practices more sustainable. Educating users and developers on sustainable design principles and a responsive approach to sustainable production and consumption can drive behaviours that support a sustainable and regenerative digital transformation (Hajj-Hassan et al., 2024; Zhou et al., 2023).

Overall, adopting regenerative sustainability principles, promoting ecological resilience, achieving climate neutrality, and implementing circular and resource-efficient eco-design practices inspired by sufficiency, can significantly contribute to driving a more sustainable and resilient digital transformation.

Emphasizing eco-social transformations through education and awareness-raising is also critical. This combination of principles and values represents a paradigm shift towards more ethical, regenerative, and sustainable approaches to technology, challenging mainstream economic and technological practices (De Vank, 2021).

Thus, the proposed Taxonomy aligns with these widely accepted environmental principles in the “ICT for Sustainability” (ICT4S) community.

In summary, for achieving the planetary sustainability of the digital transformation, a comprehensive, multifaceted approach is needed, that must address the environmental impacts but also leverage opportunities, by integrating regenerative principles for a more equitable, sustainable, and resilient future.

New strategies and values are emerging within the ICT for Sustainability community to address the sustainability imperative through innovative and tailored approaches. As follows, a critical overview of the most established principles gaining traction in the field is presented.

Digital Conviviality and Degrowth Principles

Digital conviviality involves the use of digital technologies to promote social equity, environmental sustainability, and human well-being. Rooted in Illich's (1973) concept of "conviviality", it emphasizes individual freedom in harmony with the environment.

This approach seeks to develop digital tools that foster collaboration, openness, and accessibility while minimizing adverse impacts on society and nature. It challenges the dominant technological paradigms that focus on efficiency and profit over social and ecological well-being, advocating for technologies that serve human needs and enhance social cohesion without compromising environmental integrity.

Vetter (2018) expanded on Illich's idea, introducing the concept of "convivial technology" within degrowth societies. He proposed a "Matrix for Convivial Technology" to guide ethical technology design, featuring five key dimensions: relatedness, adaptability, accessibility, bio-interaction, and appropriateness. These dimensions align technology with ecological cycles, foster community access, and ensure that technologies are locally suited and environmentally friendly.

Conviviality also contrasts with conventional growth models, suggesting a shift towards sustainable lifestyles and economies (Kallis et al., 2014). By promoting technologies that empower communities and enhance collective well-being, digital conviviality contributes to social cohesion and a sustainable digital economy.

The discourse on digital conviviality also included studies on "community informatics" and "digital activism." Gurstein (2011) underlined how digital tools can support community development through participatory decision-making and equitable information access, thereby empowering marginalized communities. Similarly, Loader and Mercea (2011) viewed digital activism as a form of convivial engagement that challenges established power structures and promotes democratic participation through digital means.

Complementing these views, Kostakis et al. (2019) introduced the "cosmolocal" framework, by merging global knowledge commons with local manufacturing practices, to create convivial production models. This model emphasises socio-ecological well-being over profit-driven production and showcases how digital technologies can facilitate distributed, collaborative production networks that support degrowth.

Carrigan et al. (2020) argued that attributes like conviviality and reciprocity are crucial for a sustainable sharing economy facilitated by digital platforms. Therefore, digital conviviality is considered a relevant concept in the research context of this dissertation.

Concerning the degrowth concept, it advocated for shifting from growth-based technological development to sustainability, by focusing on simplicity, community production, and resource sobriety. The core principles of degrowth included conviviality, autonomy, and care. This emphasized that technologies should serve to enhance human well-being and equitable access to resources, which contrasts with current mass digital consumption, often leading to social inequality and environmental degradation.

In this regard, Selwyn (2023) explored how degrowth principles could benefit the educational technology sector, recommending approaches like avoiding manipulation, reinforcing conviviality, promoting inclusivity, and reimagining traditional education models. Similarly, Aanestad (2023) stressed the importance of integrating environmental sustainability into information systems research, warning against the uncritical promotion of digital technology as a sustainability solution without considering its environmental footprint.

Alternative paradigms such as the termed "permacomputing" inspired by permaculture and focused on resource maximization and minimal impact (Mansoux et al., 2023), frugal innovation, and "computing with limits" (Vanderbauwhede, 2021) are proposed within the context of digital degrowth, advocating for technologies that operate within ecological boundaries.

Digital Sufficiency and Sobriety

The rapid evolution of digital technologies is often viewed as a solution to environmental issues such as climate change, but this naïve perspective overlooks their multiple impacts, particularly the rebound effects, which may increase overall resource consumption.

The concepts of "digital sufficiency" or "digital sobriety" advocate for reducing the absolute demand for resources and energy in ICT production and use. This idea promotes autonomy by reducing the risks related to external dependencies and contrasts with traditional strategies solely focused on efficiency, which aim to improve processes while maintaining high consumption levels.

In this regard, Gatt and Madon (2024) emphasized the limitations of current efficiency measures in data centres, calling for sufficiency strategies to decrease the absolute resource and energy demand.

Santarius et al. (2022) outlined four dimensions of digital sufficiency: hardware, software, user, and economic sufficiency. According to these scholars, hardware sufficiency aims to extend device lifespans, software sufficiency focuses on minimizing data traffic, user sufficiency encourages frugal device use, and economic sufficiency envisions an economy focused on sufficient production and consumption.

Furthermore, implementing digital sufficiency requires policies across all dimensions, including eco-design regulations, sustainable manufacturing standards, awareness campaigns, and a shift toward a degrowth economic model. Therefore, this holistic approach addresses the limitations of efficiency strategies, promoting sustainable digital technology use, production, and economic structures. For that reason, digital sufficiency is considered a relevant aspect within the proposed Taxonomy for SRDT.

Circularity principles

Integrating circularity principles in digital practices presents a critical path toward long-term sustainability in the ICT sector. In this regard, the interplay between circularity principles and digital transformation holds a dual nature with uncertain net outcomes.

On one hand, digital technologies can enhance resource efficiency, positioning themselves as part of the solution. Indeed, technologies like the Internet of Things (IoT), Big Data Analytics (BDA), and Blockchain are recognized for their potential to enhance resource efficiency, supporting the transition to circular economy practices, as already reviewed in Chapter 3.

For instance, Kristoffersen et al. (2020) proposed the alignment of digital technologies with circular strategies to enhance resource efficiency in manufacturing. Ranta et al. (2021) and Liu et al. (2022) identified key functions of digital technologies in circular strategies, such as IoT for real-time monitoring and Blockchain for transparent supply chains. Meanwhile, Khan et al. (2021) explored Blockchain's role in improving circular procurement, recycling, and remanufacturing practices.

On the other hand, digital technologies pose significant environmental challenges, such as raw materials consumption and e-waste generation for which circularity is often highly complex.

The integration of circularity in the digital sector faces several challenges due to the lack of infrastructures designed for this purpose, the absence of robust standards, traceability, and logistics barriers, making it difficult to translate principles into practice. Moreover, regulation has been reluctant to influence digital development.

These issues are often exacerbated by premature obsolescence, complex supply chains, and challenges related to economic viability, making the implementation of circularity in the digital sector particularly complex. At the same time, circularity is imperative for a sustainable and regenerative digital transformation, addressing the growing e-waste challenge, and providing an opportunity to recover critical raw materials, which are at risk of scarcity and external dependency.

The integration of circularity principles within the digital transformation can be enhanced through Green ICT strategies (e.g., Right-to-repair policies and Digital Product Passports), which are further examined in the respective section. Thus, despite the promising interplay between circularity and digital transformation, the respective net contribution to sustainability remains uncertain. Further research and empirical evidence are required to fully understand the potential of this intersection (Medaglia et al., 2024).

In essence, all the perspectives surrounding circularity principles are essential considerations within the proposed Taxonomy. Some are addressed as Green ICT strategies, while others are viewed as opportunities for advancing sustainability, which deserves further exploration.

Eco-Design Principle

The eco-design principle involves embedding environmental criteria into the design process of digital products or services to minimize the ecological impacts. This principle is closely linked with eco-innovation, as it consistently acts as an enabler for eco-design practices.

Bonvoisin et al. (2014) and Zhuang et al. (2024) underscored the need for environmentally sound ICT optimization and people-centred design that harmonizes technological advancement with health and environmental benefits. Martínez-Cámara et al. (2021) demonstrated the effectiveness of eco-design in reducing environmental impacts through a hybrid methodology combining this paradigm and life cycle assessment (LCA).

Furthermore, the eco-design principle is also strongly intertwined with other sustainability principles such as conviviality, degrowth, sufficiency, and circularity. Together, they offer transformative approaches to align digital technologies with social equity and environmental sustainability. By embracing these principles in digital transformation, society can promote community empowerment, reduce resource consumption, and create a balanced relationship between humans, technology, and nature.

Translating these principles into practice requires comprehensive policies, increased awareness, and interdisciplinary collaboration. For that reason, eco-design and eco-innovation are also considered part of the Green ICT strategies to mitigate the impacts of digital transformation. Therefore, these aspects are further examined in the respective section.

Hence, all the described principles are complementary and crucial for achieving a sustainable and regenerative transformation, and for that reason, they are thoroughly addressed within the proposed Taxonomy for SRDT.

5.2.2. Introduction to the Environmental Impacts of the Digital Transformation

Digital transformation (DT) has revolutionized numerous sectors with promising advancements in efficiency and optimisation, some of which have the potential to benefit sustainability. However, this transformation also comes with complex environmental impacts that remain inadequately understood and poorly integrated into the existing assessment methodologies.

The rapid growth of digital technologies has had far-reaching effects on the environment, both positive and negative, and across different levels of influence, from direct energy consumption to systemic, global changes.

Despite its expected potential to drive sustainability, digitalisation can also contribute to severe ecological degradation. In light of this problem, a profound understanding of the impacts of digital transformation on the environment is urgently required. This emphasizes the need for comprehensive frameworks able to guide the present and future governance of the digital transformation towards sustainability.

Current frameworks for measuring digital development overlook sustainability matters. The few specific frameworks specifically focused on addressing the environmental sustainability of ICTs, are primarily centred on direct impacts, such as GHG emissions, energy consumption, and electronic waste (e-waste). However, broader direct impacts (e.g. biodiversity loss or water pollution), along with indirect effects, rebound effects, and transboundary spillovers are insufficiently understood and poorly addressed.

The existing scientific literature and governmental frameworks are outdated in this matter, failing to incorporate contemporary sustainability concepts and methodologies, highly relevant in the digital age. A broader and holistic perspective is necessary to encompass the complexities of the digital transformation environmental effects, especially as the rapid expansion of digital technologies is posing new ecological and societal challenges.

The proposed Taxonomy aims to address this gap, by providing a comprehensive panoramic of the potential environmental impacts associated with the digital transformation. By identifying and categorizing the potential impacts into direct, indirect, rebound, systemic, and spillover effects, the stakeholders can better grasp the nuances and develop informed strategies, contributing to a more sustainable digital transformation. A comprehensive evaluation of these categories is essential to develop strategies that maximize the benefits of digitalisation while mitigating its adverse impacts.

Categorization of the Environmental Impacts of Digital Transformation

The environmental impacts of digital transformation are multifaceted and highly complex. Although there is no consensus yet on a definitive classification of these environmental effects, they are commonly categorised in the literature into the following types: direct, indirect, rebound, and systemic effects, along with spillovers.

These impacts can be further categorised into "footprints" (negative effects) and "handprints" (positive effects), depending on their outcome. Footprints represent the negative environmental effects, while handprints signify the positive impacts that contribute to sustainability.

Additionally, another crucial category to consider entails transboundary spillovers, which are effects originating in one context but impacting other geographies. This comprehensive approach allows for a better understanding of the varied and far-reaching consequences of digitalisation on the environment.

For the sake of clarity, a table summarizing the definitions of the different environmental impacts, and the mitigation strategies potentially derived from digital transformation is provided in Table 5.5.

Table 5.5. Categories of the environmental impacts driven by DT and mitigation strategies
(Own elaboration)

- **Direct Effects (First order):** immediate impacts that arise from the entire life cycle of digital devices, systems, and infrastructures, including raw material extraction, manufacturing, transportation, use, and end-of-life. They may be related to resource use, material footprint, energy, and water consumption, GHG emissions, water, air, and soil pollution, biodiversity and habitat affection, EMFs, and noise.
- **Indirect Effects (Second-order):** These impacts result from the use of digital technologies across various sectors, encompassing either positive impacts (such as optimization and substitution) or negative impacts.
- **Rebound Effects (Third-order):** They refer to unintentional impacts that can counterbalance positive effects, often related to Jevon's paradox, by which efficiency gains lead to increased overall consumption.
- **Systemic and Transformational Effects (Higher-order):** they refer to broader societal changes in lifestyles and patterns of consumption and production.
- **Transboundary Spillovers:** they refer to the impacts generated in one country or region but affecting other contexts different from where they originated.
- **Handprint:** it refers to a net-positive impact achieved by intentional actions oriented to reducing or preventing the total footprint, or generating new positive benefits, compared to "Business-As-Usual" activities (Norris, 2015). It requires intentional, voluntary positive changes with commitment and consciousness of the intervening actors. They can be either behavioural or infrastructural.
- **Green ICT Strategies:** they refer to measures aimed at curbing potential negative environmental impacts, thereby contributing to a more sustainable use of digital solutions.

Having examined the categories of environmental impacts, it is also relevant to recognize their interconnection with social aspects. While environmental and social disciplines have been traditionally disconnected, is critical to shift the perspective and acknowledge the interconnection of environmental sustainability, human health, and digital equity to achieve a regenerative and equitable digital future. By addressing these intertwined aspects, stakeholders can better navigate the challenges of digital transformation and foster a more balanced relationship between human society, technology, and the environment. This perspective is addressed as follows.

The Eco-Social Perspective

Digital transformation is redefining the relationship between nature and society, thus impacting environmental sustainability and human health. The nexus between digitalisation and sustainability is strongly influenced by geographical and socio-economic factors, and the location and context of digital interventions play a critical role in determining their impact. Therefore, to drive a "triple transition", a holistic approach must address the interconnected phenomena of development, environmental impacts, and digital divides.

The environmental impacts of digital transformation are more severe in vulnerable regions. These areas, often affluent in raw materials, are not only the primary sources of digital components but also the main dumping grounds for hazardous electronic waste (e-waste). Developing and vulnerable regions lack the infrastructure and capacity to manage digital-related risks, leading to increased environmental degradation and health hazards in these contexts.

Moreover, extractive processes related to the digital industry contribute to land degradation, deforestation, biodiversity loss, and climate change, while inappropriate e-waste disposal exposes communities to severe health issues, and widening social and economic divides.

Certainly, the extraction of raw materials and informal e-waste management in developing countries can cause significant health risks.

For instance, an estimated 12.9 million women and children work informally in the e-waste sector, facing direct exposure to hazardous substances (Parvez et al., 2021; WHO, 2021a). These practices aggravate socio-economic inequalities and hinder sustainable development.

Furthermore, human health is inherently connected to environmental sustainability. As King (2015) argued, a healthy environment fosters better decision-making and effective disease management, linking health to social and environmental justice. Integrated approaches, such as the "eco-health" framework, highlight the importance of ecological public health in addressing risks posed by environmental crises like climate change and digitalization (Bunch et al., 2011). Thus, recognizing the interdependence of social and environmental factors is vital in managing risks in the digital age (McMichael et al., 2015).

The digital divide adds another layer of complexity to the already critical eco-social perspective. While digital technologies can offer solutions to environmental and health challenges, unequal access to them magnifies environmental and equality challenges. Bridging these digital divides and acknowledging that ecology protection is related to human prosperity and well-being is essential for overcoming current dichotomies, and thereby fostering a more sustainable and equitable future.

The proposed Taxonomy fully integrates the connection between nature and societal aspects, and advocates for the consideration of an eco-social and regenerative transformation through the triple transition.

Having introduced the relevance of the environmental effects potentially posed by digital transformation, along with their interconnection with social aspects, the next section provides a more detailed examination of these impacts.

5.2.3. Direct Environmental Effects (Footprints)

The direct environmental impacts of DT refer to the immediate effects caused on the ecological systems throughout the life cycle of related digital devices, systems, and infrastructures. The life cycle includes the extraction of raw materials, manufacturing processes, transportation, usage, and end-of-life management (ITU, 2024b). As Hilty and Aebischer (2015) noted, ICTs can either contribute to environmental problems or be part of the solution, depending on how these direct impacts are managed. While most literature on this matter focuses on energy consumption and related GHG emissions, other aspects such as water use, pollution, resource depletion, and biodiversity affection, among others, need equal attention.

Direct Impacts Related to Energy Consumption and Subsequent GHG Emissions

Digital technologies are major consumers of energy throughout their life cycles (Luccioni et al., 2023). The data centres, servers, networks, and digital devices consume vast amounts of electricity and water. Verdecchia et al. (2021) projected that data centres alone could account for approximately 10% of global electricity consumption by 2030, with the digital ecosystem potentially consuming up to one-third of the world's energy supply. In particular, the manufacturing process of digital devices is an energy-intensive process, contributing significantly to GHG emissions.

Furthermore, the usage phase of digital devices also involves substantial energy consumption. While advancements in energy efficiency have been made, the increasing number of data centres and devices, along with the surge in data traffic offset these gains.

Also, large AI models are energy-eager. While AI can optimize energy systems and accelerate climate solutions it also drives resource-intensive activities, such as large energy consumption in data centres (Luers et al., 2024).

As a result, the global energy consumption of data centres is rapidly growing, adding to the carbon footprint of digital technologies. Istrate et al. (2024) argued that digital content consumption significantly impacts the per capita carbon budget necessary to limit global warming to 1.5°C. Therefore, energy efficiency alone is insufficient; a reduction in overall digital demand is also required to mitigate ICT-related emissions.

The impacts of such a growing energy demand for digital development can be partially mitigated by energy-aware “green algorithms,” and “green data centres,” integrating energy-efficiency standards and equipment, renewable energies, sustainable cooling technologies, and other green tech solutions.

While the rising energy demands of digital development can be partially mitigated through these “Green ICT” strategies and measures, a fundamental rethinking of current production and consumption patterns is essential to embed a truly sustainable approach into digital strategies.

Water Consumption and Pollution

Water use and consumption across the life cycle of DT is a critical, yet underexplored impact. As argued by Olivié-Paul (2022), digital technologies require large volumes of water during the extraction of raw materials, the manufacturing processes, as well as for the cooling of data centres and infrastructures. The water footprint of manufacturing digital devices, such as smartphones, ranges widely, with estimates from 100 to 13,000 litres per device (Friends of the Earth, 2015). In addition, data centres use substantial amounts of water for cooling.

This is aggravated by the fact that digital infrastructures are often located in water-stressed areas, which worsens the already existing water scarcity problems (Monserate, 2022). The potential impacts of climate change on water availability pose additional risks for the future. Furthermore, the issue extends to the pollution of water resources, particularly from raw material mining, the manufacturing of semiconductors (Kuo et al., 2022), batteries, and electronic components, the inadequate management of electronic waste, and the wastewater generated by operational processes.

The water-energy-climate nexus in the digital realm is intricate, as increased water usage also heightens energy demand, and subsequently affects related climate impacts (Mytton, 2021). Also, potential disruptions to local ecosystems and biodiversity arise due to the competition for water resources between digital infrastructures, agriculture, and local consumption. This underscores the need for a comprehensive strategy that addresses the interconnections between water use, energy consumption, and climate effects in digital technologies.

Therefore, this relevant nexus between water, energy and climate is soundly considered within the proposed Taxonomy.

Raw Material Extraction and Manufacturing

The production of digital devices involves the extraction of critical raw materials, including rare earth metals and other non-renewable resources. These processes often take place in less developed regions lacking environmental safeguards, leading to habitat destruction, water, air, and soil contamination, and threats to biodiversity and ecosystems (Mewes, 2023). The extraction and processing of these materials require significant consumption of energy and water, contributing to environmental degradation and posing risks to human health, particularly concerning the informal workers, typical in this sector.

Moreover, the extraction and transportation of raw materials, such as lithium and cobalt, result in GHG emissions and the release of pollutants into soil and water. Mining operations can also compete for water resources, further intensifying local water stress. The cumulative effects of these activities emphasize the need for sustainable resource management practices in the digital sector.

Addressing this, often neglected, impact is crucial for ensuring the environmental sustainability of digital development, and therefore, is robustly considered within the proposed Taxonomy.

Electronic Waste and Pollution

The end-of-life phase of digital devices and infrastructures generates large volumes of waste, particularly electronic waste, which frequently contains hazardous materials that pose risks to ecosystems and human health (Dwivedi et al., 2022). Improper handling and disposal of e-waste can lead to toxic leachates that often contaminate groundwater. Furthermore, the rapid development cycle and obsolescence of digital devices and systems exacerbate the e-waste problem, as both functioning and outdated products are frequently discarded and replaced. As previously discussed, the circular economy in the digital sector, while critical, is so far limited.

Addressing the e-waste problem requires not only safe disposal practices but also circular economy strategies that extend product lifespans, promote repair and recycling, and reduce the environmental footprint of digital products. Nevertheless, both the management of e-waste and its circularity are complex and further research, policy development and capacity building are needed in this matter.

Broader Environmental Impacts and Their Link with Social Aspects

As previously discussed, digital technologies and infrastructures generate a wide range of complex environmental impacts, including natural resource depletion, local air and water degradation, water stress, soil pollution, land use changes, harm to biodiversity and ecosystems, electromagnetic field (EMF) emissions, noise pollution, space debris, and significant waste generation.

These direct effects, or footprints, vary considerably depending on the technology, infrastructure, device, life cycle stage, and specific context. For instance, the impacts on material use, water and air quality, and biodiversity are most severe during the sourcing, production, and manufacturing phases. In contrast, waste generation becomes critical at the end-of-life phase (Ademe and Arcep, 2022; Bordage, 2019).

Additionally, the rapid pace of technological development complicates the assessment of these impacts. A multicriteria perspective is necessary to capture the diverse and evolving environmental challenges posed by digital technologies (Duporte et al., 2022).

According to Mewes (2023), biodiversity and livelihoods are especially vulnerable to water consumption and pollution caused by digital technologies, which disrupt ecosystems. Mining also leaves a substantial environmental footprint, causing soil damage and releasing toxic by-products. Hazardous leaching and improper waste disposal from processing activities may contaminate groundwater, adversely affecting biodiversity (Dwivedi et al., 2022; The Shift Project, 2019). Unlike GHG emissions, which can be offset, the negative impacts on water are context-specific and can severely affect biodiversity.

Another concerning impact of widespread digital transformation is the increased exposure to electromagnetic field emissions (EMFs), with uncertain effects on human health (WHO, 2024). This topic is further explored in the “People” pillar, underlining its significant relevance to human health and well-being.

Considering that these impacts are under-researched and poorly integrated into current measurement and monitoring frameworks, the proposed Taxonomy offers a detailed reflection of them to enhance their visibility and facilitate awareness to address these gaps.

An additional relevant barrier that impedes a full understanding and awareness of the significance of the environmental impacts of the digital sector relies on the current lack of data and standardized methodologies for measuring them. As previously described, existing data concerning the environmental footprints of digital solutions and infrastructures is limited, incomplete and inconsistent (UNCTAD, 2024).

The lack of harmonized reporting standards, reliance on outdated data sources, and fragmented and inadequate methodologies, further complicate the assessment of these critical impacts (Freitag et al., 2021). This situation is aggravated by greenwashing practices and the absence of updated regulations.

Hence, developing reliable metrics and standardized measurement methodologies to accurately assess the environmental impacts of digital technologies is essential for enhancing governance and promoting responsible digital transformation. Considering their relevance, these aspects are consistently integrated within the proposed Taxonomy.

5.2.4. Indirect Environmental Effects

Indirect effects, also known as second-order effects, result from the application of digital technologies across various sectors. These impacts can be beneficial, enabling positive changes, or harmful, depending on how technologies are used and managed.

Positive Indirect Effects (Enabling Effects)

The positive indirect effects or "enabling effects" are associated with the optimization and substitution capabilities of digital technologies. For example, digital technologies can optimize supply chains, enhance energy management systems, and facilitate the shift to a circular economy. The most widely acknowledged is the "abatement" potential of ICTs for reducing GHG emissions by optimizing processes that lead to more efficient use of resources (Bremer et al., 2023). By substituting physical goods or activities with virtual alternatives, such as virtual meetings instead of physical travel or commuting, digital solutions can mitigate some environmental impacts (Piscicelli, 2023).

However, the widely hailed "decarbonization and dematerialization" potential commonly associated with ICTs can be misleading. All virtual activities still rely on physical infrastructures, which are energy and water-eager and cause a wide range of environmental damage. Therefore, the digital sector can be considered material-intensive (CODES, 2022). The growth and widespread of the digital industry increase the demand for critical raw materials, which are also needed for green technologies, creating tensions between sectors and worsening the related environmental impacts.

Furthermore, despite extensive literature on the potential of ICTs to reduce GHG emissions, there is no consensus on the net impact of digital solutions thus far, making this matter both uncertain and controversial (Clausen et al., 2022; Schultze et al., 2016; Lange et al., 2020). Also, the uptake of digitally enabled processes remains limited across industries, and the expected efficiency and substitution benefits have not yet been fully realized.

Negative Indirect Effects

As previously introduced, the environmental indirect impacts also include potential negative outcomes, such as the "induction effect", where digitalization lowers the skill thresholds needed for some activities, potentially increasing their use (Coroamă and Pargman, 2020). This effect can lead to increased resource consumption, as has been noticed with the advancement of Generative AI.

Moreover, the "obsolescence effect" may also arise when products become less useful or outdated, and need to be changed, leading to increased waste (Hilty and Aebischer, 2015).

As argued by Wilson et al. (2024), digitalisation can reduce energy demand, but also carries risks of induced demand and rebound effects, potentially offsetting the initial environmental benefits (Wilson et al., 2024).

Therefore, the aggregate effects of digitalization across the entire sectors are relatively modest, suggesting that digital technologies should complement other decarbonization efforts to maximize their benefits. For example, according to Lange (2023), while affordable Internet access may lead to the widespread adoption of streaming services, it also increases environmental impacts from data centres.

In relation to the induction effect, refers to the increase in resource consumption caused by novel options offered by technological advancements. This effect reveals the importance of the sufficiency or sobriety principles, as strategies for sustainability. Besides, induction effects may generate new markets and demands, potentially offsetting the benefits of efficiency gains. Measuring induction effects is highly challenging due to their indirect nature, and the diverse methodologies for their assessment, such as market analysis, scenario modelling, and behavioural studies.

Addressing the induction effect requires a comprehensive approach, encompassing integrated policies, consumer education, and innovation. For instance, while digital technologies like IoT and Big Data Analytics can optimize supply chains and energy management systems, they still depend on physical devices, networks, and data centres, which require substantial material resources (Digitalization for Sustainability, 2022).

In conclusion, the indirect environmental impacts of digital technologies include both positive and negative effects, mediated through efficiency gains and changes in production and consumption patterns. While digital solutions can drive resource efficiency and reduce emissions, they also risk inducing new demands that offset those benefits.

Thus, to maximize the positive impacts of digitalisation, comprehensive strategies that integrate modern sustainability concepts, robust policy interventions, and ongoing research are essential to better understand and govern these effects. Additionally, addressing the induction effects also entails consumer education and innovation, ensuring that digital technologies complement other decarbonization efforts to achieve sustainable outcomes.

Rebound Effects (Higher-Order Effects)

After outlining the direct and indirect effects, the most complex impacts of digital transformation, known as rebound or third-order effects, are introduced. Rebound effects do not only affect the digital realm, but in this context, they are particularly significant and complex.

These effects occur when the efficiency gains from a technology lead to increased overall consumption and subsequent impacts on resource use, thereby counteracting the initial environmental benefits. This phenomenon is often demonstrated by Jevons's Paradox, by which improvements in efficiency result in higher demand and usage, aggravating overall environmental impacts (IPCC, 2022a).

According to Coroamă and Mattern (2019), several types of rebound effects applicable to digital technologies can be described, namely:

- “Direct Rebound” effects are caused when efficiency improvements lead to increased usage. For example, more efficient data centres may result in lower costs, driving higher demand for digital services.
- “Backfire” effects occur when the rebound effect is more significant than the original efficiency gain, leading to an overall increase in consumption.
- “Indirect Rebound” effects take place outside the original scope of efficiency gain. For instance, savings from reduced energy bills might be spent on other energy-consuming activities.
- “Time Rebound” effects are those related to time-saving technologies which lead to increased energy use, as users allocate saved time to other energy-intensive activities.

- “Macro-Level Rebounds” effects concern the economy-wide effects, in which increased efficiency across sectors leads to overall higher economic activity and resource use.

The rebound mechanisms are highly intricate and multifaceted, involving also economic, psychological, and time factors. Economic factors include the "income effect", where money saved from efficiency gains is spent on other goods and services, thereby increasing overall consumption.

Besides, psychological mechanisms relate to a perceived reduced impact or guilt, leading to increased consumption. For example, users of energy-efficient devices might feel justified using them more frequently. Lastly, time savings from efficient technologies may be dedicated to other activities that increase overall consumption (Coroamă and Mattern, 2019).

The complexity of measuring rebound effects is intensified by the interplay between efficiency and consumption patterns. Lange (2023) argued that a focus on efficiency alone hinders advancements in other sustainability areas. Understanding these effects requires considering external factors such as regulations, prices, and sociocultural contexts, making extrapolations highly uncertain (Horner et al., 2016).

Indeed, the rebound effects are highly controversial. Thus far, there is no consensus on which impacts should be classified as rebound effects or standardized methodologies to address them.

Wilson et al. (2024) stressed that the rebound effects of digitalization potentially offset the environmental benefits. For instance, while teleworking can reduce commute-related emissions, it can also increase energy consumption at home, and in addition, may also contribute to digital divides. Similarly, logistic optimization through e-commerce can lead to increased consumption, return rates, and carbon emissions (Bieser and Hilty, 2018b).

Thus, mitigation strategies to counter rebound effects are also complex and demand multiple considerations such as policy measures, like carbon pricing, taxes, and consumption regulations, as well as behavioural interventions through education and awareness campaigns. Additionally, providing incentives to encourage mindful consumption and sobriety is crucial.

Furthermore, given the salient gaps in terms of assessment frameworks, promoting the development of improved measurement methodologies, along with conducting holistic and interdisciplinary research, are necessary measures to better understand and manage rebound effects.

In conclusion, rebound effects are a significant challenge in the context of digitalisation. They can undermine the potential environmental benefits of efficiency gains by leading to increased overall consumption and subsequently drive negative impacts.

There is no consensus on what constitutes a rebound effect or on the mechanisms that drive these impacts. Addressing rebound effects requires a comprehensive approach that includes policy measures, consumer education, and improved research methodologies. Future directions should focus on developing comprehensive and effective tools to better assess and manage these impacts.

Systemic or Society-Wide Effects (Higher-Order Effects)

Other relevant higher-order environmental effects are those resulting from societal and behavioural changes caused by digital technologies and related interactions. For instance, remote working enabled by digital means may reduce transport emissions while increasing home energy consumption.

Besides, it may lead to demographic changes (e.g. living location), (Hilty and Aebischer, 2015; Horner et al., 2016; Pohl et al., 2019), along with changes in purchasing habits or communication. Moreover, systemic indirect effects can either mitigate or amplify environmental impacts, with uncertain outcomes.

Therefore, these systemic effects are highly complex, remain poorly understood, and are under-researched in the literature. A multidisciplinary approach is essential to fully understand and manage these far-reaching impacts effectively, but it is currently lacking. Comprehensive research integrating insights from various fields is needed to develop robust strategies for addressing these intricate challenges.

5.2.5. Transboundary Spillover Impacts

In environmental science, transboundary effects refer to impacts that cross geographical boundaries and affect regions and countries beyond their point of origin. Thus, these effects can be intricate and polyhedral, encompassing issues such as cross-border pollution, resource depletion, and climate change. Transboundary effects necessitate international cooperation and policy coordination to effectively manage and mitigate their far-reaching consequences. Examples include GHG emissions from one country contributing to global climate change, or electronic waste being exported from developed to developing nations, thus creating environmental and health challenges.

Transboundary spillovers in the context of digital environmental impacts refer to the effects that digital activities in one region or country may provoke on another, often extending beyond their origin and affecting areas in unforeseen ways. These impacts are not confined to the area where they originally occur and can manifest through various channels such as economic linkages, technological diffusion, and changes in consumer behaviour, leading to either positive or negative environmental consequences across different domains.

The transboundary spillovers are intricate and may impact the ability of different countries to achieve the SDGs, as underlined by Schmidt-Traub et al. (2019). Indeed, international SDG spillovers are widespread, affecting the environment, socio-economic factors, finance, governance, and security. Despite their significance, the monitoring of SDG progress and national strategies often overlook these transboundary spillovers, and a similar situation occurs in the digital context.

Furthermore, to illustrate their importance, the SDG Index report by Sachs et al. (2024) included a “Spillover Index” that assesses these effects along three dimensions: environmental and social impacts embodied in trade, economy, and finance, as well as UN-based multilateralism, peace, and security. A higher score on the index indicates that a country causes more positive and fewer negative spillover effects.

Positive spillovers include Official Development Assistance (ODA), sustainable trade practices, and knowledge transfers, fostering socio-economic progress and environmental benefits. Negative spillovers, on the other hand, include environmental damage from commodity demand, poor labour standards in supply chains, and financial practices like tax havens, which can undermine other countries' efforts to achieve the SDGs. Rich countries tend to generate significant negative international spillovers, primarily through trade-related activities such as unsustainable consumption.

Moreover, Ishii et al. (2024) presented the Global Commons Stewardship Index Report, which offers the latest data on transboundary spillovers affecting the Global Commons. The findings underscored the significant impact of negative trade-based spillovers and stressed the need to include effects in any strategy aimed at protecting the Global Commons.

Effective data and metrics at global, national, industry, and commodity levels are essential to tackle the negative impacts of unsustainable supply chains. However, currently, there is no global governance mechanism in place to coherently address these spillover effects and they are barely considered in the digital frameworks. Indeed, the above-mentioned renowned frameworks do not consider digital spillovers.

Despite the growing importance of understanding digital transboundary spillovers, research and policy in this area remain limited, deserving further exploration and political support.

In this regard, Liu, and Ma (2024) examined the impact of the digital economy on environmental pollution in China, finding that it reduces pollution through better governance, increased public environmental awareness, and improved technology integration. This study underscored the spatial spillover effects revealing that positive impacts on pollution reduction in one region can extend to neighbouring regions, contributing to broader environmental improvements.

Hence, to effectively manage digital spillovers, it is crucial to measure cross-data flows, and impacts within supply and global value chains, along with trade-related negative impacts such as raw materials and e-waste. Besides, it is required to explore policy and diplomatic solutions and foster North-South and South-South dialogues to enhance positive outcomes and minimize negative ones. Policy and data improvements are crucial for tackling and countering these complex and controversial negative effects.

Furthermore, global partnerships and strong multilateral norms and standards are essential elements for creating a sustainable trade system that works for both people and the planet. Enhancing governance of international supply chains, applying existing measurement methods to more SDG spillovers, promoting open-access supply chain data, improving data consistency, and advancing hybrid assessment methods are all critical steps in this mission (Ishii et al., 2024; Sachs et al., 2024; Schmidt-Traub et al.; 2019).

Therefore, comprehensive, and up-to-date frameworks that account for digital spillovers on the environment and society are essential for addressing these complex challenges. The proposed Taxonomy fully integrated this aspect.

5.2.6. Handprints of Digital Transformation on The Environment

Digital transformation affects the environment through both negative "footprints" (e.g., emissions, resource depletion) and positive "handprints" (e.g., technologies that support sustainability). Traditionally, the focus has been placed on minimizing digital footprints. However, the emerging concept of "handprints" shifts the narrative, by emphasizing the positive effects.

The notion of "handprints", introduced by Goleman (2012), emphasizes the creation of beneficial impacts instead of merely reducing the negative ones. This approach has been further developed to encourage intentional actions that produce positive social and environmental effects. The idea aligns with the "net-positive" framework (Norris, 2015; 2017), which in this context signifies achieving a balance where the positive impacts of digitalisation outweigh its negative footprints.

Indeed, handprints are created through proactive efforts of individuals and organizations not only to mitigate negative effects but also to generate net-positive benefits. Such efforts can be behavioural (e.g., adopting a plant-based diet), or infrastructural (e.g., installing solar panels). In the context of digital transformation, handprints offer significant opportunities across various socio-economic sectors, including healthcare, renewable energy, agriculture, and biodiversity conservation, among many others.

In this regard, digital technologies have the potential to optimize resource use, reduce GHG emissions, and enhance renewable energy management. For instance, smart grids can optimize energy distribution, while AI can be used for climate modelling and prediction. Data analytics enable environmental monitoring, and IoT devices support smart agriculture by improving resource efficiency.

Notably, research has explored the role of digital technologies in promoting circular economies and reducing pollution (García-Berná et al., 2019; Piscicelli, 2023).

Also, Digital Twins and energy-efficient IoT are promising innovations for environmental management, although they require further validation (Szalkowski et al., 2024). Technologies like IoT, Big Data Analytics, and Blockchain hold the potential to enhance sustainable consumption and production by improving resource efficiency.

It is worth mentioning that handprints in the digital domain often overlap with Green ICT mitigation strategies, but they present different perspectives and functions. While Green ICT strategies focus on minimizing the environmental footprint of digital technologies, “hand-printing” emphasizes the responsible application of digital solutions to tackle environmental and social challenges across sectors and disciplines. Therefore, although these strategies sometimes intersect, it is relevant to distinguish them clearly, to enable more targeted and effective interventions.

Several organizations, including the World Bank, ITU, and GSMA, have emphasized the outstanding potential contributions of digital transformation to environmental sustainability, addressing areas like smart cities, climate change, and biodiversity protection (World Bank and ITU, 2024; GSMA, 2021; ITU, 2019).

In terms of assessing the handprints of digital technologies, it is still a nascent field which requires further research. Existing methodologies include the adaptations of Life Cycle Assessment (LCA) techniques, such as the “Attributional LCA” (ALCA), “Consequential LCA” (CLCA), and “Handprint ALCA.”

Moreover, the “Handprint-based Net Positive Accounting” (HBNA) approach evaluates the net-positive change across the lifecycle of a product, thereby sharing responsibility for handprints among contributors (Norris, 2015).

In addition, the “Sustainability and Health Initiative for Net Positive Enterprise” (SHINE) has introduced approaches for measuring handprints, particularly for addressing complex “scope 3” GHG emissions (SHINE, 2021a). However, complexities in estimating these emissions, especially downstream considerations, have impeded the adoption of handprint methodologies in mainstream sustainability reporting frameworks (Elliott et al., 2022).

Considering broader aspects, social sustainability handprints are also being explored, with methodologies like the “Social Organizational Life Cycle Assessment” (SO-LCA), which provides pathways to measure social impacts within the ICT sector (Husgafvel, 2021; 2023). Despite these advancements, the application of handprints remains limited, and the focus is often overly centred on carbon emissions, neglecting broader environmental impacts.

Digital handprints have significant potential for environmental and social regeneration, but realizing this potential requires standardized methodologies, refined assessment techniques, as well as the integration of “handprint thinking” into existing sustainability reporting frameworks. Current approaches are underdeveloped and require further research to accurately assess the net contributions of digital solutions to sustainability.

Therefore, embedding the handprint concept into mainstream sustainability efforts relies on establishing theoretical support, common terminology, and universally accepted standards, and metrics. The widespread of “handprinting” holds the potential to shift the focus from challenges to opportunities, thereby empowering organizations, and individuals to pursue regenerative pathways based on robust, science-based approaches.

5.2.7. Green ICT Mitigation Strategies

As discussed previously, digital transformation (DT) has far-reaching impacts on the environment, which require comprehensive strategies to mitigate and prevent potential negative outcomes. Therefore, a strategic approach to risk assessment, and impact management, along with robust mitigation strategies is critical for achieving sustainability in this domain.

These potential strategies include robust policy interventions, sustainable production, and consumption practices, along with other actions addressing behaviour change, education, and research and innovation.

As Roussilhe et al. (2023) pointed out, the literature often emphasizes the positive aspects of digital transformation while neglecting its adverse effects. This oversight underscores the need for more robust evaluations and risk management frameworks. Addressing the multifaceted nature of the environmental impacts of DT demands a multidisciplinary and multi-stakeholder approach.

Key to this effort are the policy interventions, as well as activities addressing consumer behaviour changes, awareness campaigns, and the development of low-impact technologies (e.g., Greentech). Furthermore, strong strategic support, together with multidimensional policies and programmes, are crucial to holistically understand and tackle the impacts of the digital transformation processes.

In this context, the strategies based on “Green Information and Communication Technologies” (Green ICT) are critical for promoting sustainability in the digital age. This concept, initially termed “Green IT,” encompasses practices and strategies aiming to reduce the environmental impact of ICTs throughout their life cycle. Murugesan (2008) defined Green IT as the “designing, manufacturing, using, and disposing of ICTs efficiently and effectively, with minimal or no impact on the environment”.

While Green ICT strategies have primarily focused on direct impacts, such as energy consumption and carbon emissions, higher-order effects are still poorly understood and under-explored in current research. Notably, Green ICT not only addresses carbon footprints and e-waste, but also involves strategies like energy optimization, the adoption of low-carbon technologies, renewable energy integration, and many more.

Sustainable practices and trends like eco-design, eco-innovation, and ecological frugal innovation are increasingly recognized and integrated within Green ICT, as key elements in developing sustainable hardware and software. Moreover, Green ICT practices are often linked with smart solutions, such as smart buildings, smart grids, and smart mobility systems with strong digital components.

Beyond energy efficiency, Green ICT strategies encompass other practices such as eco-labelling, green procurement pledges, ethical green nudging, environmental education, and awareness-raising actions to promote behaviour change. According to Ojo and Fauzi (2020) raising environmental awareness, leadership and commitment are crucial factors in fostering engagement with Green ICT practices. In addition, cultivating an organizational culture that prioritizes sustainability, alongside setting clear goals, is also crucial for greening the digital sector.

Additionally, Faucheux and Nicolaï (2011) advocated for an interdisciplinary perspective to promote Green ICT practices for driving holistic sustainability in the digital realm. In this regard, Szalkowski et al. (2024) identified eight relevant strategies: Green technology-based solutions to reduce ICT impacts through AI-based optimization; the integration of renewable energies to reduce the carbon footprint; enhanced e-waste management through circular approaches; sustainable manufacturing; carbon taxes; cybersecurity measures; the promotion of sustainable lifestyles by awareness campaigns and educational programs; and novel theoretical tools, research methods, and policies to better understand and address impacts.

Despite their potential, Green ICT mitigation strategies still face challenges. The current guidelines and standards are often outdated and are inadequately adopted by practitioners (UNCTAD, 2024). Standardization organisations such as ETSI, ITU-T, 3GPP, and ATIS⁴ are working to develop methodologies for assessing the environmental impacts of ICTs, promote circular practices, and improve waste management.

However, these outstanding efforts have yet to translate into the desirable standardized methods and metrics that the digital sector needs to fully assess the environmental impact of ICTs and ensure the scalability of sustainability practices. Additionally, the rapid pace of digital development complicates the landscape, making it challenging to keep up with technological advancements. Therefore, continuous innovation and standardization efforts are needed to keep Green ICT strategies updated with the risks posed by technological advancements.

For that purpose, Green ICT practices should be more ambitious. Collaboration between academia, industry, and government is essential to provide the means, knowledge, and capacities to drive the mindful adoption of these practices on a global scale. One relevant aspect often overlooked is the need to cover the whole spectrum of environmental impacts, throughout the entire life cycle and across supply chains, as most impacts occur outside organizational boundaries and must be carefully considered.

Additionally, these practices should align with widely acknowledged sustainability principles, and regeneration vision, along with being adaptable to novel trends such as sufficiency, conviviality, or degrowth. This alignment is paramount for ensuring a suitable future evolution of Green ICT practices towards a more ambitious regenerative approach.

After outlining the general context of Green ICT strategies, a more detailed examination of the most impactful mitigation practices is provided. The proposed taxonomy of Green ICT strategies integrates a wide range of these practices (see Table 5.6).

Table 5.6. Green ICT Mitigation Strategies in the Taxonomy for SRDT
(Own elaboration)

- *“Greentech” solutions, such as renewable power to reduce GHG emissions and air pollution.*
- *Eco-design measures for sustainable materials, processes and infrastructures based on the sufficiency and resilience principle.*
- *Eco-innovation and frugal innovation.*
- *Eco-entrepreneurship for conscious digital business models.*
- *Green virtualization.*
- *Circularity by right-to-repair policies, Digital Product Passports, strategies for extending lifespan, reuse, and recyclability, along with urban mining for material recovery.*
- *Responsible second-hand and sharing economy platforms.*
- *Robust and updated environmental standards, assessment methodologies and metrics for the ICT sector.*
- *Green procurement and digital infrastructure pledges.*
- *Green software strategies, including computing within limits.*
- *Green labels, auditable certification schemes for green algorithms and responsible and sustainable AI.*
- *Sustainability regulation and incentives for the ICT sector (e.g., green data centres).*
- *Policy and financing mechanisms such as carbon taxes.*
- *Green skills and sustainability education programs, ethical green nudging schemes.*
- *Enhanced, dynamic and double-material ESG reporting for the ICT sector.*
- *Updated responsible consumption and production guidelines for Sustainable ICTs*
- *Standardized and robust Corporate Digital Responsibility schemes.*
- *Open environmental data repositories for mindful decision-making.*

⁴ ETSI (European Telecommunications Standards Institute); ITU-T (International Telecommunication Union - Telecommunication Standardization Sector); 3GPP (3rd Generation Partnership Project); ATIS (Alliance for Telecommunications Industry Solutions).

Circularity Strategies

Embedding circular economy principles within digital transformation is a promising strategy to enhance resource flows and promote sustainability as argued by Ranta et al. (2021) and Liu et al. (2022). However, these technologies themselves present a challenge to sustainability, as previously discussed.

Some promising strategies for addressing the circularity in the digital domain, are the right-to-repair (R2R) policies, and the Digital Product Passports (DPPs), which are particularly relevant for digital products.

The R2R movement advocates for the consumers' rights to repair electronic devices, addressing issues like product obsolescence and limited access to repair tools. This strategy reduces the material footprint, and the generation of e-waste, and extends the lifespan of products while making more accessible the repair markets (Manwaring et al., 2022). Yet, several barriers like repair costs, availability of spare parts, logistics and facilities for reparability, need to be addressed (Manwaring et al., 2022; Roskladka, 2023).

Regarding the DPPs, they compile lifecycle information of products to support sustainable use, maintenance, and end-of-life management. Jensen et al. (2023) emphasized their role in providing data for informed decision-making. Besides, the DPPs enhance transparency and traceability within supply chains, fostering global standards and sustainable practices. Gonzales et al. (2023) argued that combining R2R policies with DPPs can address digital disparities and e-waste issues.

This synergy between right-to-repair and DPPs empowers consumers to make informed, sustainable decisions. Circular practices must be underpinned by guidelines, policies, and standards to ensure effective implementation. Some initiatives in this regard include the Circular Transition Indicators (WBCSD, 2023) and the recent EU's Right to Repair Directive (EU, 2024b). Nevertheless, further research is needed to assess these initiatives' effectiveness and explore their socio-economic impacts.

Another promising circular approach that requires further exploration is the "urban mining" of e-waste. Yet, the recyclability of electronics remains complex. As argued by Ouro-Salim (2024) and Xavier et al. (2023), urban mining involves extracting valuable resources, such as raw materials, from e-waste to promote circularity in the digital sector, inspired by industrial metabolism and ecology. This strategy requires innovation, along with comprehensive regulations to address technical and social barriers, extending producer responsibility, and broader stakeholder participation, including consumers and informal workers.

Eco-Design Strategies

The eco-design strategies and practices are critical in minimizing resource consumption and waste generation throughout the life cycle of digital products, systems, and infrastructures, with a focus on promoting durability, reparability, and recyclability. In this regard, Szalkowski et al. (2024) underlined the potential of eco-design to substantially enhance resource efficiency, particularly during the production phase. Similarly, Martínez-Cámara et al. (2021) demonstrated the effectiveness of integrating eco-design with life cycle assessment (LCA), achieving a 30% reduction in environmental impact and an 11% cost reduction.

A holistic approach that incorporates eco-design principles across the product lifecycle is advocated, aligning with movements such as "Computing within Limits" (Chen et al., 2016), which emphasizes the need for sustainable and resilient computing systems.

Relevant standards supporting eco-design in the ICT sector include the ITU-T L.1306 (2023) guidelines for green data centres and the IEC 62430 standard for electrical and electronic products, including ICT equipment.

Sustainable Computing Paradigms

The growing focus on sustainability has given rise to computing paradigms inspired by eco-design, sufficiency, and degrowth. For instance, the low-carbon computing and the "computing within limits" communities advocated for resilient ICTs that function within planetary boundaries (Vanderbauwhede, 2021). Nardi et al. (2018) and De Valk (2021) called for a shift in computing research to prioritize resource-conscious technologies that contribute to the ecological balance within material limits, criticizing growth-oriented paradigms that disregard ecological boundaries. These emerging concepts push the boundaries of current practices, promoting a more sustainable digital future.

Similarly, the "LIMITS" research community brings together scholars to explore the computing role in addressing ecological constraints, emphasizing the need for sustainable human-computer interaction (SHCI), crisis informatics, and ICTs for sustainable development. However, existing metrics that reflect planetary limits and sufficiency strategies remain underdeveloped. In this context, Van der Bauwhede (2021) discussed "frugal computing", which aims to achieve traditional outcomes with fewer resources by promoting energy efficiency and hardware longevity. This requires changing computing structures, business models, and consumer awareness.

Furthermore, Mansoux et al. (2023) introduced the notion of "permacomputing", a practice inspired by permaculture that embraced constraints and scarcity in computational culture. This paradigm challenged digital norms that promote resource maximization, and advocates for sustainable and regenerative practices that prioritize low-impact, resource-efficient computing. De Valk (2021) critiqued the dominance of green capitalism in sustainability discussions, calling for increased visibility of small-scale practices that challenge mainstream technological and economic paradigms.

In this regard, the Green ICT and ICT4S communities have introduced groundbreaking concepts focused on minimizing the environmental impacts of computation. De Valk (2021) introduced terms like "convivial computing", which promotes community autonomy, "salvage computing", which emphasizes circularity by repurposing obsolete systems, and "collapse informatics", which designs low-resource tools for potential environmental collapse. These ideas advocated for resource efficiency and sufficiency, along with environmental mindfulness in IT practices.

Eco-Innovation and Frugal Innovation

Concerning eco-innovation, it involves technological, social, and cultural changes to promote sustainable development within the ICT sector (Faucheux and Nicolai, 2011). It extends beyond technological advancements to embrace new business models and practices, supporting a circular economy.

Similarly, frugal innovation focuses on creating affordable, high-quality solutions with minimal resources, promoting resource efficiency and social value (Yousaf et al., 2021). However, not all frugal innovations are inherently sustainable, therefore the term "ecological frugal innovation" should be used when environmental benefits are explicit (Albert, 2019).

Moreover, Aanestad (2023) cautioned against the uncritical promotion of digital technology as a sustainability solution, advocating for alternative paradigms like "permacomputing" and frugal innovation within sufficiency-oriented approaches. These concepts align with a regenerative vision for the digital sector, emphasizing mindful consumption, minimal impact, and positive social and environmental contributions.

Green Procurement

Responsible sourcing and green procurement processes are crucial for sustainability in the digital sector (Szalkowski et al., 2024; CODES, 2022). Green procurement policies not only protect the environment but also counter human rights abuses, often prevalent in global digital and “GreenTech” value chains. Ethical and sustainable practices within green procurement contribute to a more just digital economy, ensuring environmental and social responsibilities throughout the supply chain.

In this regard, Barbini et al. (2020) proposed using life cycle data in Building Information Modelling (BIM) to enhance green public procurement processes. This approach integrates environmental and economic impacts into decision-making, promoting sustainability in public infrastructure projects. Similarly, Rane and Thakker (2019) underlined the potential of Blockchain and IoT to improve green procurement processes, while Wang et al. (2023) emphasized the role of digital technologies in enhancing green supply chains with efficiency and effectiveness.

However, successful green procurement heavily relies on political awareness and support. In this sense, political commitment to sustainability is essential for setting regulations and providing incentives for sustainable practices. Lăzăroiu et al. (2020) argued that green public procurement (GPP) fosters environmental responsibility and sustainable purchasing, advancing investments in the circular economy.

According to ITU (2023), green procurement in the digital realm involves integrating sustainability principles into purchasing ICT equipment, systems, or services. Its core principles include sustainability awareness, alignment with policies, and the promotion of circularity. In addition, effective governance and stakeholder engagement are vital to connect implementation with policy.

Thus, a synergistic relationship exists between digital technologies that enhance green procurement processes and the application of green practices to make the procurement of ICT systems more sustainable and transformative.

Green Nudging, Environmental Awareness, and Education

Promoting sustainable lifestyles through educational programs and awareness campaigns can shift behaviours toward environmentally friendly practices. "Green nudging" leverages digital technologies, like AI, to encourage sustainable behaviour (Bartmann, 2022). For instance, Grelle et al. (2024) found that nudging strategies framed on a personal level are more effective when the effort required is minimal.

Yet, green nudging raises ethical and legal concerns. While it aims to influence behaviour while preserving freedom of choice, its use can lead to issues around democracy and autonomy (Liu et al., 2019). In this regard, Bartmann (2022) argued that AI-powered climate nudging is ethical if aligned with "self-governance", characterized by symmetry, democracy, and transparency.

Furthermore, wicked problems such as climate change, are framed as "collective action" issues, which require overcoming the "tragedy of the commons", and addressing the market failures caused by GHG emissions. In this realm, green nudging, when ethically implemented, can be a tool to promote sustainable practices and address environmental challenges.

Robust Standardization

Many environmental aspects of digital transformation, particularly the assessment of the carbon footprint, e-waste management, or circularity practices aiming to reduce the planned obsolescence of digital devices, strongly depend on standardization. Several Standard Developing Organizations (SDOs), including ETSI, ITU-T, ECMA, and ISO/IEC have provided guidelines for energy efficiency, waste management, and Life Cycle Assessment (LCA) of ICTs.

Notably, the standards provide consensus metrics and methodologies to ensure compliance with sustainability and technical requirements, consistency and legitimacy of green claims and are also useful for comparing the sustainability performance among organisations and contexts.

Most standards focus on resource efficiency and carbon footprint aspects. For instance, the “ISO/IEC 30134 series” provides pathways for enhancing energy efficiency, promoting carbon neutrality, and water conservation in data centres, including the following metrics: Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), Water Usage Effectiveness (WUE), Renewable Energy Factor (REF), among others. While the “ITU-T L.1470” supports resource management in ICT infrastructures.

Other key standards include the “IEC 62430:2019,” which offers guidance on environmentally conscious design, and the “ECMA-370 standard”, also known as “The Eco Declaration”, which defines environmental attributes and measurement methods for ICT and consumer electronics products.

Relevant guidelines in this field include the “Green Data Centres” (ITU, 2023), Greening Digital Companies (ITU, 2023), and the ECMA-341 “Environmental Design Considerations for ICTs” (ECMA, 2010).

In addition, another collective effort towards sustainability in the digital realm is the Climate Neutral Data Centre Pact (CNDP), setting ambitious targets for energy efficiency, renewable energy use, water conservation, and circular economy practices. By 2030, the pact aims for 100% renewable energy use and water conservation strategies. It also promotes the reuse and recycling of server equipment to reduce e-waste, aligning with broader sustainability goals. Therefore, these efforts underscore the relevance of standards to guide a more sustainable digital transformation.

Nevertheless, as previously mentioned, existing guidelines and standards in this field are often outdated, narrowly designed by focusing on energy consumption and efficiency, carbon footprint, and e-waste, and insufficiently adopted by practitioners (UNCTAD, 2024). Therefore, further research and policy development are necessary to reinforce the development and adoption of Green ICT standards (Szalkowski et al., 2024), particularly for AI.

Dynamic ESG Reporting

Environmental, Social, and Governance (ESG) reporting is crucial for assessing and addressing the environmental impacts of ICTs. Several global standards, such as the Sustainability Accounting Standards Board (SASB) and International Financial Reporting Standards (IFRS), have been adapted to support ESG reporting in the digital, ICT, and electronics sectors.

Leveraging these standards through sustainability analytics supports the identification and management of impacts, as well as the development of suitable Green ICT strategies to tackle them.

In this context, the concept of double materiality is central to ESG reporting, especially within the novel European Sustainability Reporting Standards (ESRS). Double materiality considers both impact materiality (inside-out perspective) and financial materiality (outside-in perspective). This holistic approach ensures that sustainability reports reflect the environmental and financial risks of an organisation, thereby offering a comprehensive view of its contributions to sustainability.

Renowned standardisation organisations in the digital realm, such as ITU and IEC, have also released guidelines to support sustainability reporting in the ICT sector. Nevertheless, challenges remain, and further efforts are needed to enhance ESG reporting to better align with the emerging needs and impacts brought about by digital disruptions.

Regulation, Policy, and Incentives

Regulations and policies play a crucial role in driving sustainability in the ICT sector. Policies like carbon pricing and taxes incentivize companies to reduce GHG emissions by imposing financial costs on emissions. Similarly, the EU's Right-to-Repair Directive promotes circularity by enabling consumers to repair electronic devices, thus extending their lifespan and reducing the demand for new products. Besides, the “Green Taxonomies” for sustainable economic activities and the reporting regulations like the EU’s Corporate Sustainability Reporting Directive (CSRD), can also contribute to promoting a sustainable digital transformation, by channelling investments in this direction.

Furthermore, internal corporate policies are also essential for fostering sustainability. However, these policies are often under-researched and under-implemented in practice, limiting their potential impact (Szalkowski et al., 2024). For instance, the “ICT Sustainability Global Benchmark” by Fujitsu (2020) emphasized the importance of internal sustainability policies within organizations.

In essence, effective regulation, and policy, at both governmental and organisational levels, are vital for promoting sustainable practices in the ICT sector.

Following the review of the most relevant Green ICT strategies, it can be concluded that despite their potential, several challenges persist. These include significant upfront investment requirements, technical hurdles in integrating new technologies with existing systems, and the need for suitable policies to maximize their environmental benefits.

Also, the lack of comprehensive standards, and updated sustainability frameworks that incorporate emerging trends underlines the need for further research, standards, and methodologies, along with policies to promote sustainability across stakeholders in a more comprehensive manner.

These strategies must also align with broader sustainability principles, including regeneration, sufficiency, and degrowth, to ensure their future evolution. In addition, the focus of Green ICT strategies must extend beyond energy savings and the reduction of carbon footprint to encompass broader environmental impacts. Policies such as right-to-repair, digital product passports, and green software development need to be enforced and supported by updated regulations, standards, and metrics.

5.2.8. Digital Opportunities for Regenerative Sustainability

This aspect has been already introduced in Chapter 3, concluding that digital solutions hold outstanding opportunities for regenerative sustainability, but they remain still poorly researched and implemented at a large scale. In this section, this intriguing aspect is further developed.

Indeed, digital technologies and innovations, inspired by regenerative principles, hold significant potential to contribute to environmental sustainability. They can enhance ecosystem management and protection, sustainable urban design, sustainable materials discovery, nature-based solutions, climate action, resource efficiency, bioinformatics, and bioprocesses, among others.

A relevant advancement in this field is the integration of biological principles into computing, giving rise to novel paradigms such as bioinformatics. Indeed, bioinformatics could contribute to sustainable development by optimizing computational methods to reduce carbon footprints, enhance bio-based processes, and support sustainable agricultural practices. In this regard, Krüger et al. (2020) emphasized the crucial role of digitalisation in transitioning to a sustainable, bio-based circular economy. However, the full potential of these approaches remains untapped.

Similarly, biomimicry, the discipline that emulates natural designs to address societal challenges, is gaining traction in the digital realm. Biomimicry shows potential to contribute to several SDGs, as underlined by Raman et al. (2024).

According to Hayes et al. (2020), biomimicry could support regenerative performance in infrastructure by using natural models to inspire innovative design and engineering solutions. However, this field is still in its infancy and requires further research to clearly articulate its benefits.

Martin (2023) examined the application of biomimicry in virtual reality (VR) technologies, concluding that it could create advanced digital ecosystems that mirror the balance and resilience of nature, thereby enhancing user experience and engagement, and raising awareness of conservation efforts. Nevertheless, ethical considerations must be addressed when employing biomimetic VR.

Biomimicry also finds application in Industry 5.0. In this regard, Unruh (2023) argued that the adoption of biomimetic principles in production processes could lead to more sustainable and resilient systems, transforming industrial operations.

Other technologies, when managed responsibly, also have the potential to advance regenerative sustainability. For example, Kadar and Kadar (2020) ventured that AI-supported design could speed the transition toward regenerative industrial design.

The field of bionic design is also gaining momentum. Jiang et al. (2024) described "bionic" design as a harmonious blend of nature-inspired innovation, eco-design, aesthetics, and resource efficiency, with applications across various industrial domains. Similarly, Bensaude-Vincent (2019) explored the alignment of synthetic biology, materials chemistry, and soft robotics with broader bio-informed design trends like biomimicry and biomimetics, which challenge traditional perspectives on the roles of nature and engineering.

Another field of application is regenerative agriculture within "AgriTech" communities (Umantseva, 2022). Digital solutions, such as IoT and AI, can optimize water usage, reduce chemical inputs, enhance crop yields, and promote soil regeneration.

Additionally, this influential relation is symbiotic, since regenerative agriculture practices like "permaculture," have also inspired regenerative digital paradigms, such as "permacomputing." This novel application, inspired by the principles of permaculture and sufficiency, aims to provide a sustainable approach to computing that promotes resource-efficient systems that respect natural boundaries (Mansouz et al., 2021).

As Naboni and Havinga (2019) explained, regenerative practices are also becoming relevant to urban design. In this regard, digital tools like BIM (Building Information Modelling) and digital twins are being used to design regenerative and nature-based infrastructures and to create more sustainable urban environments.

Despite their potential, these technologies remain in their early stages and face significant challenges, including regulatory hurdles, market acceptance, integration issues, and ethical considerations. Thus, further research is essential to fully unlock their potential and ensure their responsible implementation.

5.2.9. Reflections on the Planetary Sustainability Pillar

Digital transformation has the potential to cause a wide range of environmental effects, both negative and positive. Overall, the environmental impacts of digital transformation are diverse and multifaceted, encompassing direct, indirect, rebound, systemic, and spillover effects. To foster a sustainable and regenerative digital future, it is essential to understand comprehensively these impacts. Addressing the environmental impacts of digital transformation requires a balanced, multidisciplinary, and holistic approach.

However, current assessment frameworks and standards for evaluating digital impacts are inadequate, as they are often narrowly focused on a few matters such as GHG emissions, neglecting the broader ecological considerations, the principles of resilience, regeneration, and the eco-social nexus.

Furthermore, indirect and rebound effects are complex to evaluate, and their exclusion from most assessments hinders a comprehensive understanding of the environmental impact of digitalisation. Consequently, the net impact of digital transformation on the environmental dimension remains uncertain.

Green ICT practices for mitigating the negative impacts of digitalisation on the environmental dimension encompass a wide range of strategies, from renewable energy integration to circularity, eco-design, eco-innovation, education, and policies. Although challenges persist in the implementation, integrating these practices into organizational and societal frameworks can significantly contribute to a sustainable and regenerative digital transformation.

Nevertheless, to fully address the environmental impacts of digital transformation, it is imperative to go beyond mitigation and embrace regenerative approaches. This requires enhancing and broadening the existing frameworks, since they tend to focus on minimizing negative footprints, but often overlook the potential for positive handprints, regeneration opportunities and eco-social interconnections.

Therefore, integrating these aspects and, particularly, the perspective of environmental regenerative sustainability into the Digital Agenda and related frameworks is essential. This involves embedding comprehensive sustainability policies, practices, and monitoring frameworks into digital transformation efforts.

Future research should focus on refining methodologies, creating standards, and developing robust metrics, which align with modern sustainability demands and principles.

This will facilitate a more effective and accountable assessment of the environmental impacts of digital technologies while ensuring that Green ICT strategies and digital solutions for sustainability evolve in tandem with technological advancements and societal needs.

Moreover, these strategies should be complemented by cross-sector collaboration and partnerships, sustainable procurement practices, behaviour change, education and awareness raising, along with suitable policies and regulations, to involve all the stakeholders to collectively contribute towards a sustainable digital future that prioritizes environmental and social well-being.

In essence, acknowledging and addressing the complex nature of the environmental effects of digital transformation through a regenerative perspective is crucial for navigating the associated challenges and opportunities and contributing to harmonious coexistence between technological progress and ecological preservation.

The proposed Taxonomy for SRDT aims to contribute to bridging current gaps, by providing a comprehensive panoramic of the impacts and opportunities of the digital transition across the most relevant domains of sustainability in this research context and with a regenerative perspective.

In conclusion, the “Planetary Sustainability Pillar” represents the environmental dimension of the triple transition, and encompasses the principles and policies, environmental impacts (direct, indirect, rebound, systemic, transboundary), mitigation strategies (Green ICT) to counter the negative impacts, and digital opportunities for regenerative environmental sustainability. The summary of this pillar and the respective alignment of their domains with the SDGs is provided in Table 5.7.

Table 5.7. Domains within the Planetary Sustainability Pillar and their Alignment with SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PLANETARY SUSTAINABILITY (ENVIRONMENTAL DIMENSION)	Planetary Sustainability and Regeneration Principles and Policies	SDG 3, 6, 7, 11, 12, 13, 14,15, 17
	Environmental Direct Impacts (first-order effects or footprints, e.g. direct GHG emissions or electronic waste)	SDG 3, 6, 7, 11, 12, 13, 14,15
	Indirect Impacts (second order): desirable enabling effects (optimisation, substitution)	SDG 6, 7, 11, 12, 13, 14,15
	Indirect Impacts (second order): undesirable effects (induction, obsolescence).	SDG 6, 7, 11, 12, 13, 14,15
	Rebound and Systemic Effects (unintended high-order effects, societal effects)	SDG 6, 7, 11, 12, 13, 14,15
	Transboundary Spillover impacts (beyond system limits)	SDG 3, 6, 7, 11, 12, 13, 14, 15, 17
	Environmental Handprints (net-positive effects within or beyond the ICT sector)	SDG 6, 7, 9, 11, 12, 13, 14,15, 17
	Green ICT Mitigation Strategies and Awareness-Raising	SDG 3, 6, 7, 9, 11, 12, 13,14,15,17
	Digital Opportunities for Regenerative Sustainability and the SDGs	SDG 6, 7, 11, 12, 13, 14, 15 All SDGs

5.3. The People Pillar: the socially just transition

The "People Pillar" of the proposed Taxonomy, addresses the social dimension of the digital transformation, aligning with a vision of socially just transition (WBA, 2023). Therefore, it focuses on creating societal value and resilience through the mindful use of digital technologies, while promoting responsible adoption and regenerative opportunities, thereby ensuring that no one is left behind.

This pillar encompasses several domains, including the following: equitable and inclusive digital development; digital human rights and human-centred digital transformation; responsible use and safe adoption of digital solutions; digital culture, creativity, and humanism; digital opportunities for social resilience and regeneration; and societal engagement and empowerment by inclusive e-participation.

All these aspects are relevant for ensuring a robust just transition within digital transformation, and for that reason are thoroughly integrated within the proposed Taxonomy for SRDT. A detailed substantiation of these domains is provided in the next sections.

5.3.1. Equitable and Inclusive Digital Development

Digital equity is essential for ensuring that everyone has the necessary skills and access to technology to engage fully in society, democracy, and the economy. In this regard, digital inclusion refers to providing equal access to information and opportunities via ICTs, including civic engagement and social justice. The term "equity" is preferred over "equality" because it recognizes the systemic barriers that must be addressed before true equality can be achieved (NDIA, 2023).

Achieving digital inclusion relies on implementing specific programmes, policies, and incentives aimed at ensuring that all communities have access to ICTs and ensure safe use of these solutions. Additionally, digital inclusion is strongly linked with digital readiness, which depends on affordable internet access, digital literacy, and meaningful online content (UNDP, 2019).

In this regard, expanding access to ICT is crucial not just for digital capabilities but also for enhancing educational skills, as Song and Jang (2023) underlined. Digital access is increasingly significant as online education and training become more prevalent.

However, the current digital landscape is often shaped to primarily meet corporate interests, leading to issues such as "digital redlining" (NDIA, 2023), a form of discrimination by internet service providers that disproportionately affects vulnerable populations.

This emphasizes the need to embed a stronger focus on inclusiveness and social protection in the digital agenda.

5.3.2. Digital Human Rights, Co-responsibility, and Human-centred Digital Transformation

The rapid advancement of digital technologies is significantly affecting human rights and democratic processes. While digital transformation offers many benefits for society, it also poses risks, including societal division, polarization, and the erosion of human rights and trust in democracies. Therefore, a collaborative global effort involving governments, businesses, and civil society is needed to ensure that technological progress aligns with human rights and democratic values.

Key aspects of digital human rights include privacy, data protection, freedom of expression, access to accurate information, protection from digital manipulation, and the right to participate in digital public spaces (URG, 2021a). The "Seventh Glion Human Rights Dialogue" (URG, 2020) emphasized that digital technology must work for human rights, therefore it advocates for stronger collaboration among stakeholders to actively position technology "at the service of human rights".

This vision aligns with the concept of social regeneration embedded within this dissertation, which also advocates for digital spaces safeguarding human rights and values and fostering civic engagement.

Additionally, environmental human rights are integral to digital transformation, in alignment with the previously described nexus between human prosperity and natural well-being.

These include substantive rights that rely on healthy environmental conditions and procedural rights related to information access and participation (URG, 2024). Although there is no comprehensive international instrument governing all environment-related human rights, a complex body of laws forms the basis of the right to a healthy environment, underscoring the intertwined nature of social and environmental aspects in this pillar.

Despite efforts to create global frameworks for protecting human rights online, significant gaps remain. Many countries poorly endorse available principles for digital rights, which reveals the need for further efforts in terms of research, policy development, diplomacy, and global cooperation.

Protecting digital human rights involves fostering awareness, co-responsibility, and ownership among all stakeholders. This includes educating people about their rights and encouraging communities to advocate for fair, secure and rights-protective digital environments, and practices.

Concerning the advancement of human-centred digital development, this also entails working on the transformational aspects related to human well-being, inner growth, and personal development.

As noted by UNDP (2024a), digital transformation is reshaping fields like health, education, social norms, relationships, employment, and individual agency, while also contributing to challenges such as disinformation, polarization, and other destabilizing societal trends. Therefore, it is also important to consider the inner dimension of human development, to promote a culture of responsibility, digital well-being and conscious engagement based on self-reflection, awareness, and purpose, enabling both personal and collective resilience (UNDP, 2024b).

In this regard, aligning digital transformation with inner growth frameworks, such as the Inner Development Goals (IDGs) (Ankrah et al., 2023), may foster a more balanced approach to the triple transition, ensuring that technological advancements are aligned with human well-being, ethical growth, and inner transformation.

As Ankrah et al. (2023) argued, without a significant shift in human values, inner transformation, and leadership, external interventions alone would be insufficient to address complex societal challenges, such as digital transformation. In this context, Laitsou et al. (2023) explored the bidirectional impact between digital transformation and human well-being: digital technologies should be used mindfully to safeguard human well-being, while human values should serve as the foundation for digital development.

5.3.3. Responsible Use, Safe Adoption of Digital Solutions, and Digital Well-being

This section provides insights into domains such as the responsible use and safe adoption of digital solutions, which are related to digital well-being, as well as societal controversies that may hinder digital adoption, including the effect of EMF fields on human health.

Responsible Use and Safe Adoption

Closely to the aforementioned aspects of digital human rights, the responsible use and safe adoption of digital solutions across all individuals and organisations is critical for achieving a sustainable and resilient digital transformation. This requires promoting education to enhance social responsibility and acceptance of digital technologies, as highlighted by several institutions (UNDP, 2019; World Bank, 2024).

In this regard, digital safety is a key global concern, affecting over five billion internet users (WEF, 2023). The World Economic Forum's "Global Principles on Digital Safety" addressed issues like misinformation, cyberbullying, hate speech, and exploitation.

These principles aim to protect human rights in the digital realm, promote positive online behaviours, and inform regulatory and industry efforts towards safety (WEF, 2023). However, challenges remain, and more research and policy development are necessary to measure impact, map effective interventions, and combat misinformation.

While digital safety primarily impacts individuals and for that reason is placed within the "people" pillar, it also relates to the governance dimension, within the "peace" pillar. Civil society plays a crucial role in promoting digital safety by bridging the gap between public and private sectors and advocating for protecting the most vulnerable.

Furthermore, another relevant aspect in this matter is the societal acceptance of digital technologies, which involves technological factors, psychological aspects, and risk perception (Park et al., 2022).

Several controversial aspects influence societal acceptance of digital technologies in the current context. A common public concern relies on the potential health impacts of electromagnetic fields (EMFs) from wireless technologies, which has sparked lively debates and fuelled resistance to technologies like 5G (Russel et al., 2018; Suresh et al. 2023). Addressing these concerns requires reinforcing scientific research, science-based health, and safety standards, and implementing effective mechanisms to counter misinformation. This aspect is further elaborated later on.

Additionally, the spread of mass surveillance technologies raises concerns about privacy and human rights. Clear regulations and oversight mechanisms are essential to protect individual rights and ensure ethical use.

Another aspect gaining social protests is the digital-driven gentrification or e-gentrification. This concept refers to the socio-economic changes driven by digital platforms and infrastructures, often leading to community displacement or disadvantages. For instance, data centres and telecom networks can disrupt local resources, creating tensions between global and local interests (Libertson et al., 2021). Besides, digital platforms for the shared economy (e.g. short-term accommodation) have disrupted urban life across the world, causing serious social problems and reinforcing gentrification trends. Digital gentrification requires a holistic approach that recognizes the ethical implications of technological deployments and promotes inclusive urban planning.

Digital Well-being and Health

Digital technologies have revolutionized communication and daily life, offering benefits for wellbeing but also posing health risks (Büchi, 2021). Features like anonymity and disinhibition in digital spaces can lead to negative behaviours such as cyberbullying, problematic internet use, and social media addiction (Suler, 2004; Whitty and Young, 2017).

The "Goldilocks hypothesis" suggests that moderate digital use is beneficial, while excessive use can be harmful (Przybylski and Weinstein, 2017). Thus, mental health problems caused by unsafe behaviours online are on the rise, affecting particularly girls (OECD, 2024).

Emerging immersive technologies (e.g., virtual worlds) add to these concerns. In this matter, Zallio and Clarkson (2022) explored factors such as inclusion, diversity, equity, accessibility, and safety in digital immersive environments.

To counter harmful practices, expert recommendations include raising awareness, promoting media literacy, implementing safety-by-design strategies (e.g., AI-based filters), enacting regulations to protect digital wellbeing, and encouraging corporate transparency (OECD, 2024).

Electromagnetic Fields (EMFs) and Social Acceptance

The massive spread of ICTs in all socioeconomic activities has significantly increased the exposure and presence of electromagnetic fields (EMFs) in the environment. As digital technologies and supporting infrastructures become ubiquitous, concerns about their potential negative effects on health and, subsequently, social acceptance problems are growing (e.g. 5G technologies, mobile antennas).

EMFs are produced by various sources, including telecommunication systems, electrical equipment, and radio terminals. The World Health Organization (WHO), ITU, and other bodies have consciously studied these emissions and established guidelines for safe exposure levels. However, the potential health impacts of EMFs remain a controversial topic, lacking consensual conclusions.

Research evidenced that short-term exposure to RF energy from mobile phones primarily causes tissue heating, which is mainly absorbed by the skin and superficial tissues with negligible effects on health (WHO, 2014). Moreover, according to WHO (2014), studies on the effects of RF on brain activity, heart rate, sleep or cognitive functions have not evidenced adverse health effects.

Long-term epidemiological research has found some, yet inconclusive, evidence of a relation between RF exposure and brain tumours in adults or leukaemia in children. Therefore, evidence of potential effects on health remains elusive and demands further empirical research.

Furthermore, another relevant issue linked to EMFs is electromagnetic hypersensitivity (EHS), also known as "idiopathic environmental intolerance attributed to electromagnetic fields" (IEI-EMF). EHS is featured by non-specific symptoms such as fatigue, sleep disturbances, headache, and cognitive issues potentially attributable to EMF exposure. Belyaev et al. (2016) concluded that EHS symptoms often rise in frequency and severity over time, suggesting a "chronic multisystem" syndrome.

As argued by Leszczynski (2024), despite being recognised by health authorities, this phenomenon has not yet been classified as a disease by the WHO, and treatment protocols are still lacking.

The widespread use of digital technologies has led to public concerns regarding their safety, exacerbated by a combination of divergent scientific studies, the media, and misinformation messages spread in social networks. This has led to fear among the public and undermined social acceptance of some technologies (e.g. 5G, mobile phone communication antennas).

Linder (1995) argued that the controversy surrounding EMFs has been shaped by public discussions, disagreements on government actions and a lack of scientific consensus on the matter.

Moreover, public perception of EMF risks is influenced by media coverage, personal experiences, and trust in regulatory authorities. As argued by Belyaev et al. (2016), the contradictory results from scientific studies, together with the considerations of RF fields as “possibly carcinogenic” by the International Agency for Research on Cancer (IARC) have contributed to expanding public concerns.

Regulatory and standardisation bodies like the WHO, IEEE, ICNIRP, and ITU, have provided guidelines to inform and protect public health. Additionally, ITU-T Recommendations and guidelines provide support for EMF exposure caused by emerging ICTs such as IoT, 5G, and future 6G. Nevertheless, health policies and strategies addressing EHS are lacking, aggravating the problem (Leszczynski, 2024).

Therefore, addressing the potential health effects and social acceptance of digital technologies relies on more comprehensive research on long-term effects, effective risk communication, along with the implementation of robust health policies (Belyaev et al., 2016).

In conclusion, the potential impact of EMFs on human health remains a highly complex, controversial, and evolving field of study. While current research indicates that EMF exposure at recommended levels does not pose significant health risks, enduring studies are essential to fully characterize the long-term implications.

Effective communication along with health policies and empirical research are relevant aspects to address to deal with potential public concerns that may jeopardise the social acceptance of digital technologies.

5.3.4. Digital Culture, Creativity, and Digital Humanities

Despite the importance of culture, creativity, and humanism in society, these aspects are often overlooked in the Digital Agenda. On the one hand, the digital era has revolutionized the preservation, production, and distribution of culture and art, making cultural experiences more accessible, thereby reshaping societal interactions. Digital media platforms, for example, have democratized access to culture, enabling creators to reach global audiences without traditional gatekeepers (Pesce, 2024).

As argued by Zhao et al. (2023) this underscored the critical importance of digital spaces in the cultural realm. However, on the other hand, digital culture also faces challenges, including intellectual property rights violations, oversaturation of content, reduced revenue from digital streams, and increased environmental impacts of data centres and communication networks.

Recent disruptions, such as generative AI, pose new risks to human creativity. Therefore, it is more important than ever to promote a responsible and safe digital culture and protect virtual spaces (UNESCO, 2019; UNDP, 2019). Thus, to safeguard human values, it is critical to include digital culture, creativity, and humanism in both the digital and sustainability agendas.

Concerning digital humanism, as described by Simondon (2017) and Serrano (2024), this concept captures the collective cultural effort involving multiple disciplines. This inclusive perspective aims to navigate and guide the ongoing transformations in society, addressing the alienation that may arise from technological advancements. Digital humanism is essential to keep the undergoing transformations connected to human values and needs.

Notably, digital transformation is affecting society and humanism in complex and interrelated pathways yet insufficiently understood. Digital technologies dramatically change the ways individuals, firms, and governments interact. Thus, the societal effects of digital transformation are multifaceted, with overall impacts varying across countries.

While digital transformation provides increased access to information, improved healthcare (e.g., telemedicine), and enriched education (e.g., open online courses), it also poses severe risks. Caveats of the digital era impacting societal well-being cover a wide range of issues, such as work-life imbalances caused by remote working, segregation or isolation of people, like-minded groups, negative mental health outcomes, or digital divides (e.g., digital literacy in elderly people), among others.

To ensure that digital transformation promotes human well-being and values it is essential to reorient current mindsets and structures towards regenerating a positive and inclusive digital society.

5.3.5. Digital Opportunities for Social Resilience and Regeneration

In analogy with the application of digital solutions for regenerative environmental sustainability, digital technologies and innovation have also become powerful tools for societal regeneration.

According to Morales and Calvo (2017), social regeneration refers to the transformative process that leverages institutional choices focused on cooperation, inclusion, and empowerment to build opportunities and capacities across society. However, digital solutions also face challenges and ethical concerns, which need to be addressed.

Indeed, Morales and Calvo (2017) underscored the potential of digital technologies, particularly Web 2.0, in advancing social regeneration by enhancing connectivity, accessibility, and community interaction. The digital interconnectedness empowers communities to engage more actively in knowledge sharing, collaboration, and societal participation while granting access to essential information and services (e.g. financial services).

Furthermore, digital platforms enable virtual collaborative spaces that allow citizens to participate in local governance and decision-making. In this regard, De Filippi and Cocina (2022) emphasized the relevance of ICTs in empowering citizens through digital participatory platforms, which allow urban regeneration, civic engagement, and sustainable initiatives.

Moreover, as emphasized by Qureshi et al. (2021) and Mehmood et al. (2019), digital social innovation is particularly relevant for social regeneration, as it leverages technology to address challenges and create opportunities for social cohesion and inclusion.

Digital solutions such as “AgriTech” communities, do not only support regenerative agriculture practices benefiting natural ecosystems, but also contribute to food security, and more empowered and resilient communities (Umantseva, 2022). In addition, “permacomputing” communities are also revolutionizing fields like culture, art, and design (Mansouz et al., 2021) while creating sustainability awareness and stewardship. Indeed, digital tools also allow regenerative opportunities for education (Raman et al., 2024), community-based initiatives and citizen-driven projects.

Furthermore, digital technologies hold an outstanding potential for enhancing healthcare, particularly concerning regenerative medicine (Webster and Terzic, 2021; Banda et al., 2019), and platforms for mental wellness. Nevertheless, this field faces barriers related to regulation and ethical standards (Webster and Terzic, 2021; Banda et al., 2019).

The application of digital solutions for societal regeneration remains a nascent field facing multiple barriers (De Filippi and Cocina, 2022), and potential trade-offs on well-being.

Sujon and Dyer (2020) underlined that while digital advancements such as datafication and social media enhance connectivity, they also promote mass surveillance, and monetization of communication, and pose threats to social values like connection and togetherness. These concerns suggest a need to reevaluate the concept of "the social" and adapt it to an evolving digital landscape and ethical considerations.

In conclusion, digital technologies and innovation offer promise for social regeneration provided that the challenges such as ethical issues, regulatory and acceptance barriers, inclusiveness, and accessibility are addressed. Implemented with responsibility, digital social regeneration opens new opportunities to reshape societies towards sustainable development.

5.3.6. Societal Engagement by Inclusive e-Participation and Safe Virtual Spaces for All

Regarding the relevant aspect of participation, the digital development strategies must consider the promotion of inclusive involvement in the digital spaces, along with the design of inclusive digital solutions, for leveraging the opportunities in both digital and sustainable development. Moreover, ensuring the participation of the entire civil society in virtual spaces (Lee-Geiller, 2024) is crucial for reorienting digital frameworks towards sustainable development and leveraging the opportunities they provide.

Therefore, all relevant voices must be heard to ensure that digitalization contributes to societal regeneration. For that purpose, digital solutions must be reoriented to promote participation, social resilience, and societal opportunities rather than perpetuating inequalities, divides, and human rights abuses as they often do today (Robinson et al., 2015).

In this regard, the concept of "e-participation" is critical, which involves citizen engagement through government-led online platforms, fostering transparency, inclusivity, and civic involvement (UN, 2022). This ambition is well reflected in the UN e-participation Index (UN, 2022), although it is scarce in real life.

As Stratu-Strelet et al. (2021) argued, while citizen participation is crucial for sustainable development, engaging citizens in e-participation is challenging. Digital readiness, usage, and governance strongly influence the success of e-participation initiatives, together with other factors like legitimacy, democracy, and government efficiency.

Therefore, effective e-government policies should provide incentives for civic society participation, support democratic systems, and offer a strategic vision for technology integration.

According to Lee-Geiller et al. (2024), key factors influencing e-participation readiness include good governance practices, robust telecommunications infrastructure, and demographic diversity linked with social justice and multiculturalism. Indeed, e-participation fosters transparency, inclusivity, and civic involvement. Besides, it contributes to transforming governmental processes into more dynamic, effective, and interactive systems.

Thus, both technological conditions and institutional factors are crucial for e-participation preparedness, which confronts, the typical “technological determinism” (Chandler, 1996) and accentuates the need for a holistic understanding and governance of e-participation.

In conclusion, further research is needed to characterize the complex relationship between e-participation readiness and people's willingness to engage in virtual spaces.

5.3.7. Reflections on the People Pillar

A successful social transition in the digital era requires social cohesion, equity, and human rights protection, along with inclusive and accessible participation and well-being for all individuals. This involves fostering participatory decision-making processes supported by robust welfare policies and addressing public concerns about emerging technologies. Embedding a regenerative approach is vital to ensure that digital solutions contribute positively to societal opportunities rather than exacerbating inequalities and social unrest.

Existing frameworks in this realm address aspects like inclusiveness, digital human rights, responsible use, safety, and e-participation (World Bank, 2024; WBA, 2023; UNDP, 2023), but often neglect the regenerative approach and the link between social and environmental transformations.

The novel approach proposed in the suggested Taxonomy contributes to addressing these limitations, by creating the social fabric and awareness for an inclusive, resilient, and sustainable digital society. This involves comprehensive strategies and policies that integrate regenerative principles and human values at the core of digital transformation, ultimately fostering a digital society that promotes human well-being, inner growth, resilience, and sustainable development.

In conclusion, the “People Pillar” represents the socially just dimension of the triple transition. Therefore, it encompasses achieving an equitable and inclusive digital development, ensuring that digital human rights are safeguarded by human-centred digitalisation, and responsible, and safe adoption of digital solutions while promoting well-being and health. It also includes the promotion of a digital culture that values creativity and humanism.

Moreover, it emphasizes the creation of digital opportunities for promoting societal engagement through electronic participation spaces, along with responsible digital solutions for social resilience and regeneration. An outline of the domains of the People Pillar and their alignment with the SDGs is provided in Table 5.8.

Table 5.8. Domains within the People Pillar and their Alignment with the SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PEOPLE (SOCIALLY JUST DIMENSION)	Equitable and Inclusive Digital Development	SDG 4, 5, 8, 9, 10, 16, 17
	Empowerment, Shared Responsibility for Digital Human Rights and Human-Centred Digital Development	SDG 1, 5, 10, 16, 17
	Responsible Use and Safe Adoption of Digital Solutions (Digital Well-Being, Social Acceptance)	SDG 3, 4, 5, 10, 16, 17
	Digital Culture, Creativity, and Digital Humanities	SDG 4, 5, 10, 16
	Digital Opportunities and Empowerment for Social Resilience and Regeneration	SDG 1, 2, 3, 5, 6, 8, 10, 11, 12, 16, 17
	Societal Engagement by Inclusive e-Participation	SDG 4, 5, 10, 17

Having substantiated the importance of the Planetary Sustainability and People pillars within the proposed Taxonomy for SRDT, as the driving forces behind the environmental and socially just transitions, this dissertation now turns to the substantiation of the “Peace Pillar,” which represents a cross-cutting crucial component for the triple transition: mindful governance.

5.4. The Peace Pillar for Mindful Governance

The UN’s 2030 Agenda (UN, 2015) and the recently launched Global Digital Compact (UN, 2024b) emphasized peace and mindful governance as essential elements for achieving sustainable and regenerative digital transformation. In this context, the peace pillar for mindful governance serves as a cross-cutting element, intersecting with other pillars within the proposed Taxonomy, and encompassing a wide range of themes strategically allocated to maximize the positive impact.

Existing digital governance frameworks often favour the economic dimensions, and the perspectives of dominant countries, or large corporations, rather than promoting a human-centred and sustainable approach to digital transformation. This imbalance is driven by power disparities, digital oligopolies, and practices such as “digital neocolonialism”, where powerful corporations or nations, primarily from the Global North, dominate the digital spaces, often to the detriment of the Global South (Kwet, 2019; Young, 2019) and users.

Considering the borderless nature of digital activities and the challenge of governance being primarily managed by domestic authorities, it is crucial to promote a “pluriversal” perspective (De Vank, 2021) and encourage mindful governance through a whole-of-government approach. Additionally, other critical aspects such as decentralizing and opening digital assets, enhancing human rights protections, strengthening digital sovereignty, fostering democracy, and building trust and accountability need to be promoted to balance mindful digital governance.

Furthermore, to address the detrimental practices that undermine a peaceful digital society, the policies and regulations must prioritize the public interest on both local and global scales, while reducing dependencies on dominant players. In this regard, collaborative governance and grassroots movements emerge as essential factors in challenging oligopolistic structures and creating a more equitable and sustainable digital realm.

Hence, the “Peace Pillar” of the proposed Taxonomy includes the following domains: responsible, agile and multilevel oversight, regulation, and policies; digital ethics governance for safeguarding human rights, sovereignty, peace, and democracy; digital responsibility schemes; openness and stewardship of digital commons; digital trust, transparency, and accountability; and responsible, inclusive, secure, and accessible e-government opportunities.

Altogether, this pillar aims to foster a governance model that supports sustainability, inclusivity, and resilience by emphasizing responsible policies, digital ethics, human rights, and decentralized digital assets. These domains are further examined as follows.

5.4.1. Responsible, Multilevel, and Agile Oversight, Regulation, and Policies

In the proposed Taxonomy for SRDT, the domain concerning responsible oversight, policies, and regulations represents a variety of interventions aimed at mindfully addressing the challenges and opportunities of digital transformation, particularly those affecting society and nature.

In this regard, the suggested Taxonomy offers a regenerative perspective, and whole-of-government approach to digital governance, by emphasizing agility to keep pace with technological, and eco-social advancements and transformations.

In this context, promoting mindful policies and regulations, which include both hard regulations (e.g., laws) and soft regulations (e.g., principles, standards), is critical for steering digital transformation toward human and ecological values and regeneration. However, current digital policies and regulations often remain underdeveloped, and, in addition, they disregard sustainability aspects, especially in areas like AI, where technological progress has outpaced regulatory frameworks.

Furthermore, economic and technocentric perspectives promoted by major global players and wealthy northern countries frequently overshadow social and environmental concerns.

Many digital frameworks, such as the Digital Development Compass (UNDP, 2021), the OECD's Going Digital initiative (OECD, 2020b), the Global Digital Regulatory Outlook (ITU, 2023), and the UNESCO ROAM-X framework (UNESCO, 2019; 2024) address aspects related to digital governance. Additionally, recent frameworks like the European Union Digital Decade (EU, 2024a) and the recently launched Global Digital Compact (UN, 2024b), show promise in advancing mindful digital governance. Nonetheless, even in these advanced frameworks, the environmental and social dimensions are insufficiently considered, and besides, they lack a regenerative vision.

Additionally, digital regulation has traditionally relied on soft interventions, such as voluntary principles and standards, with the argument that strict regulations could stifle innovation. Yet, voluntary standards alone have proven insufficient for ensuring mindful governance, and many countries and corporations fail to adhere to them.

Consequently, binding regulations, particularly in uncertain areas like AI, are urgently needed. In this regard, the European Union's AI Act (EU, 2024c) represents a significant step toward comprehensive regulation, although it has faced criticism for being insufficiently ambitious. The Global Digital Compact (UN, 2024b) also emphasizes the need for international governance of AI and other digital technologies, although global regulations remain elusive.

Innovative regulatory approaches, such as "regulatory sandboxes", provide opportunities for developing mindful regulation by allowing new technologies to be tested in a controlled environment.

Overall, fostering responsible and agile oversight, regulation, and policies is essential for aligning digital transformation with ecological and societal values, thereby promoting the triple transition.

Digital Colonialism and Neocolonialism

As previously introduced, one relevant aspect affecting the advancement of more sustainable digital governance is "digital colonialism." This concept refers to the domination of digital infrastructure, data, and technology by powerful countries or corporations from the Global North, exacerbating inequalities and dependencies in the Global South.

This phenomenon manifests through control over critical digital infrastructure (software, hardware, network connectivity), extensive data extraction, and influence over digital policies that hinder local development.

Digital colonialism also leads to unfair labour and resource exploitation, with high-value work and profits concentrated in wealthy countries, while lower-value labour and environmental burdens are allocated to less developed regions (Dahiya, 2023).

Another related phenomenon is "digital neocolonialism," which involves more subtle means of power extension, often under the excuse of development support.

It uses cultural hegemony, economic policies, and indirect influence to maintain dominance, propagating Western-centric ideologies and practices that erode local cultures and knowledge systems (Adam, 2019).

This includes the commodification of e-education and communication services, data extraction without compensation, and corporate control over digital ecosystems, leading to what Kwet (2019) describes as a "digital empire".

Countering digital colonialism and neocolonialism requires reinforcing open and decentralized digital assets, promoting digital sovereignty, and regulating monopolistic practices. Other strategies rely on the promotion of "pluriversal" governance that integrates diverse perspectives, by combining bottom-up and top-down approaches to benefit local knowledge, innovation, and sustainable development (De Valk, 2021).

Embedding Regeneration in Digital Governance

This dissertation advocates for embedding a regenerative perspective into digital governance, and the proposed Taxonomy strongly reflects this purpose. Regenerative governance aims not just to regulate but also to restore, promote, and enhance the resilience of social, economic, and environmental systems in a balanced manner. This involves adopting an approach akin to natural ecosystems, by providing mindful and restorative solutions tailored to each community while achieving overall harmony of all socioeconomic and ecological systems.

In the digital realm, regenerative governance may entail a better integration of social and environmental dynamics, by safeguarding human rights, promoting equity, ensuring multi-level participation, and achieving sustainability within planetary boundaries. This balance is particularly relevant considering the need to recover from crises like the COVID-19 pandemic while addressing pressing global challenges such as climate change, biodiversity loss, geopolitical conflicts, and social polarization.

The discourse on regeneration has expanded across multiple disciplines, emphasizing the potential for restorative and revitalizing practices that also provide competitive advantages, while contributing to the health and well-being of socio-ecological systems, as argued by Fischer et al., (2024), and Hahn and Tampe (2020). Notably, regenerative governance also involves renewing institutions and human values, by fostering mindful leadership and acknowledging the interconnectedness of social, environmental, and governance factors.

Despite its potential, regenerative governance is largely absent in the digital realm and even in the sustainable development field. Hence, further research and policy action are necessary to wholly embed this promising approach in both digital and sustainability governance. By doing so, both digital and sustainability agendas will contribute to restoring and enhancing the resilience of social, economic, institutional, and environmental systems.

5.4.2. Digital Ethics, Human Rights, Sovereignty, Peace, and Democracy

Digital ethics has emerged as a central aspect of mindful digital governance, gaining increasing attention in both political and research domains (WBA, 2023; Wiley, 2021). Notably, ethics has become increasingly relevant for ensuring an inclusive, responsible, and sustainable digital transformation, especially given the proliferation of emerging technologies like AI, which raise concerns about human agency and security.

Digital ethics plays a central role in safeguarding human rights, sovereignty, and democracy, and therefore, it should be soundly embedded in both societal and governance structures. This holistic approach is fundamental for achieving a peaceful and sustainable digital future.

In this context, Digital Human Rights (DHR) represent the core fundamental aspect of the ethical framework.

While DHR is often associated with governance, they fundamentally belong to the societal realm. The proposed Taxonomy addresses DHR at both levels: the individual (micro) level in the societal pillar and the macro level in the peace for mindful governance.

This dual approach ensures that Human Rights are protected through principles, governmental instruments, regulations, and policies, both locally and globally while promoting ownership and co-responsibility at the individual level. Moreover, it acknowledges the importance of DHR for a human-centric digital transformation, promoting equality, protecting individual freedoms and overall community well-being, and building public trust in digital solutions.

In the social dimension, DHR involves ensuring individual protection and promoting safe technology use, digital empowerment, and human dignity. While in governance, it includes establishing legal and policy frameworks that regulate the digital sphere, mitigate digital divides, and ensure that all individuals have access to quality internet services.

Building on this explanation, the key aspects of ethics and human rights in the digital context are further elaborated and substantiated as follows.

Digital Ethics

The complexity of ethics, which is strongly influenced by cultural values and contexts, requires a flexible and inclusive perspective, especially in the digital realm. Thus, it needs to be informed by bottom-up approaches and a balance between cultural sensitivities and universal human values.

Certainly, as advocated by Serrano (2024), a bottom-up approach to digital ethics rooted in digital humanism is needed, by emphasizing multi-stakeholder dialogue over traditional perspectives. This strategy would provide more flexible and inclusive means to capture ethical considerations with fewer conflicting values. Similarly, Lennerfors and Murata (2023) stressed that the ethical and sustainability impacts of digital disruptions vary significantly across cultural contexts, therefore, it is crucial to consider and integrate the cultural nuances in ongoing ethical debates.

Furthermore, the recent rapid expansion of AI has imposed the development of ethical frameworks to guide its inherent risks and opportunities. Also, other emerging technologies, such as Quantum Computing, have recently sparked ethical debates and concerns about their potential risks.

In this regard, Floridi (2019) noted that the ethical debate surrounding digital technologies has finally gained prominence due to their pervasive impact on daily life. Cath et al. (2018) argued that digital technologies evoke both hopes and concerns regarding their design, development, and deployment, which require sound ethical approaches.

The growing public interest has led to numerous initiatives aimed at establishing ethical principles and frameworks for digital innovation, particularly in AI, to benefit humanity and the SDGs. This rising interest in digital ethics is evident in the growing number of publications and principles focused on this subject, particularly in AI.

Notable frameworks include the UNESCO's Recommendation on the Ethics of Artificial Intelligence (UNESCO, 2021), the OECD AI Principles (OECD, 2019e and 2024), the G20 AI principles (2019), the Asilomar AI Principles (Future of Life Institute, 2017), the EU Ethics Guidelines for Trustworthy AI (European Commission, 2019), the IEEE Ethically Aligned Design Principles (IEEE, 2019), the Montreal Declaration for a Responsible Development of Artificial Intelligence (Université de Montréal, 2018), the Toronto Declaration (Amnesty International & Access Now, 2018), the G7 Hiroshima AI Process (2023), the Bletchley Declaration (2023), the UN General Assembly AI Regulation (2024), and the EU AI Act (2024), among others.

However, as argued by Floridi (2019) the debate now needs to shift "from principles to practice", which emphasizes the need for an effective application of these ethical standards to create a tangible positive impact in the digital world and across sectors impacted by the data-driven era.

A major shortfall in current digital ethics debates is the lack of integration of environmental sustainability, which remains largely ignored, particularly in AI ethics. This omission is partly due to the general absence of environmental considerations in the digital agenda, which many digital actors and governments support. This gap may have contributed to the rise of greenwashing and ethics-washing practices, which undermine genuine sustainability and ethical efforts.

Fjeld et al. (2020) conducted a comparative analysis of thirty-six prominent AI frameworks, advocating for a harmonized global discourse on AI ethics. Their study identified eight key themes: privacy, accountability, safety and security, transparency and explainability, fairness and non-discrimination, human control of technology, professional responsibility, and the promotion of human values.

Notably, it is observed that environmental sustainability was absent in this first generation of AI principles. Similarly, Cumming et al. (2024) reviewed 28 AI frameworks, emphasizing the importance of algorithmic trust for sustainable AI practices. Although they identified key ethical principles (i.e., beneficence, non-maleficence, justice, explainability, autonomy, privacy, and bias mitigation), environmental sustainability was still not sufficiently considered.

In this regard, experts like Bolte et al. (2022) criticized existing AI ethics frameworks as mere "box-ticking exercises" while advocating for an "ethics of desirability" inspired by complex systems to include ecological considerations.

The UNESCO's Recommendation on the Ethics of Artificial Intelligence (2021) was one of the first approaches to include mentions regarding environmental sustainability. Both this framework, together with the recent Global Digital Compact (UN, 2024b) within the "Pact for the Future", advocated for considering environmental sustainability throughout the lifecycle of AI. Additionally, they encourage digital-based green innovation to advance the SDGs. Nevertheless, while these frameworks acknowledge environmental concerns at a high level, their implementation largely depends on voluntary commitments from organisations and nations, which are largely absent.

Moreover, Falk et al. (2023) argued that terms like "Sustainable AI" or "AI for Good" have been overused to the point of losing their original purpose.

They distinguish between AI applications that merely meet necessary conditions (predictive systems) and those that meet sufficient conditions (actively contributing to sustainability).

According to these scholars, the latter is the one that should be considered "AI for Sustainability". They also suggest a "gradient for Sustainable AI", including the application domain, AI towards sustainability, and AI for sustainability. Still, this perspective requires further refinement to establish clear terminology and sustainability readiness levels akin to the innovation Technology Readiness Levels (TRLs).

Hence, for digital ethics to be truly robust and comprehensive, environmental sustainability must be fully integrated into the debates, principles, regulations, and practices. Ethical discussions and governance frameworks, particularly in AI, should address all sustainability dimensions and adopt regenerative approaches. This perspective is further substantiated by the recognition of the human right to a clean, healthy, and sustainable environment (URG, 2024; Bennett et al., 2024).

Various frameworks have been established to assess and monitor ethical and responsibility challenges in AI, including the Artificial Intelligence and Democratic Values Index (CAIDP, 2023), Stanford's AI Index (Stanford HAI, 2022; 2024), and the recently launched Global Index on Responsible AI (GIRAI, 2024).

In this regard, the GIRAI Index primarily focuses on human rights, gender equality, responsible AI governance, and capacities, but lacks explicit consideration of environmental sustainability, emphasizing the significant research and practice gap that exists in this matter.

Nevertheless, the GIRAI Index (2024) uncovered critical insights regarding AI governance, revealing that current frameworks do not necessarily translate into responsible AI practices. Mechanisms to safeguard human rights are limited, and international cooperation through global standards and shared efforts remains crucial. Moreover, aspects like inclusion, gender equality, and worker protections in AI are inadequately addressed. This Index concludes that, despite some advancements, most AI challenges remain unresolved, necessitating further global efforts toward ethical and responsible digital systems.

Therefore, the digital ethics landscape needs to be reoriented to place greater emphasis on environmental sustainability. Additionally, more concerted efforts are required to translate conceptual discussions and ongoing debates into tangible, real-world implementation.

Digital Human Rights

While digital technologies offer new opportunities for exercising human rights, for example opening virtual spaces for participation, they also present significant risks. Therefore, the regulation and protection of Digital Human Rights (DHRs) through national and global regulations, principles and diplomatic efforts are essential for achieving a regenerative and inclusive digital transformation.

DHRs encompass the civil liberties and democratic values in virtual spaces, as a mirror of the same protections afforded in the physical world (URG, 2021a). Yet, digital disruptions have introduced new risks to human rights and exacerbated existing threats.

In this context, digital governance is expected to create a digital sphere that serves the common good, ensuring that rights such as freedom of speech, privacy, data protection, safety, security, access to information, protection from manipulation and surveillance, and non-discrimination are upheld.

Indeed, the already existing Human Rights treaties also apply online. Frameworks like the UN's Guiding Principles on Business and Human Rights (UNGPs) can hold corporations accountable for their digital activities. These principles require companies to conduct due diligence, address adverse impacts, and provide remedies for the harm caused by their digital operations.

Additionally, the World Economic Forum's Global Principles on Digital Safety (2023a) focused attention on issues like misinformation, cyberbullying, and the exploitation of vulnerable groups, which have been amplified by the digital age.

Despite global efforts, DHRs remain inadequately endorsed and protected, even in developed countries. Strengthening both national and global frameworks, along with increased global cooperation and diplomacy, is necessary for improving the protection in this domain. As digital transformation transcends borders, the protection of Human Rights online must also extend globally. In addition, public awareness and education campaigns can help individuals understand and protect their Digital Rights.

In conclusion, governance must integrate DHRs to ensure a just and equitable digital society. This integration includes implementing robust national regulations and participating in global cooperative efforts to make digital spaces safe, inclusive, and supportive of human dignity, sustainable development, and democratic values.

Overall, the integration of ethical considerations, human rights, and environmental sustainability within the digital governance frameworks is imperative to achieving a regenerative, responsible digital future.

5.4.3. Openness and Stewardship of Digital Commons for All

Achieving a sustainable and inclusive digital transformation depends on universal access to open digital commons, including data, software, standards, and infrastructures. Open access to environmental data infrastructures is particularly crucial for meeting sustainability goals.

However, the realization of this ambition faces significant challenges, mainly due to the tight control exerted by major technological players over data and infrastructures across various jurisdictions, coupled with the absence of robust global regulation. This, in part, is caused because digital commons are seen as strategic assets to protect, as they drive competitiveness and capital creation.

In this context, Shulz et al. (2024) emphasized the importance of digital commons in addressing ecological concerns and integrating them into digital ethical frameworks and practical operations. Key obstacles are the dependence on unsustainable digital products, scalability barriers, and inadequate policy support.

These scholars advocated for approaches that challenge dominant narratives by promoting ecological sustainability in the digital sphere, such as the digital commons as an ecological alternative. Similarly, Kostakis et al. (2019) introduced a "cosmolocal" framework, integrating global knowledge commons with local manufacturing practices while emphasizing sustainability and socio-ecological well-being.

Additionally, Velkova (2024) underscored the need for equitable principles in developing digital commons and infrastructures to avoid "digital gentrification". The need for regulation of data centres and infrastructure capacities is emphasised to prevent monopolization and ensure that digital resources serve the public interest.

In this regard, grassroots movements can support the development of alternative digital commons with a decentralized perspective, fostering community ownership and co-responsibility. Therefore, local digital infrastructures, controlled and maintained by their users, can help protect local interests, promoting a more inclusive digital ecosystem.

The Role of Openness in Sustainable Digital Governance

Openness is a key principle for mindful, sustainable, and inclusive digital governance. It facilitates the equitable distribution of digital assets, enabling individuals, businesses, and governments to access relevant data and software necessary for thriving in the digital age. Open digital commons support the democratization of research breakthroughs, help to tackle societal challenges, and provide essential environmental data.

However, access to these commons is hindered by barriers such as digital colonialism, power asymmetries, and oligopolistic practices. Addressing these issues requires strengthening global cooperation and enacting robust regulations, which remain limited to date.

Indeed, the significance of digital commons lies in their potential to democratize access to critical digital resources and assets, counteracting the negative effects of digital colonialism. Decentralizing digital infrastructure and empowering local digital sovereignty are crucial steps in promoting equitable access to digital commons.

This process involves policy reforms that protect local interests and promote fair competition, thereby nurturing local digital ecosystems and challenging the monopolistic power of major technology companies. As Firican (2023) argued, openness is a key attribute of responsible digital culture and leadership, essential for building digital preparedness and competitiveness.

In summary, sustainable and regenerative digital transformation hinges on universal access to digital commons through conscious stewardship and policy reforms.

By decentralizing digital infrastructures and fostering local innovation, the dominance of major tech companies and powerful nations can be countered towards a more equitable, sustainable, and inclusive digital future. In this regard, the ecological sustainability aspects of the digital commons should also be a foundational principle in their governance.

Several frameworks address both digital commons and openness, which have been included as relevant aspects of the proposed Taxonomy. These include the Global Data Barometer (2022), the Digital Public Goods Alliance Standard (2021), the World Development Report (World Bank, 2021), and the UNESCO ROAM-X Indicators (UNESCO, 2019; 2024). Central to these discussions is data governance, as a cornerstone of digital oversight.

Data infrastructures and stewardship create social value and significantly impact economic progress, trade, innovation, human rights, and national security as argued by UNCTAD (2021b). The Global Digital Compact (UN, 2024b) emphasizes the importance of data governance, advocating for interoperable frameworks, privacy, security, and user consent, along with open data initiatives to foster data sharing. It also underlines the need for promoting open-source software, standards, and investments in digital commons.

Digital Public Goods

Among the most relevant digital goods for sustainable development are the Digital Public Goods (DPGs), which play a crucial role in harnessing digital technologies and data to advance the SDGs, especially in low- and middle-income countries. DPGs, which include non-excludable and non-rivalrous assets like the Internet, have been crucial in addressing development challenges. However, over time, the proportion of open-source public content has declined, limiting universal access to information and services.

The use of Big Data Analysis (BDA) and AI in creating digital public goods offers actionable insights in areas such as disease outbreak management, poverty measurement, and biodiversity protection. Yet, access to these digital goods is often impeded by language, infrastructure, and other barriers. Scaling up DPGs to serve sustainable development requires investments and support, currently lacking.

International efforts to promote DPGs for sustainable development include the "Digital Public Goods Alliance", the "DataPop Alliance", the "Global Data Access Framework", the "Global Partnership for Sustainable Development Data," and the "Open Data Charter". These initiatives advocate for common standards and collaboration between the private and public sectors to ensure the effective use of open data for sustainable development. Furthermore, robust human rights and governance frameworks are essential to building trust and inclusivity in implementing digital public goods.

Governance Models for Digital Commons

Traditional governance models for common-pool resources cannot be directly applied to digital commons due to their unique nature as argued by Prainsack (2019). According to Almeida et al. (2020), new governance models are needed to address the dilemma of the "tragedy of the commons" and promote resilient institutions that leverage the societal benefits of digital transformation.

In this context, Blockchain technologies offer a promising tool for supporting the sustainable management of global digital commons. As suggested by Rozas et al. (2021), Blockchain can create decentralized power structures, enhancing scalability, traceability, compliance monitoring, and community cooperation. Moreover, the environmental impacts often associated with Blockchain are primarily linked to Proof of Work (PoW) mechanisms. However, these are being replaced by more advanced and energy-efficient Proof of Stake (PoS) mechanisms, which have significantly lower environmental effects.

Fritsh et al. (2022) discussed the resurgence of "commoning" as a shift towards generative organizations that align with the carrying capacity of the Planet. Distributed Ledger Technologies (DLTs), including blockchain, support the sharing economy by prioritizing "use-value over exchange-value", thereby they could be supportive in promoting social equity, and preserving natural habitats. Nevertheless, as previously discussed, digital technologies are not a silver lining, and a cautious approach is essential to ensure they truly add value to sustainability efforts.

Other innovative mechanisms for enhancing the governance of digital commons are the data cooperatives. Bühler et al. (2023) suggested that data cooperatives can facilitate secure and trustworthy data exchanges, particularly benefiting small and medium-sized enterprises (SMEs).

These cooperatives contribute to bridging the gap between data-rich corporations and data-poor communities, ensuring a more balanced distribution of digital resources.

Other approaches are provided by Carlisle and Gruby (2019), who introduced "polycentricity" as a sophisticated governance system characterized by multiple centres of decision-making, aiming at promoting competitive and cooperative relationships. Polycentric governance offers advantages such as adaptive capacity, better alignment with natural resource systems, and risk mitigation. However, its application in digital commons remains limited and requires further exploration.

Digital Public Infrastructures (DPIs) Governance

The role of Digital Public Infrastructures (DPIs) is examined in the context of digital preparedness. However, due to their significance for digital governance, they are also addressed in this section. DPIs facilitate electronic government services, in close alignment with digital commons, therefore they are crucial for ensuring inclusive access to open data (UNEP, 2024c).

Defined by the World Bank (2024) as foundational components for implementing digital services, DPIs act as intermediary layers bridging physical infrastructures and sector-specific applications. The G-20 framework for DPIs emphasized that foundational principles for these infrastructures are inclusivity, interoperability, modularity, scalability, security, privacy, collaboration, governance for public benefit, trust, and sustainability.

In the proposed Taxonomy, DPIs are primarily allocated to the preparedness pillar, where they can be oriented toward resilience and regeneration to maximize their impact. Yet, the governance of DPIs is also included within the e-government domain of the governance pillar, given its importance in fostering a supportive environment for sustainable digital transformation.

5.4.4. Digital Responsibility Schemes for Shared Ownership of Governance

Governance in the digital age must be driven by a culture of responsibility. In this regard, the concept of Corporate Digital Responsibility (CDR) has emerged as an extension of the CSR notion (Corporate Social Responsibility), tailored to the digital sphere (Stahl, 2024; Carl and Hinz, 2024). CDR encompasses principles and practices guiding organisations towards responsibly achieving their economic, social, and environmental goals through their digital operations. This concept is related to digital literacy, data privacy, fairness, transparency, human agency, and identity (Identity Valley Research, 2022).

Despite its growing importance, CDR remains an immature concept, lacking well-established methodologies, and consensus on its dimensions and metrics. Stahl (2024) argued that CDR should extend beyond economic responsibilities to encompass broader moral, social, and environmental duties. The concept of "responsible digital ecosystems" assigns balanced responsibilities in the digital contexts, supporting both existing and emerging forms of responsibility.

Promoting responsible leadership and a mindful mindset is also crucial for building digital readiness and preparedness for the triple transition, as underlined within the preparedness pillar, though with a different nuance. While the "peace for mindful governance" pillar focuses on the external dimension of leadership and mindset, such as ethical practices, transparency, accountability, and institutional integrity toward external stakeholders, the preparedness pillar addresses culture as an internal dimension, focusing on agility, adaptability and the organisation's ability to respond to digital disruptions and opportunities.

Furthermore, considering the relevance of resilience in governance, it refers to the ability of a system, organisation, or individual to adapt and thrive amidst adversity, change, or uncertainty. Resilience goes beyond recovering from disruptions since it also involves learning, adapting, and growing stronger through challenges.

In the context of organisational sustainability, resilience is closely integrated with readiness and maturity models, especially in the realm of digital transformation, as argued by Rugeviciute and Courboulay (2024).

The "digital tsunami" has profoundly transformed organisational operations, providing benefits such as increased efficiency, improved decision-making, and enhanced customer experiences. However, it also brings challenges, including cybersecurity threats, data privacy concerns, and environmental impacts. In response, building resilience in the digital age involves managing these risks while capitalizing on digital opportunities to enhance the capacity to adapt and flourish in a rapidly changing environment. Resilience and regeneration are closely interconnected. Therefore, strengthening digital resilience is essential for achieving a sustainable and regenerative digital transformation.

Hence, organizations must assess and enhance their readiness and maturity levels to reinforce resilience through digital transformation. In this context, readiness refers to an organisation's preparedness to advance in its digital transformation journey.

Mechanisms such as CDR and Green ICT strategies help organisations enhance their capacity to leverage the benefits of digital transformation while promoting sustainability and resilience. For instance, Rugeviciute and Courboulay (2024) proposed a CDR maturity model, which comprises six levels of progress towards responsibility, reflecting the progression from initial awareness to leadership in best practices and standards. This model supports organizations in the identification of areas for improvement, along with in the formulation of strategies to enhance both their digital responsibility and resilience.

In conclusion, mindful leadership and digital responsibility are essential for navigating the complexities of digital transformation. Integrating Corporate Digital Responsibility with broader sustainability objectives ensures that digital transformation aligns with regenerative sustainability principles, promoting long-term success, resilience, and socio-ecological well-being.

5.4.5. Digital Trust, Transparency, and Accountability

Trust is a foundational aspect of effective digital governance since it supports the engagement of stakeholders and fosters transparency and human rights protection. Digital trust relies on robust governance frameworks that prioritize data privacy, cybersecurity, and user participation, as argued by the OECD (2020a).

According to Janssen et al. (2017), trustworthiness is a relevant concept in digital governance since it influences the relationships between the different actors in the digital sphere. Nevertheless, further conceptualization of trustworthiness is needed beyond current narrow approaches.

A relevant framework for data protection, aiming at promoting trustworthy digital environments is the European Union's General Data Protection Regulation (GDPR), which aims to foster trust between users and providers, by clear guidelines and strict enforcement and penalties for non-compliance.

Furthermore, the OECD (2020a) provided a “Digital Government Policy Framework”, which draws a comprehensive approach to progressing digital governance through six key dimensions: “digital by design, data-driven governance, government as a platform, open by default, user-driven approach, and proactiveness”. Thus, this framework could support the transition towards a fully digital government, while addressing agility, transparency, and public trust.

Along the same line, the recent Global Digital Compact (UN, 2024b) also emphasizes trust and accountability as key aspects for achieving good governance of digital transformation. The GDC advocates for ensuring transparency and human rights compliance in all digital activities, particularly concerning AI technologies. Additionally, it encourages ethical use of data and privacy protection and proposes to implement robust mechanisms to monitor these relevant aspects in collaboration with all stakeholders.

Moreover, as proposed by the WEF (n.d.) the “Digital Trust Framework” defines shared goals, such as security, reliability, accountability, and oversight, along with inclusive, ethical, and responsible use, which are pivotal for building digital trust. Another relevant framework is the “Paris Call for Trust and Security in Cyberspace” (Internet Just Society, n.d.), launched in the Internet Governance Forum of 2018.

In this context, Hanish et al. (2023) argued that the rise of digital technologies has brought forth new governance challenges, rendering traditional mechanisms like contracts and relational norms inadequate, since oversight now relies on algorithmic protocols and verification mechanisms such as blockchain.

These scholars proposed a typology of digital governance modes encompassing analogue (centralized), augmented (distributed and multilateral), and automated (decentralized), each associated with control, trust mechanisms, and incentives. The termed “augmented governance” combines traditional and automated approaches, becoming more cost-efficient as the number of contributors and connections increases (“transactivity”) increases.

As Hanish et al. (2023) argued, governance mechanisms, including accountability, must evolve to address emerging forms of competition and cooperation, with a focus on fostering collaboration amidst competing interests. This novel understanding of digital governance illustrates how to navigate the complexities of digital exchanges, by balancing cooperation and competition.

Furthermore, accountability mechanisms are essential for preventing power abuses, protecting consumers, and ensuring ethical digital practices. Indeed, it is a crucial aspect to facilitate a transition to a sustainable digital future. According to the Global Digital Compact (UN, 2024b), accountability in digital governance should extend beyond ethical practices to include environmental impacts and sustainable finance.

The Global Digital Compact (GDC) underscored the need to embed robust accountability within global governance frameworks to mitigate the increasing disparities in power distribution between technology companies and users (UN, 2024b; WBA, 2024). As digital technologies permeate every aspect of life, it is imperative to ensure that they are developed and implemented in an ethical, inclusive, and sustainable manner. Accountability mechanisms rely on setting clear responsibilities, providing compliance monitoring, and enforcing penalties for misconduct.

In addition, technological companies also bear a significant responsibility in reinforcing accountability mechanisms to foster ethical digital practices.

The co-development of accountability frameworks, involving both companies and stakeholders, is crucial (UN, 2024b), for defining clear responsibilities, formulating standards, and ensuring transparency through auditable public reports. This collaborative approach builds trust and ensures that digital transformations are inclusive and equitable.

Concerning the sustainability realm, Kramarz, and Park (2016) argued that accountability in global environmental governance can significantly enhance effectiveness provided that is intricately linked to the design of related interventions.

This approach, focused on addressing environmental problems rather than merely monitoring compliance, can be effectively applied to the realm of sustainable digital transformation.

Moreover, Pina et al. (2007) highlighted that ICTs enable better accountability through various e-governance initiatives. These initiatives include financial accountability, openness, and transparency, all of which are crucial for building a resilient and trustworthy digital governance framework.

Digital accountability also plays a transformative role in e-governance. As Petrakaki (2018) pointed out, it involves shifting traditional sources of accountability to include digital interfaces and making officials accountable for their management. Diakopoulos (2015) introduced the concept of "algorithmic accountability reporting" as a novel tool to scrutinize these aspects. This shift not only enhances the transparency of governmental operations but also involves citizens as co-producers of digital information, fostering a more participatory, trustworthy, and accountable governance.

Nevertheless, trust is an intangible and complex aspect that is difficult to assess, requiring further interdisciplinary research and policy development. Besides, accountability mechanisms need to be reinforced to tackle the growing risks in the digital sphere.

Overall, openness and stewardship of digital commons, combined with mindful leadership, digital responsibility strategies, and robust governance frameworks promoting trust and accountability, can counter current barriers and misconduct and foster a more equitable, sustainable, and resilient digital governance landscape.

5.4.6. Accessible and Secure e-Government Opportunities for Regenerative Governance

The concept of electronic government (e-government), also referred to as "govtech" or "digital government," involves delivering governmental services through universally accessible digital means, enabled by ICT technologies. By leveraging ICTs, e-government plays a crucial role in enhancing and transforming governmental services while fostering interaction with diverse stakeholders, from economic entities to civil society (Alshehri et al., 2012; Dawes, 2009).

Besides, it emphasizes administrative efficiency, service quality, transparency, accessibility, inclusiveness, and democratic participation, thereby contributing to environmental sustainability goals by minimizing commuting and resource use through virtual applications.

As digital transformation continues to deepen, aligning e-government initiatives with regenerative digital governance principles is imperative. Regenerative governance goes beyond mere efficiency, since it embeds ecological and social considerations into government operations, thereby promoting a more sustainable future. Key aspects of e-government include ensuring access to services for people with disabilities or those in remote areas and promoting e-democracy to make governance more responsive and inclusive.

Numerous frameworks from international and governmental organisations focus on digital government. For instance, the "Govtech Maturity Index" by the World Bank (2022a) underlines the effectiveness of government electronic services for citizens and businesses.

Similarly, the UN's "E-Government Development Index" (UN, 2022) comprises three sub-indices: the "Online Services Index" (OSI), which covers institutional frameworks, service and content provision, technology, and e-participation; the "Human Capital Index" (HCI), which focuses on education and human capital creation; and the "Telecommunication Infrastructure Index" (TII), which addresses broadband and usage aspects.

This framework illustrates how digital government interrelates with other domains, such as supporting infrastructures, education, and participation.

Other relevant frameworks analysed for the taxonomy development include the Digital Global Compass (UNDP, 2021), the Digital Progress and Trends Report 2023 (World Bank, 2024), and the Digital Economy and Society Index (DESI) (EC, 2023d).

These frameworks provide comprehensive insights into the components necessary for effective digital government, offering guidelines for implementing successful e-government strategies. Yet, sustainability aspects are not sufficiently considered within these frameworks.

Furthermore, as argued by numerous experts, e-government initiatives face various challenges, including technological, institutional, and societal barriers. In this regard, Stratu-Strelet et al. (2021) examined e-participation in European e-government initiatives, underscoring the relevance of leadership and technology in institutionalizing these efforts, and overcoming resistance to change. Addressing challenges related to cybersecurity, the digital divide, and resource limitations is also crucial for the success and sustainability of e-government initiatives.

Similarly, Köhler et al. (2019) emphasized that e-government options within socio-technical transitions are vital for orienting digitalization towards social challenges. Engaging citizens in the digital pathway is important for achieving sustainable development and democratic societies. However, digital participation platforms present challenges that must be carefully managed to ensure broad and effective citizen involvement.

Despite the promising benefits of e-government, its implementation has not always been successful, especially in developing countries, where project failure rates reach as high as 60% (Malodia et al., 2021). These scholars proposed an integrated conceptual framework, in which e-government is seen as a "multidimensional construct" encompassing three dimensions: (1) empowered citizenship through digital tools, (2) hyper-integrated networks representing interoperability among service-providing actors, and (3) evolutionary system architecture, designed to allow modular upgrades. They identified factors shaping e-government success, including digital divides, political stability, privacy protection, and economic growth.

According to the literature, part of the barriers faced by digital government are caused by the following factors: the limited integration between research streams covering information systems and public administration; a focus on perceptions and services rather than on needs and expectations; along with the absence of multidimensional and multilevel conceptualization of the concept.

For instance, Okan (2024) explored e-government maturity models, analysing their capabilities, performance, and impact. Assessing and enhancing e-government capabilities through maturity models is crucial for understanding and improving government performance. Similarly, Weigl et al. (2024) examined the relationship between public values and user-centricity in e-government, revealing tensions between these aspects.

Bannister and Connolly (2014) proposed a taxonomy of public values for user-centric e-government which includes duty-oriented values (e.g., accountability, sustainability), service-oriented values (e.g., effectiveness, efficiency, transparency), and socially oriented values (e.g., inclusiveness, justice, fairness, accountability, pluralism, diversity, trust).

Electronic Government and Sustainability

While e-government can offer significant benefits, its full potential is often unrealized due to the "design reality gap", where societal and institutional realities diverge, leading to conflicting interests. Effective citizen engagement in digital government initiatives relies on understanding and meeting their needs. However, user-centred design often overlooks sustainability and societal impacts (Sevaldson, 2018).

Only a limited number of studies have explored the intersection of e-government strategies and environmental sustainability outcomes. In this regard, Huang et al. (2024) examined the impact of digital government on GHG emissions across fifty-one economies, concluding that enhanced e-government correlates with lower carbon emission intensity, contributing positively to environmental goals, particularly in Asia and Europe. Similarly, Abbas et al. (2022) studied the intersection of e-government, cybersecurity, and public service sustainability in Asia, concluding that e-government is critical for enhancing sustainable public services and improving institutional quality.

In this matter, Japan's "Society 5.0" strategy serves as a notable example of a holistic approach to e-government that aligns with the principles of regenerative digital governance. Introduced in 2016 as part of Japan's Science and Technology Basic Plan, this strategy aims to address societal disparities through people-centred digital government, enhancing quality of life while promoting the SDGs. The subsequent evolution of this strategy into the "Society 6.0" paradigm has seen a more consistent integration of environmental sustainability, underscoring the significance of nature in digital transformation efforts. Yet, it remains a conceptual concept with uncertain implementation.

Hence, to contribute to regenerative sustainability, digital government strategies should evolve to better integrate sustainability as a core principle for mindful governance. In that way, e-government services can become at the same time more effective and resilient, ensuring that they meet current needs while adapting to future demands.

Overall, e-government holds significant potential for promoting sustainability through regenerative digital governance. Nevertheless, some enhancements are needed in terms of balancing user-centricity with public values, leveraging maturity models, and addressing technological and institutional challenges.

Despite facing various barriers, e-government is essential for enhancing public services and citizen engagement. Integrating regenerative sustainability into e-government strategies can elevate their effectiveness and resilience, ensuring that these services meet current needs while adapting to future demands.

5.4.7. Reflections on the Peace Pillar

Governance is a cross-cutting issue that influences all pillars and dimensions of the proposed Taxonomy. To fully leverage the opportunities of the triple transition, governance must adopt a mindful approach, integrating regenerative sustainability, equity, inclusiveness, and human rights into every aspect of digital transformation.

Currently, governance in digital transformation is often a weak point, frequently overlooking sustainability and lacking a global consensual vision. Therefore, adopting a holistic, whole-of-government approach is essential to ensuring that mindful and responsible governance becomes mainstream, contributing to the regeneration and resilience of both societal and natural ecosystems.

The Peace Pillar emphasizes the importance of mindful, multilevel governance that encourages shared responsibility and ownership among all stakeholders. A central focus is placed on ethics and regulation to safeguard human rights, sovereignty, and democracy, thereby promoting peaceful digital societies.

In this regard, key domains such as responsible oversight, regulation, and policies on critical issues such as human rights, cybersecurity, and Internet governance are particularly emphasized. In addition, complementary soft approaches, such as voluntary standards, digital responsibility schemes, and guiding principles, are also encouraged.

Trust and accountability are also underscored as essential for fostering mindful governance. Additionally, the pillar advocates for accessible and secure regenerative e-government opportunities and underlines the need for regenerative governance to align digital transformation with sustainability and resilience objectives.

This pillar also underlines the significance of decentralizing digital assets to improve access to open digital commons, such as data, while addressing monopolistic practices, digital colonialism, power asymmetries and divides.

In summary, the Peace Pillar for mindful governance provides a comprehensive compendium of the most critical domains for promoting a responsible, equitable, sustainable digital transformation that contributes to regenerative governance and the triple transition.

An outline of the domains within the Peace Pillar, along with their alignment with the SDG goals is provided in Table 5.9.

Table 5.9. Domains within the Peace Pillar and their Alignment with the SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PEACE (MINDFUL GOVERNANCE)	Responsible and Agile Oversight, Regulation, and Policies	SDG 16, SDG 17 All SDGs
	Digital Ethics Governance for Safeguarding Human Rights, Sovereignty, and Democracy	SDG 5, SDG 10, SDG 16
	Mindful Leadership and Digital Responsibility Schemes	SDG 8, 12, 16, 17 All SDGs
	Openness and Stewardship of Digital Commons	SDG 9, SDG 17
	Digital Trust, Transparency, and Accountability	SDG 16, SDG 17
	Inclusive, Accessible, and Secure e-Government Opportunities for Regenerative Governance	SDG 9, SDG 11, SDG16, SDG 17 All SDG

5.5. The Prosperity Pillar: Purposeful and Regenerative Digital Development

The “Prosperity Pillar” for Purposeful and Regenerative Digital Development encompasses the socioeconomic aspects of sustainability and the triple transition towards regenerative development. This approach aims to balance socioeconomic progress with the protection and regeneration of societal and environmental systems, thereby promoting a digital, ecological, and equitable transition.

In the post-pandemic era, global economies, including the European Union, have concentrated their efforts on recovery and resilience plans, which offers a unique opportunity to pursue the triple transition. However, traditional economic frameworks with strict adherence to economically driven values pose significant challenges to achieving sustainability, particularly in the context of the ongoing global disruptions.

Redirecting prosperity towards competitive and regenerative sustainability is a challenging endeavour, due to the dominance of purely economic narratives that prioritize growth over ecological well-being, and social development. The vested interests of economic actors and the inertia of prevailing growth-based narratives are substantial obstacles to this shift. If prosperity is not oriented towards a regenerative mission, achieving a sustainable and inclusive digital transformation will remain elusive. A systemic reshaping of socioeconomic structures is required, involving efforts to dismantle unsustainable practices while maximizing the benefits of a regenerative digital economy.

This reorientation includes addressing issues related to globalization, trade, and the uncertain future of work while leveraging responsible innovation and mindful digital adoption to enhance sectoral competitiveness and societal opportunities.

Digital transformation has already altered every economic sector by improving productivity and efficiency through technological advancements and enhanced skills. Nevertheless, the benefits have not been equitably distributed across all communities and remain intertwined with environmental degradation. Besides, socioeconomic development must be regarded beyond merely efficiency gains and provide socio-ecological opportunities that support regeneration across all societal and economic systems.

Hence, the reorientation of current perspectives towards purposeful and regenerative prosperity represents a crucial opportunity to reconcile prosperity with sustainability, expanding the opportunities for the triple transition.

Following this substantiation, the Prosperity Pillar for a Purposeful and Regenerative Digital Development includes several interconnected domains that are critical for promoting a balanced and sustainable digital deployment with regenerative qualities, encompassing the following:

- (i) Equitable digital competitiveness across value chains, by promoting equal opportunities across all regions and demographics to access and benefit from digital advancements.
- (ii) Equitable and fair digital economy, commerce, and trade which advocates for digital practices that respect human rights, justice, and regenerative sustainability, thereby benefiting all stakeholders.
- (iii) Responsible digital innovation and entrepreneurship ecosystems, by encouraging an R&I environment that aligns with sustainability goals and providing responsible responses to eco-social challenges.
- (iv) Fair digital labour, decent work, reskilling, and upskilling, aiming to protect the workers' rights amidst digital disruptions, ensuring fair wages and working conditions, and preparing the workforce for the future.
- (v) Responsible digital uptake for regenerative development, encouraging all sectors to adopt digital technologies responsibly and sustainably, including the creation of smart and sustainable communities and ecosystems.
- (vi) Inclusive digital financing and taxation, focusing on financial systems and tax policies that support inclusion and sustainability in the digital economy.

These domains are interdependent and highly relevant to ensure that digital transformation benefits not just the economy but also society and the environment, contributing to creating regenerative opportunities for all, instead of merely focusing on economic growth. The domains within the prosperity pillar are closely intertwined with the preparedness and peace dimension, complementing, and enhancing each other.

As argued by Tufts University (2017b), key drivers for DT include being supported by a robust institutional and business environment (ease of doing business), supply conditions (access to infrastructures), and demand conditions (customer engagement and digital uptake), along with innovation and change management. Thus, these enablers have been properly considered within the proposed Taxonomy.

Furthermore, this research emphasizes that prosperity should be purpose-driven and viewed through a regenerative lens to promote social and environmental flourishing. For that purpose, a compelling new narrative around regenerative economic competitiveness and development must be established to disrupt existing inertia. Hereby, terms such as "equitable", "sustainable", and "responsible" are not merely cosmetic but essential for evolving economic structures and discourses towards sustainable and regenerative development.

Decoupling economic rhetoric from the outdated notion of exploiting nature or society is paramount. Promoting a development model that cares for and regenerates both nature and people is not only possible but as research proves can be also more profitable and productive in the long term since it generates greater added value, durable resilience, and ultimately, the creation of more capital in all its forms.

A more detailed substantiation of the domains within this crucial pillar of the Taxonomy concerning prosperity is provided as follows.

5.5.1. Equitable and Sustainable Digital Economy and Competitiveness across Value Chains

The digital economy serves as the backbone of modern development activities, contributing significantly to sustainable competitiveness. According to the World Economic Forum (WEF, 2024a), it is underpinned by the development of novel technologies, the widespread adoption of affordable digital services, sustainable industry transformation, and enhanced digital competencies. This also includes the importance of cross-border trade, strategic investments, robust financial markets, and geo-economic considerations. The digital economy succeeds in the broad integration of digital technologies and capacities across all economic sectors, primarily driven by the ICT sector, which is essential for innovation (OECD, 2024).

The integration of technologies like IoT, BDA, AI, Cloud Computing, and Blockchain has been instrumental in enhancing business performance and driving sustainable practices. Consequently, the digital economy includes all economic activities that result from the interconnection of online services, devices, data, business processes and people.

This includes e-commerce, e-trade, digital payments, financial transactions through digital means, and digital services (EU, 2023, 2024). These activities and capabilities enhance the competitive advantage in the digital era, driving digital competitiveness.

Moreover, the development of the digital economy and subsequently digital competitiveness relies on institutional, supply chain, and demand conditions (Tufts University, 2017b). The institutional conditions are also relevant for the preparedness dimension since they influence the "ease of doing business" (World Bank, 2020). The supply conditions encompass access to ICT infrastructure, transaction infrastructures (financial), and fulfilment infrastructure (e.g., transport and logistics). Lastly, the demand conditions include the consumers' capacity to engage, digital uptake, and financial inclusion. All of them are properly considered within the proposed taxonomy.

Moreover, economic development and competitiveness in a globalized world rely on intricate cross-border supply and value chains exposed to disruptions and geopolitical tensions that can hamper inclusive and sustainable development. Efforts should ensure that value chains are accessible, reliable, and compliant with sustainability and human rights requirements (Liu and Ma (2024).

In addition, digital technologies promise to enhance economic sustainability by fostering innovation, and entrepreneurship, and increasing market share (Cricelli and Strazzullo, 2021).

The convergence of digital innovation and Environmental, Social, and Governance (ESG) commitments is seen as crucial for fostering long-term resilience and value creation (WEF, 2023), driving digital competitiveness.

However, the digital economy evolves at different speeds and scopes across countries and organisations, which requires constant innovation to remain competitive, and suitable and mindful policies to mitigate potential divides (Tufts University, 2017).

Measuring the socioeconomic impacts of the digital economy is highly complex, as underlined by most international organisations working in the field (e.g., OECD, WEF, ITU, World Bank). Research also acknowledges that there is an urgent need to harmonise definitions at the global level, as well as to develop enhanced conceptual frameworks and tools to monitor digital technology adoption, and subsequently measure the derived productivity and eco-social effects (OECD, 2021a). The rapid evolution of the digital economy requires continuous adaptation and strategic planning to ensure that equitable and sustainable development is achieved across all sectors and regions.

Therefore, considering the above, the proposed Taxonomy integrates all these elements of digital competitiveness within the Prosperity Pillar.

Digital Competitiveness and Fair Markets

Digital competitiveness refers to an organization's or nation's ability to adopt, implement, and effectively use digital technologies, infrastructures, and skills to improve economic performance, productivity, and the overall capacity to compete in the markets (IMD World Digital Competitiveness Ranking, 2023). Digital transformation is a critical driver of competitiveness, enhancing performance through the adoption of novel technologies and capabilities (Stankovic et al., 2021).

Certainly, nations and organisations that effectively harness digital opportunities can improve productivity, reduce costs, enhance services, foster innovation, and maintain a competitive edge in the global market (He, 2024; Williams et al., 2022).

Digital productivity is achieved through the integration of digital technologies and skills in various processes, leading to improved workflows, reduced costs, increased pace, and enhanced production quality. As underlined by the OECD (2024), key enablers of digital productivity include automation, data analytics, and cloud computing for scalability and flexibility.

Furthermore, digital competitiveness also drives socioeconomic development as argued by Kiselakova, (2021). Leveraging digital capacities offers unparalleled competitive advantages (Martincevic, 2022). However, disparities in technology adoption and digital skills can lead to unequal opportunities and in addition they hinder competitiveness (OECD, 2024). The scientific literature covers both digital competitiveness and development at the micro (entity) and macro (country) levels.

According to Delgosha (2020), digitalisation enhances sustainable competitiveness, particularly with robust ICT infrastructures and capabilities. Knudsen et al. (2021) noted that digitalization can offer significant and sustainable competitive advantages, especially when business models effectively integrate Big Data and network effects. Also, Parida (2019) emphasized that firms can achieve competitive advantages through sustainability by transforming capabilities, business models, and networks, leveraging digitalization, the circular economy, and “product-as-a-service”.

These perspectives highlight the critical role of digitalisation in driving sustainable competitive advantages, demonstrating that ethical and sustainable digital business models are essential for long-term success in the digital economy.

Fair Digital Markets and Digital Marketing Risks

Another crucial aspect of the digital economy relies on ensuring fair competition, responsible behaviour, and a level playing field in digital markets. This is essential to combat current oligopolies, power concentration, neocolonialism, and digital divides. Such aspects are intertwined with mindful governance, as underlined in the proposed Taxonomy.

A fair digital market will allow the participation of new actors, ensuring that the benefits of digital transformation are fairly distributed, particularly to those most adversely affected by its inherent disruptions.

Moreover, a just transition and sustainable competitiveness approach must permeate the digital economy sphere. Indeed, “sustainable competitiveness” refers to the ability to sustain economic performance while ensuring social inclusion and environmental sustainability. The Cambridge University-CSIL (2022) described “competitive sustainability” as an economy’s capacity to outperform international rivals in their journey toward sustainable development.

Digital transformation can significantly contribute to sustainable competitiveness through several factors: a) enhancing productivity and efficiency, since optimized resource use reduces waste and environmental impacts; b) driving innovation, as digitalisation opens new markets and opportunities for sustainable development; c) promoting inclusive opportunities, provides a platform for small businesses and entrepreneurs; d) fostering global cooperation, since it facilitates knowledge and technology transfer and supports the SDGs; e) data-driven decision making, considering that it enhances informed policymaking for sustainability.

Additionally, to ensure fairness within digital markets, incentives for digital development must be designed to provide equal access to opportunities and inclusiveness, thus, contributing to a just transition. Certainly, equal access to quality infrastructures is crucial for inclusive competition and development.

A widely acknowledged risk of the digital economy relies on harmful marketing practices. Indeed, digital marketing faces sustainability challenges requiring further research to bridge the gap between society and business needs (Díez-Martín et al., 2019). Several digital marketing practices, such as using AI for nudging and targeted advertising, pose ethical challenges (e.g., including privacy, transparency, and discrimination). It is crucial to mitigate these risks and ensure ethical practices through regulations and standards to protect consumer rights.

Cano et al. (2022) explored the expansion of e-marketplaces and their role in fostering sustainable development. They argued that benefits such as reducing transaction costs and increasing business visibility come with adoption challenges. Thus, open innovation and stakeholder collaboration are relevant factors for sustainable business models that benefit the economy, society, and the environment.

According to Chenli et al. (2024), fairness in online data trading involving sellers, brokers, and buyers is paramount, and novel verification mechanisms and protocols are needed for this realm. They focused on Ethereum, a decentralized, open-source blockchain platform, which enables the creation and execution of smart contracts and decentralized applications and is used to pay for transaction fees and computational services. This platform allows developers to build and deploy applications without centralized servers, providing a foundation for innovations like decentralized finance (DeFi) and non-fungible tokens (NFTs).

However, Ethereum, like other blockchain platforms, has significant environmental impacts primarily due to its energy-intensive consensus mechanism, known as Proof of Work (PoW). This mechanism requires substantial computational power to validate and record transactions, leading to high electricity consumption and a large carbon footprint.

Yet, Ethereum is transitioning to a more energy-efficient consensus mechanism called Proof of Stake (PoS), which is expected to significantly reduce its environmental impact.

All in all, ensuring fair and ethical practices in digital markets and marketing is essential for fostering sustainable development and equitable opportunities in the digital economy.

Relevant frameworks in this domain that have been analysed for the Taxonomy development are described as follows: Digital Development Compass (UNDP, 2023; 2019); Digital Economy and Society Index (DESI) by the European Union (EC, 2023d); Digital Economy Outlook (OECD, 2024); Digital Economy Report (UNCTAD, 2024; 2021b); Building Smart Societies and Digital Planet-Digital Evolution Index (Fletcher School, 2017a, b); Going Digital (OECD, 2020b); Digital Progress and Trends Report (World Bank, 2024); World Bank's Digital Adoption Index (DAI); Digital Financial Inclusion in Emerging and Developing Economies (IFM, 2021); Global AI Index (Tortoise, 2023); Mobile Industry Impact Report (GSMA, 2021); Handbook on Measuring Digital Trade (IMF et al., 2023).

5.5.2. Equitable and Fair Digital Economy, Commerce and Trade

Digital competitiveness is intrinsically linked to the development of commerce and trade. This section examines the challenges and opportunities in shaping a more equitable and fair digital economy so as to contribute to a regenerative digital transformation.

Digital Trade and Cross-Border Challenges

Digital trade, as defined by the IMF (2023), refers to all international transactions and deals involving goods or services that are digitally ordered, delivered, or enabled. This encompasses cross-border e-commerce, digital services, goods trade, and transactions on digital platforms.

Technologies, including IoT, AI, Cloud computing, and Blockchain, are rapidly transforming international trade by enhancing efficiency, and productivity, and generating new business models (IMF et al., 2023). Certainly, digitalisation is expanding the scale, scope, and pace of trade, creating new ecosystems such as digital platforms that support global commerce connectivity.

Moreover, digital connectivity is significantly fostering trade flows, with data flows becoming a strategic asset in organizing global value chains (GVCs). However, this transformation also increases the complexity of international transactions, raising new challenges for market openness, security, and sustainability.

As trade becomes faster and more reliable, it also demands addressing privacy, data protection, consumer protection, and cybersecurity concerns. As underlined by relevant multilateral institutions like the OECD (2024), cross-border data flows present unique regulatory challenges that require international cooperation for effective governance.

Regarding the accurate measurement of digital trade, it becomes crucial for areas such as international trade and competition policies, and taxation, but remains highly challenging (OECD, 2024). Relevant frameworks like the OECD's "Digital Services Trade Restrictiveness Index" and the IMF's "Handbook on Measuring Digital Trade" (IFM et al., 2023), support governments navigate these challenges.

Nonetheless, further efforts and international cooperation are needed to better depict the socioeconomic impacts of digital trade, particularly the transboundary spillovers. Indeed, Liu and Ma (2024) underlined the relevance of these transboundary effects, with the impacts of the digital economy in one region extending to neighbouring regions.

Furthermore, the impact of digital trade on sustainability is considered significant, as noted by UNCTAD (2024). The multilateral organisations such as the UNCTAD, call for sustainable and equitable strategies to mitigate adverse effects of digital trade on the environment and people.

International collaboration is of the utmost relevance to address environmental impacts such as e-waste, infringements of human rights, and digital divides, as well as to prevent unfair competition, job displacement, and increased inequality. The dependency on global value chains and geopolitical conditions can pose sustainability challenges.

Despite trade agreements and regulations like the Basel Convention for waste trade, compliance and responsibility are not always ensured, causing severe environmental and social risks.

Thus, more robust, and fair-trade mechanisms are needed, particularly to counter illegal e-waste trade and Human Rights abuses.

Digital Commerce

Digital commerce, or “e-commerce,” involves buying and selling goods and services via the Internet, digital networks, and commerce infrastructure. This includes B2B, B2C, and C2C transactions, online retail, marketplaces connecting buyers and sellers, and payment gateways facilitating transactions (UNCTAD, 2021b; OECD, 2024).

Digital commerce, particularly the so-called “platform economy” activities, must comply with responsible and sustainable requirements. The platform economy, “gig economy,” or “attention economy” have often disrupted the socioeconomic realm with unethical behaviours, regulatory arbitrage, and unfair competition. Issues such as informal and insecure jobs, privacy concerns, monopolistic practices, tax evasion, offshoring, job losses, and gentrification have been prevalent in this area.

While e-commerce offers outstanding opportunities for socioeconomic development, especially for small enterprises and rural inhabitants, it also depends on global supply chains with uncertain social and environmental conditions. The electronic commerce sector also contributes to a growing environmental footprint. While the net environmental impact of e-commerce remains uncertain, research suggests that it could drive overconsumption and unethical practices.

Integrating social, environmental, and economic aspects into e-commerce is essential for promoting digital economy sustainability (Oláh et al., 2018). Sun et al. (2021) found that enhancing the sustainability aspects of an e-commerce business model improves performance across economic, environmental, and social dimensions.

Zahn et al. (2021) contended that AI fairness in e-commerce could promote justice requirements but involve trade-offs in prediction performance and costs. As underscored by Sakar (2023), achieving environmental sustainability in e-commerce requires a comprehensive approach addressing logistics, packaging, and carbon emissions to maximize benefits and minimize trade-offs. Popescu (2015) indicates that integrating sustainability into e-commerce can enhance competitiveness, reduce environmental impact, promote ICT utilization, and foster sustainable development in energy-intensive industries.

Ethical business models

In the digital realm, user-centric and eco-design perspectives are crucial for reducing environmental impacts and maximizing social benefits. Despite prevalent greenwashing and ethical washing in the digital sector, many business models remain neither ethical nor sustainable, exacerbating environmental and social issues. Therefore, it is imperative to encourage and mainstream ethical and sustainable digital business models.

As underscored by Rosa (2021), business ethics is crucial for making right decisions and achieving long-term sustainable development in the digital transformation era. Wörsdörfer (2021) argued about the antitrust implications of “Big Tech” platforms' business models and strategies, suggesting that ethical considerations are often overlooked in the pursuit of market dominance.

Besides, Palmer (2010) underscored the ethical issues in e-business, such as online security, moral dilemmas, and privacy concerns, advocating for a robust framework to ensure safety and reliability. These viewpoints collectively emphasize the critical need for ethical considerations in the evolving digital landscape.

According to Gregori and Holzmann (2020), digital technologies can improve sustainable business models by enabling innovative value-creation configurations and strengthening the connection between digital and sustainability principles.

Thus, the integration of ethical considerations and sustainable practices can lead to more responsible and socially beneficial business models for addressing the complex challenges of the digital era.

5.5.3. Fair digital labour, decent work, reskilling, and upskilling

The digital economy has significantly transformed work and employment patterns. It has also promoted novel paradigms like remote working (teleworking) or the digital nomads. While teleworking offers benefits like increased productivity and flexibility, it also raises concerns about worker isolation and unequal access to digital tools. Similarly, gig economy platforms provide flexible jobs but often result in precarious work conditions and a lack of social protections (OECD, 2024).

Certainly, digital labour offers benefits but also poses risks. As asserted by Graham et al. (2017), it is crucial to understand the gig economy and digital labour impacts on workers, particularly in terms of bargaining power, economic inclusion, intermediated value chains, and upgrading. For that purpose, strategies such as certifications, regulation, organization of digital workers, and control of platforms could mitigate potential risks.

For instance, Bajwa et al. (2018) highlighted that gig workers face significant health vulnerabilities due to occupational hazards, job precariousness, and platform-based challenges, which vary across regions. In the same perspective, Freni-Sterrantino and Salerno (2021) emphasized that gig workers experience job instability, poor job quality, and low salaries, exposing them to high-stress levels.

Besides, Wood et al. (2019) noted that while digital labour in the gig economy lacks social protections, it benefits from interpersonal networks of trust, enabling work completion in low-trust environments. Collectively, these studies underscored the precarious conditions and vulnerabilities faced by gig workers.

Furthermore, the adoption of technologies such as AI in organizations requires strategies for mapping transversal skills, supporting skill development, and addressing challenges such as job loss and diversity (Morandini et al., 2023). Therefore, advances in automation, AI, and other technologies are transforming workplaces, necessitating reskilling and upskilling efforts (Semenova et al., 2023). Both studies highlight the importance for businesses, policymakers, and individuals to adapt to ensure a more inclusive and sustainable future in the face of technological changes.

Considering the future of work, Santana and Cobo (2020) explored themes like job satisfaction, leadership values, corporate social responsibility, and technological change. Their research investigated how these factors impact employment, wage inequality, and vulnerable workers. Thus, the future of work will be shaped by automation, new technologies, and the rise of contingent workers, significantly affecting jobs and the economy.

Similarly, Johnson (2020) discussed the role of automation, AI, and hybrid working arrangements, emphasizing a shift towards a more collaborative, value-based economy with increased remote work and alternative work arrangements. In addition, Beno (2020) identified four key factors shaping the future of work: technological progress, globalization, glocalization, and societal and institutional change.

These factors, combined with enhanced connectivity, and the emergence of empowered consumers, collectively redefine the workforce landscape. This also underlined the need for adaptability and innovation in addressing the evolving work environment.

Thus, the future of work remains uncertain, surrounded by digital disruptions that alter traditional work and living structures, along with societal protection mechanisms. Digital platforms are often linked to worker exploitation due to a lack of bargaining power and the absence of regulatory protections for informal jobs. Traditional labour rights and protections, along with tax systems, may be eroded as a significant number of workers shift to freelance informal roles.

Opportunities such as remote working, self-employment, and virtual meetings provide benefits to workers and sustainability, but challenges like precarity, informality, tax evasion, and offshoring are harmful. There are also significant risks of job losses with the advancement of digital technologies related to automation, such as robotics or AI. Hence, the digital disruption necessitates reskilling and upskilling programs to keep pace with technological developments.

Relevant frameworks in this domain that have been considered for the proposed Taxonomy included: the Going Digital tool (OECD, 2020b); the World Employment and Social Outlook 2021 (ILO, 2021); and the Digital Employment Diagnostic Guidelines (IMF, 2023).

In conclusion, ensuring fair and ethical practices in digital labour is essential for fostering sustainable development and equitable opportunities in the digital economy. For that purpose, fair labour policies and incentives are needed to promote decent work, fairness, and quality living wages and working conditions for workers. Additionally, educational programs for digital skills should be reinforced and accompanied by sustainability education to ensure awareness and sustainable futures.

5.5.4. Responsible Digital Innovation and Entrepreneurship Ecosystems

Innovation stands as a cornerstone of both digital and sustainability transformations, as previously introduced in Chapter 4. Certainly, digital technologies are driving innovative solutions to tackle climate change and sustainable development, fostering entrepreneurship, innovation, and strategic advancements (George et al., 2020). In this regard, Fernandes et al. (2022) identified three key research clusters: innovation, digital transformation, and sustainability.

As argued by Nambisan et al. (2019) digital technologies have profoundly impacted innovation and entrepreneurship, with three key themes emerging: openness, affordances, and generativity.

Ma and Zhu (2022) suggested that industrial structure adjustment and green technology innovation are crucial mechanisms through which the digital economy drives high-quality green development. Additionally, the digital economy has spatial spillover effects, influencing sustainable development in neighbouring areas.

Considering digital entrepreneurship, Satalkina and Steiner (2020) emphasized its impact on innovation systems, disrupting traditional business structures. Xu et al. (2022) underlined that digital capabilities and innovation orientation enhance digital sustainable entrepreneurship, moderated by the managers' cognition of sustainable opportunities. Similarly, Baranauskas and Raišienė (2022) noted the benefits and challenges of digital entrepreneurship, while Bican and Brem (2020) discussed how digital readiness and technology support sustainable innovation through digital transformation processes.

However, current innovation frameworks and policies often remain entrenched in outdated perspectives. To address modern eco-societal needs, digital innovation and entrepreneurship should be responsibly reoriented. This reorientation involves integrating conscious business models, fostering open collaborative environments with diverse stakeholder participation, and ensuring responsible and impactful uptake paths.

In this context, frugal and open innovation fits well within the digital sphere and should be promoted to ensure sustainable and inclusive outcomes. Embedding responsible innovation within ecosystems, programs, and incentives is essential for making a meaningful contribution to regenerative sustainable development.

Furthermore, the diffusion and transfer of knowledge and technology across borders, sectors, and actors are pivotal and must be reinforced. For that purpose, funding incentives and programs should encourage sustainability in digital activities to fully harness the opportunities they offer.

Public-private collaboration, along with other multistakeholder communities and innovation valleys, should expand innovation as a driver of sustainable competitiveness in the digital era. To achieve this, incubators, accelerators, and digital innovation hubs offer outstanding opportunities to reorient innovation and entrepreneurship towards eco-social regeneration.

Sassanelli and Terzi (2022) suggested that the “Value Proposition Canvas” can help Digital Innovation Hubs (DIHs) define their unique value propositions, guiding their sustainability strategies and fostering collaborations with key customer segments. Similarly, Zamiri et al. (2021) proposed a conceptual framework with five dimensions to support the establishment and development of sustainable DIHs, thereby enhancing competitiveness and customer engagement through tailored products and services. As argued by Lepore et al. (2023), digital innovation hubs can promote inclusive smart cities by acting as transformation mediators and knowledge brokers.

Relevant frameworks covering innovation and entrepreneurship include the Digital Development Compass (UNDP, 2019), the Global Innovation Index (IPO, 2023), Going Digital (OECD, 2020b), and the Digital Inclusion Benchmark (WBA, 2023).

Despite the significant role of innovation and entrepreneurship in addressing eco-social transformation, there is still a lack of regenerative approaches that ensure genuine sustainability within planetary and societal boundaries. Innovation itself necessitates evolution, as discussed in Chapter 4. An intriguing nexus among innovation, sustainability, and digital transformation is emerging, which deserves further research and robust policy support.

In conclusion, the integration of mindful innovation and entrepreneurship approaches and frameworks is essential for achieving sustainable and inclusive outcomes in the digital era, addressing both current and future eco-societal challenges. Further research and policy development are needed to unlock their opportunities in this realm. Therefore, the proposed Taxonomy soundly integrated these domains so as to raise awareness about their potential.

5.5.5. Responsible End-to-End Technology Lifecycle for Regenerative Development

The adoption and responsible use of digital technologies across all economic sectors are fundamental factors for modern development and sustainability transformations. Promoting a responsible digital uptake can provide significant socioeconomic opportunities across sectors and geographies, including e-health, e-education, Smart Energy, Smart Mobility, Smart Logistics, Smart Manufacturing, Smart Water, Smart Building, Smart Agriculture or “Agri-tech,” and emerging concepts like Industry 5.0 and Society 6.0.

This widespread adoption has led to the emergence of the "smart everything everywhere" phenomenon (Streitz, 2019), which aims to drive sustainable and smart communities that empower individuals and optimize processes. The Internet of Everything (IoE) may alter business models and value creation processes, requiring a clearer understanding of its impact across various levels (Langley et al., 2021). Wireless-IoE aims to connect smart devices to smart spaces, enabling new services in personal healthcare, smart cloud, smart city, smart home, and smart transportation.

Certainly, as already examined in Chapter 3, the advent of digital technologies such as Big Data Analytics (BDA), Artificial Intelligence (AI), Industrial Internet of Things (IIoT), High-Performance Computing (HPC), Cloud services, Distributed Ledger Technologies (DLTs), Virtual Worlds, Extended Reality (XR), Digital Twins, has revolutionized multiple sectors. Businesses and organisations in general, are increasingly adopting digital technologies to enhance efficiency, productivity, and innovation. This results in the creation of smart systems that enhance functionality and efficiency, yet, they also add complexity and sustainability concerns.

Achieving a responsible adoption and uptake of digital technologies is influenced by organisational, individual, and contextual factors. Digital adoption in sectors such as manufacturing, construction, healthcare, and education is shaped by organisational structure, leadership knowledge, stakeholder engagement, and technology awareness (Modupe, 2023; Zulu et al., 2023; Kimuli et al., 2021).

The readiness of the innovation ecosystem, digital competencies, and digital resilience are also crucial factors influencing technology adoption, which is the first step for the uptake (Masrianto, 2024; Aminu et al., 2021; Zeng et al., 2022). Therefore, an effective digital uptake relies on these interrelated factors, which foster successful integration and utilization of digital technologies.

For instance, the Industrial Internet of Things (IIoT) in combination with robotics are transforming manufacturing processes by enhancing human-machine communication and enabling flexible and efficient smart factories. This shift supports the emergence of "Industry 5.0," which emphasizes human-centric and sustainable practices (Ivanov, 2022), as examined in Chapter 3.

Furthermore, HPC and Cloud services provide the computational power and scalability needed for complex data processing and storage. Similarly, Big Data Analytics and AI are powerful tools for strategic decision-making and for augmenting human capacities. In addition, advanced connectivity, such as 5G and future 6G technologies, offers higher speeds efficiency, and lower latency, essential for real-time applications that allow smart manufacturing, mobility, and logistics.

Lastly, DLTs enhance traceability and transparency, complementing BDA and AI ecosystems by ensuring data integrity and accountability. Moreover, and thinking in the long-term, emerging technologies like Quantum Computing promise to solve intricate scientific and practical problems with unprecedented capacities.

Another sector that has been revolutionised by ICTs is Digital Healthcare, also known as "e-health," or "Health-tech." By integrating technologies like AI, IoT, and wearables, research and patient care can be enhanced, through remote monitoring and improved diagnosis. The adoption of digital healthcare solutions facilitates more accessible medical services and optimizes resources and care, but also raises data privacy concerns and the potential for unequal access (Sun et al., 2020; Labrique et al., 2018). Indeed, digital inclusion in healthcare systems can ensure equitable and impactful adoption of mobile health technologies, reducing health disparities and promoting participation and collaboration (Sieck et al., 2021).

Moreover, digital wellness technologies also raise ethical concerns (Sullivan & Reiner, 2019). Wearable computing and AI are expected to enhance human wellness by providing personalized care, though, they face challenges in data processing and analysis (Chen et al., 2022).

Other factors such as political commitment, financial support, and stakeholder engagement are crucial for driving digital health innovation and adoption (Xiong et al., 2023).

Digital technologies have greatly enhanced public health functions, including epidemiological surveillance, contact tracing, and mass immunization (Wong et al., 2022). Nevertheless, aspects such as health literacy, personal contexts, and technological proficiency, significantly impact the uptake of digital health tools (Azzopardi-Muscat & Sørensen, 2019; Sturman, 2024).

Concerning the education realm, digitalisation has also enhanced this sector, by promoting self-directed learning, massive education platforms, and powerful assessment tools. However, digital solutions may also lead to information overload and reduced interpersonal communication skills (Frolova et al., 2020). Besides, technologies such as Generative AI are challenging the educational and research landscape, raising unanswered ethical concerns. Another controversial digital advancement, like the massive online courses (i.e. MOOCs), has been criticized for promoting colonialist approaches and hindering local knowledge (Kwet, 2019).

Therefore, achieving a sustainable and ethical digital uptake is paramount but it relies on the responsible development and integration of technologies by businesses and organizations with a keen awareness of their associated risks. Ensuring transparency, accountability, and the mainstream adoption of sustainable and ethical standards can help mitigate risks and foster trust and safety in the digital landscape. As argued by Streitz (2018), a human-centred design approach, integrating “privacy by design” and empowering people, can reconcile technology and human needs.

Regarding the transportation sector, smart mobility and logistics have benefited from IoT, 5G, BDA, and AI advancements, enabling real-time monitoring, optimized routing, and predictive maintenance, thereby enhancing efficiency, and reducing environmental impacts. “Mobility 5.0” is a novel paradigm which integrates emerging technologies into “Cyber-Physical-Social Systems,” potentially revolutionizing intelligent logistics and transportation services (Lin et al., 2023).

Similarly, IoT technologies can significantly improve smart logistics by creating vast amounts of data and exploring complex transaction relationships, reducing costs, and increasing efficiency in transportation, warehousing, and information processing (Song et al., 2021). However, increased efficiency can lead to unintended rebound effects in energy consumption and subsequent GHG emissions. Besides, the growing market for IoT contributes to raw materials demand and e-waste generation (Paiva et al., 2021).

Concerning the manufacturing sector, digital technology adoption and uptake in manufacturing firms, “smart manufacturing,” allows enhanced supply chain efficiency, sustainability, and innovation, with technological intelligence and cooperation as key factors (Yang et al., 2021). Besides, Digital Twins are pivotal in smart manufacturing, supporting product design, alongside monitoring and maintenance management.

The novel paradigm of “Industry 5.0” emphasizes the responsible adoption of AI, BDA, IIoT, and human-machine connectivity for the supply chain, while supporting sustainability and human-centred innovation (Akundi et al., 2022; Mourtzis et al., 2022). Nevertheless, as underlined by Frank et al. (2019), Industry 4.0 driven by Smart Manufacturing, faces challenges in implementing those technologies, such as BDA, as well as others such as cybersecurity.

One of the most widely known and extensively applied uses of digital technologies is in the urban environment, embodied in the concept of “Smart Cities”. Indeed, the Smart and Sustainable Cities, as well as the Smart Energy Communities, are outstanding examples of the potential benefits of digitalisation for both sustainability and people empowerment. The relevance of Smart Cities and Communities and Smart Energy Communities was already examined within Chapter 3 and Chapter 4.

As underlined by Huston et al. (2015), digital or smart technologies, offer significant advantages for urban regeneration by fostering local engagement, institutional strengthening, project screening, and innovative funding. Thus, smart solutions catalyse inclusive and coordinated urban renewal and promote local innovation (Huston et al., 2015). However, strategic plans for urban regeneration need to better integrate smart technology information.

In this regard, efforts to promote Smart Cities and Communities have shown that they do not always result in sustainability, inclusiveness, or participatory governance. These initiatives must be renewed to secure responsibility, collaboration, and sustainability for maximizing their opportunities to regenerate social communities and the natural environment. These communities, particularly in urban, energy, and agriculture domains, can promote eco-social regeneration.

Yet, they must integrate diverse technologies and socio-economic factors to achieve truly sustainable systems and economic efficiency. For that purpose, they also require enhancing citizens' technical knowledge and confidence in smart energy technologies to unlock their full potential (Ceglia et al., 2020).

Therefore, Smart and Sustainable Communities must move away from technocratic approaches and genuinely embrace sustainability and democratic values and practices. To achieve this, suitable policies are needed to enhance awareness of sustainable urban regeneration concepts, as argued by Kim et al. (2020).

Furthermore, the proliferation of Smart Systems extends to areas such as Smart Water Management, Smart Buildings, Smart Homes, and Smart Living, all contributing to a smarter society. In this regard, according to Ramos et al. (2019), Smart Water management can lead to significant savings and reduced GHG emissions, supporting more sustainable water networks. As argued by Windapo (2020), smart technologies in buildings benefit circular economy performance by saving energy and water, improving decision-making, and enhancing user satisfaction.

Hence, the integration of smart systems across sectors offers significant opportunities in the sustainability arena but also poses challenges related to growing material footprints from new devices, sensors, data centres, pressure on energy systems and natural resources, and e-waste generation. They also pose ethical concerns and inequalities, as previously mentioned. These aspects need to be addressed by responsible policies and practices focused on sustainability and ethics, yet to be developed.

In conclusion, the responsible and strategic uptake of digital technologies is essential not only for economic development but also for driving sustainable and regenerative development across all sectors and communities. By ensuring ethical and sustainability high standards and policies, empowering citizens, fostering cross-sector collaboration, and focusing on responsible and sustainable innovation, society can harness the full potential of digital technologies to create a smarter, resilient, and regenerative future.

Considering the increasing relevance and rapid growth of paradigms related to “Agritech” Communities, as well as the “Internet of People,” and “HealthTech” solutions, these topics are further examined below.

AgriTech Communities, Smart Agriculture and Forestry

The advent of digital technologies is revolutionising the agriculture and forestry sectors by promoting sustainability, productivity, and efficiency. Indeed, data-driven technologies have reshaped the agricultural sector giving birth to “AgriTech.” The so-called “Digital Agricultural Revolution” is driven by five main research streams: Climate-Smart Agriculture, Site-Specific Management, Remote Sensing, IoT, and AI (Bertoglio et al., 2021). These technologies help to adapt traditional practices to climate change and promote sustainability and food security. Besides, they support productivity, improved product quality, and efficient resources (Santiteerakul et al., 2020).

As argued by Spanaki et al. (2021), the integration of AI solutions in agricultural operations has led to more efficient, and sustainable farming practices. Nevertheless, this field is still in its infancy, and further research is required to fully harness the benefits of digital transformation in agriculture.

Moreover, Rialti et al. (2022) argued that digital “4.0 technologies” foster open innovation and sustainability in agrifood businesses. Their research concluded that digital solutions facilitate swift information exchanges between consumers and agri-businesses, reducing resource waste and enabling just-in-time approaches. In addition, they underlined the relevance of absorptive capacities and knowledge management in enhancing open innovation performance and sustainability, as crucial factors for successful agribusiness.

Additionally, precision agriculture, enabled by BDA, is another critical area where digital solutions are making significant advancements. Gardezi and Stock (2021) examined how PA technologies influence agricultural practices and power dynamics between Agritech firms and farmers. A complex interplay is revealed in the social construction of trust in PA. Similarly, Eashwar and Chawla (2021) presented the concept of “Agritech Business 4.0”, which integrates agricultural production with food distribution networks using technologies such as Blockchain, IoT, BDA, and AI. These scholars proposed a transparent model for integrating these technologies to create an interoperable and decentralized agricultural system, enabling enhanced productivity, food security, and trust.

Furthermore, “Digital Twins” are another promising technology for sustainable agriculture and forestry. This technology creates a virtual representation of physical assets, enabling better decision-making and resource management. According to Nie et al. (2022), Digital Twins could advance smart agricultural solutions with low cost and high precision, achieving high-yield production.

Basso and Antle (2020) argued that digital agriculture, which involves digital and geospatial technologies to monitor and manage resources, can help to balance economic, environmental, and social dimensions of sustainable food production towards a highly needed global sustainable food system.

Despite the potential benefits of digital solutions for sustainable agriculture and forestry, implementation challenges remain. According to Mushi et al. (2022), digital services for smallholder farmers lack sustainability and fail to cover the complete farming cycle. Therefore, comprehensive digital platforms that address smallholder challenges throughout the farming process are needed to enhance adoption. Besides, Mustapha et al. (2022) uncovered knowledge gaps in digital agriculture, particularly in context, theory, and content, demanding further research.

In conclusion, digital solutions hold relevant potential for transforming agriculture and forestry into more sustainable, efficient, and productive sectors. However, addressing the existing challenges and knowledge gaps is crucial for materialising the full benefits of these innovations.

Internet of People Solutions

The rapid growth of sensors and data-driven solutions has led to the emergence of the “Internet of People” (IoP) paradigm. IoP refers to the ubiquitous connections between social space and cyberspace, where humans, through their devices, become participants in the cyber world, as argued by Shi et al. (2021). According to Conti et al. (2017), this shift derived from “pervasive mobile computing”, where users act as proxies in cyberspace while sensing the physical world. According to these scholars, effective and sustainable, robust quantitative methodologies and interdisciplinary collaboration among social sciences, cognitive psychology, complex networks, and microeconomics are required for an effective IoP implementation.

The implications of IoP for sustainability are profound and multifaceted. One of the major challenges is ensuring the responsible and ethical use of technology by addressing data privacy, security, and potential access divides (Conti et al., 2017).

Furthermore, the proliferation of sensors and devices contributes to increased energy consumption, material usage, GHG emissions, and electronic waste. Despite these concerns, IoP presents opportunities for more responsive resource use and waste management. However, research on the environmental aspects of IoP is limited, necessitating further exploration.

In summary, the IoP represents a paradigm shift, placing human behaviour at the core of digital network functionality. This human-centric approach has significant implications for sustainability, presenting both challenges and opportunities. Future research must address both the ethical and practical challenges to ensure IoP's contribution to sustainable and inclusive digital development.

Wearable Technology and Healthtech Solutions

The “Wearable” technology is closely related to the previously reviewed IoP paradigm and is revolutionizing healthcare by enabling health monitoring, real-time data collection, and personalized treatment plans. Advances in miniaturization, sensor technology, and wireless communication have driven the evolution of wearable devices, which can monitor health indicators and facilitate treatments for chronic diseases and elderly care (Lukowicz et al., 2004). Further advancements in flexible electronics, electrochemical biosensors, and AI have enabled wearables to track vital signs, and metabolic status, and facilitate drug delivery (Yetisen et al., 2018). Additionally, wearable solutions have also supported citizen science experiments, contributing to research and healthcare delivery.

Despite their potential, the adoption of wearable health monitoring faces challenges, including data privacy concerns, the need for seamless monitoring, and low-latency communication (Lončar-Turukalo et al., 2019). Additionally, wearable technology presents sustainability challenges, akin to other digital paradigms, such as high energy consumption and limited battery life, with the consequent issue of electronic waste and pollution. Hence, developing energy-efficient sensors and network architectures is crucial for ensuring the long-term sustainability of wearable devices. Furthermore, privacy and security of health data collected by these devices are critical issues that need to be addressed to gain trust and ensure ethical widespread adoption.

In the “Healthtech” sector, meaning the digitally augmented healthcare industry, digital platforms play a vital role, by facilitating interactions and resource sharing among healthcare actors, thereby promoting co-creation (Faggini et al., 2018). These platforms also enable the integration of wearable technology into healthcare workflows, empowering both patients and healthcare providers.

However, further research is necessary to fully realize the potential of wearables in healthcare, focusing on energy efficiency, privacy, and long-term sustainability impacts. Interdisciplinary research is crucial for ensuring human-centric and sustainable “Wearables” and “Healthtech” development.

5.5.6. Inclusive Digital Financing and Taxation

Achieving inclusive digital financing and taxation is crucial for unlocking and channelling investments equitably and sustainably towards advancing the triple transition. This section examines these aspects, starting with digital finance mechanisms and concluding with digital taxation.

Digital Finance

Digital finance encompasses the financial services delivered through digital channels, such as online banking, digital payments, and transactions, along with cryptocurrencies. Digital transformation has transformed the financial sector with novel opportunities, such as more accessible and innovative e-banking, “Fintech,” “Insurtech,” and “DeFi” (Decentralised Finance) solutions, cross-border transactions, e-wallets, and Smart Contracts.

Digital financial services, like FinTech, have emerged as valuable tools for improving financial efficiency, and inclusion, as well as for contributing to sustainable development. They provide easier access to banking services, including underserved populations in less developed countries, rural areas, or women (Bala and Singhal, 2022). For instance, the responsible development and use of solutions like “Pay-As-You-Go” (PAYG) systems can enhance access to finance for the most vulnerable, and require less energy consumption (Werthschulte, 2023). Yet, according to Barry and Creti (2020), PAYG solutions primarily serve well-electrified areas as substitutes for expensive grid electricity, but face effectiveness barriers in bridging the “last mile” electrification gap.

Certainly, digital finance offers numerous benefits, including accessibility, cost reduction, and increased stability. According to Liu et al. (2022), they also contribute to service efficiency and innovation and facilitate the development of human capital in rural areas. Also, inclusive digital finance is associated with sustainable development and green innovation in small enterprises (Yang & Zhang, 2020; Du, 2024).

Nevertheless, barriers remain, such as the difficulty that elderly and rural populations face in adapting to e-banking. Furthermore, digital finance has also introduced novel risks such as privacy concerns, cyberfraud, volatility of cryptocurrencies, along with regulatory challenges related to those aspects, challenging financial stability (OECD, 2024).

Ensuring that the digital transformation is accessible for all, relies on promoting secure, inclusive, and sustainable finance. Indeed, sustainable financing and impact investment are growing and spreading rapidly, and digital finance represents a great opportunity and a pillar for their development. Financial incentives should ensure that high environmental and social standards are met. As argued by Vergara and Agudo (2021), both digital and sustainable finance share common aspects, and with suitable regulation and consumer protection, they can significantly enhance green finance, particularly in climate change mitigation and adaptation (AFI, 2022).

Concerning FinTech, according to Arner et al. (2019), this innovative solution can support the SDGs through four pillars: digital identity, open payment systems, infrastructures for e-government services and payments, and digital markets.

Notably, FinTech platforms are becoming crucial for facilitating cost-effective financial services to underserved populations (Ravi, 2024). Digital payment platforms and novel financial products for “Base-of-the-Pyramid” (BoP) communities, combined with enabling policies, can support sustainable development and resilience. For instance, digital retail payment platforms, mobile money services, “Person-to-Person” (P2P), and “Government-to-Person” (G2P) payments offer affordable and flexible financial services to low-income and rural households. They also serve as saving tools to combat natural disasters or climate-related shocks (AFI, 2022). Therefore, digital finance is also crucial and related to the preparedness pillar.

However, challenges remain such as literacy barriers, inefficiencies in technology utilization, and privacy concerns (Parvin and Panakaje, 2022).

Additionally, digital saving and lending services may support small enterprises, particularly those led by women (e.g. microfinance). They are useful in emergency response and for facilitating green tech investments. Besides, Pay-As-You-Go services and blockchain for smart contracts have been widely applied to promote solar energy integration and digital carbon credit trading.

Digital finance has also permeated the sustainable agricultural sector by enhancing insurance efficiency, accessibility, and cost, and supporting digital marketplaces. Yet, agricultural marketplaces and digital financial services must overcome last-mile delivery challenges in rural areas (AFI, 2022).

A particular application of these technologies is termed “Green FinTech,” which represents a burgeoning sector which aims to address environmental challenges through digital financial innovation. According to Puschmann and Hoffmann (2020), Green FinTech can contribute to mitigating the impacts of climate change by providing innovative financial products and services that promote sustainable practices such as responsible consumer behaviour. Examples include green bonds, sustainable investment platforms, and tools that facilitate the measurement of carbon footprints.

However, the integration of sustainability into FinTech is still nascent. As argued by Puschmann and Leifer (2020), while some startups are promoting this realm, major financial institutions are slower to adapt to green FinTech solutions. This lag can hinder the broader impact of these technologies, as the scale and resources of established financial institutions are crucial for widespread adoption.

The alignment between digital and sustainability finance can promote environmental and social goals if appropriate policies support societal expectations (Dell’Erba, 2021; AFI, 2022). Policies should address divides and inequalities, particularly those affecting women, small enterprises, and low-income households. Incentives may be useful to promote green digital financial services and tailored education programs to overcome barriers and enhance access and usability. Nevertheless, synergies between green and digital finance remain underexplored and deserve further research and policy development.

Concerning the Decentralized Finance (DeFi) innovation, based on platforms like Ethereum, it may bring efficiency, transparency, accessibility, and interoperability, for realising a robust and trustable financial infrastructure (Schär, 2020).

As argued by Makarov and Schoar (2022), while both DeFi and cryptocurrencies have the potential to lower transaction costs, they also face unclear legal boundaries and relevant challenges, including tax compliance, anti-money laundering regulations, and potential financial misconduct and environmental negative impacts linked to the energy-eager PoW Blockchain technologies, as described in Chapter 3.

Furthermore, another relevant digital finance solutions are the Smart Contracts facilitated by Blockchains, which are transforming business processes, by promoting efficiency, and traceability, along with cost and risk reduction (Zeng et al., 2019). They can also promote social trust and support sustainable business models in realms such as energy trading (Mas et al., 2020). However, they also face technical and regulatory challenges that require further research.

Research on the environmental impacts of digital financial services, existing literature described them as limited in relation to other digital paradigms, and mainly focused on energy consumption, subsequent GHG emissions, and ethical aspects such as privacy and security. According to Sadiq and Ali (2024), while digital financial platforms and services may increase GHG emissions, the integration of renewable energy may reduce such impacts. Nevertheless, this aspect is underrepresented in the literature and should be considered with caution.

According to Oxford Economics (2024), the environmental impact of digital payments in Europe is comparable to that of traditional payments. Yet, the study concluded that this area is poorly researched, and Life Cycle Assessment (LCA) evaluations are required to understand this aspect.

Considering the application of digital finance to sustainability, Xiangling and Qamruzzaman (2024) explored the interplay among investment in ICTs, digital financial inclusion, and environmental tax policies, demonstrating a positive effect on sustainable energy development within the MENA region. Besides, Li and Pang (2023) suggested that the development of digital inclusive finance enhances both ESG performance and green technology innovation.

Similarly, Xiao et al. (2024) found that green digital finance positively impacts sustainable regional development goals in China, particularly through the upgrading of industrial structures.

Nonetheless, those effects vary across regions and sectors, therefore, further research is needed to better depict the impacts of digital finance solutions.

When it comes to cryptocurrencies, the potential risks and impacts are more significant. Some activities, platforms, or virtual currencies, pose environmental, social, and financial risks that must be addressed.

Cryptocurrencies, supported by blockchains, have gained attention due to their potential to provide decentralized and transparent financial transactions. However, their sustainability remains controversial. As Vaz and Brown (2020) pointed out, cryptocurrencies face substantial sustainability issues, particularly in terms of energy consumption, inequality, and security.

For instance, cryptocurrencies like Bitcoin use energy-intensive proof-of-work (PoW) consensus mechanisms, which may raise energy consumption and subsequently GHG emissions (Kohli et al., 2022). Nonetheless, the trend is to evolve towards proof-of-stake (PoS) mechanisms, which are energy-efficient and support a more sustainable financial system. Indeed, energy-efficient DLTs and Blockchain based on PoS mechanisms, can support green finance by providing transparent, secure, and efficient ways to track and verify transactions (Tasca et al., 2021).

Moreover, Arnone (2022) suggested that some Blockchains underlying cryptocurrencies could facilitate sustainability by improving green production and enabling real-time tracking and analysis of environmental data, which supports enhanced decision-making.

Another concern relies on the anonymity and decentralization of cryptocurrencies, which may allow illicit practices such as money laundering and financing of terrorism. Besides, cryptocurrencies are prone to volatility, which may introduce systemic risks and instability into financial markets.

On a more positive side, Mora et al. (2021) argued that social cryptocurrencies may promote community development and cooperation among small businesses. Besides, digital currencies may support social entrepreneurship and innovation, fostering economic inclusion. However, their impact largely depends on the specific conditions and implementation of the local environment.

Concerning “InsurTech” innovations, they refer to the integration of digital technologies to improve efficiency, transparency, and customer engagement into insurance practices. According to Stoeckli et al. (2018), the transformational capabilities of InsurTech include personalized risk assessments and real-time data analytics, which promote value creation. Moreover, the integration of digital technologies may also support sustainability by providing more accurate risk assessments related to climate change and natural disasters, thereby promoting proactive environmental management.

However, the rapid digitalisation of the insurance sector also raises concerns related to data privacy and security. Additionally, the disruption caused by InsurTech could induce job displacement and surely demand reskilling of the workforce. Hence, balancing the positive and negative aspects brought by digital finance solutions is crucial for leveraging digital transformation to achieve the SDGs effectively.

Relevant frameworks in the domain of digital finance, that have been analysed for the proposed Taxonomy include the following: World Development Report (World Bank, 2021-2022), the Global Findex Survey and Database (WB, 2021), the Digital Economy Trends Report (DCO, 2024), Going Digital (OECD, 2020b), and the Digital Financial Inclusion Index (Sahay et al., 2020); The Digital Report 2024 (OCDE, 2024); The Digital Trends Report 2024 (World Bank, 2024).

In conclusion, sustainable digital finance solutions, particularly Fintech, have shown significant potential in driving financial inclusion and sustainable development. Nevertheless, they must be managed with appropriate regulations and consumer protections to address the inherent risks and challenges. Additionally, further research is needed to fully understand their impact and application on environmental sustainability.

Digital Taxation

The digital era has significantly reshaped tax management, leading to a new socioeconomic reality (Kulkova et al., 2022). As argued by Ruiz (2022), digitalisation, coupled with reliable non-financial information, offers new opportunities for fairer taxation and sustainable development by aligning tax treatment with actual sustainability impacts.

Similarly, Malvika and Vikram (2023) explored the impact of digital taxation on sustainability, while Ganter (2020) contended that digital taxes can support the adequate taxation of multinational corporations, thus enabling sustainable development investments.

Besides, Russel et al. (2014) underlined that a suitable taxation design should recognize externalities to improve sustainable reporting and practices, ensuring the alignment of costs and prices with sustainability objectives. Lastly, Ouyang et al. (2023) found that digital finance improves small business tax compliance, thereby enhancing overall financial transparency and sustainability.

As argued by the European Council (2024) and the World Bank (2024), while the rise of digital activities presents outstanding financial opportunities, it also introduces challenges such as tax avoidance and evasion. Thus, updated regulations based on good governance are required (European Council, 2024). Traditional tax rules presume a physical presence in the country, but digital activities are borderless, leading to difficulties in taxing them in the correct market jurisdiction.

Regarding the impacts of taxing digital services, for instance on inclusion, they are highly complex to assess. Pobeet et al. (2023) found that while mobile money technology enhances financial inclusion, taxation of this service can negatively influence its adoption.

Silue (2022) asserted that although taxes can initially reduce transaction values, the use of mobile money increases during economic crises. As argued by Pobeet et al. (2023), the “performance expectancy”, “effort expectancy”, social influence, and enabling conditions may substantially influence the behavioural intentions of users. Hence, taxation of some financial activities could be detrimental to adoption and use.

Furthermore, global efforts are being devoted to providing a fair digital taxation structure. The European Union (EU) and the OECD G20 countries are jointly working on a global “Inclusive Framework on Base Erosion and Profit Shifting” (OECD, 2021b; European Council, 2024). This framework involves a two-pillar solution: firstly, by reallocating taxing rights to ensure that profits from digital activities are taxed where users are located; and secondly, by establishing a minimum global tax rate of 15% to prevent tax erosion.

Additionally, the EU is working on the automatic exchange of tax information regarding platform revenues and crypto assets. This aims to reinforce e-reporting, e-invoicing, and VAT reforms to enhance revenue collection and reduce fraud (European Council, 2024). Besides, effective governance in this area is crucial, which relies on both regulation and international cooperation.

Hence, digital taxation plays a crucial role in adapting tax systems to the realities of an equitable digital economy while curbing the potential risks. Achieving a fair and updated tax regulation is crucial to ensure that the benefits of digital finance are fairly distributed and contribute to a more inclusive and just development.

In conclusion, mitigating the risks of an unfair digital economy while promoting opportunities to regenerate decent jobs and economic sectors is crucial for ensuring a sustainable and responsible digital transformation (SRDT). Well-design, mindful and robust policies and incentive mechanisms are essential to overcome systemic inertia and drive meaningful change.

The exposed insights underscore the interconnectedness of digital economy components and the need for comprehensive, evidence-based policies to foster an inclusive and sustainable digital future.

5.5.7. Reflections on the Prosperity Pillar

The Prosperity Pillar for purposeful and regenerative digital development, addresses the socioeconomic dimensions of digital transformation and the triple transition, emphasizing the necessary shifts from traditional economic growth models to those that promote social cohesion and progress, and environmental well-being and regeneration.

Digital transformation offers unprecedented opportunities to enhance competitiveness, trade, commerce, finance, and socioeconomic development opportunities through Smart and Sustainable Communities across sectors. However, it also presents challenges related to ethics, fairness, inequality, and uncertain environmental impacts.

Achieving a balanced digital economy requires the sound integration of relevant ethical considerations, fair competition, and sustainable practices across all its components, with a regenerative focus on creating opportunities for everyone.

To this end, digital trade, commerce, innovation, entrepreneurship, and finance must be managed responsibly, while striving for equitable and sustainable development across sectors, value chains and regions.

Ultimately, a systemic approach is essential to harness the benefits of the digital economy while ensuring it aligns with the values of a regenerative and sustainable economy. This will bring long-term benefits and resilience, not only in the socioeconomic sphere but also for society and the planet as a whole, thereby contributing to the vision of a regenerative and resilient triple transition.

An outline of the domains within the Prosperity Pillar, along with their alignment with the SDG goals is provided in Table 5.10.

Table 5.10. Domains of the Prosperity Pillar and their Alignment with the SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PROSPERITY <i>(SOCIO-ECONOMIC DIMENSION)</i>	Equitable Digital Economy and Competitiveness, Commerce and Trade for Regenerative Development across Value Chains	SDG 8, 9, 11, 12, 17
	Responsible Digital Innovation and Entrepreneurship Ecosystems	SDG 8, 9, 17
	Fair Digital Labour, Decent Work, Reskilling, and Upskilling	SDG 4, 8, 9
	Responsible Digital Development and Uptake for Regenerative Prosperity	SDG 8, 9, 11, 12, 17 All SDG
	Smart and Sustainable Communities and Ecosystems	SDG 8, 9, 11, 12, 17 All SDG
	Inclusive Digital Financing and Taxation	SDG 8, 16, 17

5.6. The Partnerships Pillar for Multilevel Cooperation

In an increasingly interconnected world, reinforcing digital cooperation is critical for addressing global challenges that cannot be faced by any country alone, as emphasized by the UN's 2030 Agenda (UN, 2015), the UN's "Our Common Agenda" (2021), and the more recent "Pact for the Future" (UN, 2024a), and "Digital Global Compass" (UN, 2024b).

Certainly, the 2030 Agenda emphasized the importance of multistakeholder partnerships for sustainable development, dedicating an entire pillar to this purpose. Achieving the SDGs and the objectives of the Digital Agenda requires concerted efforts from all stakeholders and nations worldwide. Hence, strengthening global cooperation is essential for realizing the triple transition and driving digital transformation, sustainability, and inclusivity.

However, current digital transformation and sustainable development frameworks often overlook this crucial domain. Both literature and practice in this area remain underdeveloped, with few frameworks providing comprehensive metrics or successful approaches. The OECD (2023a, b) asserted that recent global crises underscored the increased interconnectedness of the world and the need for international cooperation to jointly address underlying challenges and crises. Hence, multilateral cooperation is vital to ensure the equitable development of the evolving digital space, and, in addition, it offers new opportunities through a reinvigorated cooperation development agenda.

In the digital realm, institutions like the World Summit on the Information Society (WSIS, n.d.) and the Internet Governance Forum (IGF, n.d.) are expected to lead in developing a robust architecture for global digital cooperation that benefit the common good, including environmental sustainability. According to Leenders and Grishin (2020), UN institutions dedicated to digital cooperation are committed to upholding values, standards, and the public good while providing non-state actors with opportunities to participate in global digital politics. This inclusivity is vital for ensuring that digital governance frameworks reflect diverse perspectives and meet the needs of all stakeholders.

Nonetheless, the role, efficiency, and architecture of current digital cooperation, and global cooperation in general, have been heavily criticized and face ongoing reflection about their future.

The United Nations Development Programme (UNDP) (2022) emphasized that the global nature of digital transformation poses significant challenges, exacerbated by inequalities in global governance and taxation arrangements. The fragmented global governance architecture for digital technologies requires multilateral approaches to bridge gaps between powerful actors and low and middle-income countries (LMICs).

Thus, a profound rethinking and promotion of digital cooperation is essential for addressing the challenges of the digital era and the triple transition, through collaborative multilateral efforts involving diverse stakeholders.

The Role of the Global Digital Compact in Shaping the Future Governance

In response to the challenges that global cooperation faces in the context of the triple transition, the UN Secretary-General initiated a multi-stakeholder consultation on digital cooperation which led to the creation of the Global Digital Compact. The GDC was adopted at the 2024 Summit of the Future, alongside the "Pact for the Future".

The GDC aims to address digital governance and global digital cooperation issues through shared principles and commitments, thereby providing a universal guide for an inclusive and sustainable digital governance approach to achieving the SDGs. The GDC is rooted in international law, including the UN Charter, international Human Rights, humanitarian laws, and the 2030 Agenda.

The GDC principles include inclusivity, equity, multi-stakeholder engagement, sustainable development, human rights protection, gender equality, accessibility, interoperability, responsibility, innovation-friendliness, and forward-looking governance. It also incorporates advisory mechanisms for DHRs and AI governance and establishes a global fund for digital technologies applied to sustainable development. Besides, it proposes a Digital Cooperation Forum led by the IGF to promote global dialogue and collaboration.

Aligned with the Geneva Declaration of Principles and the Tunis Agenda for the Information Society (UN-WSIS, 2003; 2005), the GDC emphasizes transitioning from principles to action to enhance digital governance by aligning national and global goals, reinforcing international cooperation, bridging divides, and ensuring responsible access to digitalisation. Having outlined the theoretical aspirations of the GDC, the following dissects the potential drawbacks and challenges of this approach.

While the GDC has the potential to drive positive change, a profound reflection is required about this framework. The principles outlined in the Geneva Declaration (2003) and the Tunis Agenda (2005) were recognized two decades ago, yet efforts have not fully translated into tangible results. Since then, the digital landscape has drastically evolved, becoming increasingly complex, and adding new risks. Hence, a comprehensive renovation of global and regional cooperation architecture, agendas, mechanisms, and partnerships seems imperative.

Initial drafts of the GDC received criticism from the digital, social, and environmental research and policy communities (e.g., Unwind, 2024; CODES, 2023; Simon Institute, 2024). The concerns focused on the perceived lack of ambition of the GDC and its insufficient integration of social and ecological aspects, potentially leading to outcomes similar to previous frameworks.

Additionally, it has faced disapproval for prioritizing nation-states over independent multi-stakeholder governance. In this regard, the Internet Society (2024) firmly critiqued the GDC's proposal of new multilateral implementation processes that sideline existing mechanisms (e.g., IGF, WSIS), and potentially limit the participation of smaller actors or states. Moreover, Gurumurthy et al. (2024) denounced that the GDC inadequately addresses issues such as digital colonialism and power concentration.

Therefore, experts called for equitable international data governance to safeguard local interests and sovereignty and stressed the lack of mechanisms to tackle historical democratic deficits in multi-stakeholder negotiations. Experts also advocated for a stronger emphasis on economic justice, the public control of digital infrastructure beyond mere openness, and the decolonization of the data economy.

In a similar perspective, the Alliance for Universal Digital Rights (AUDRI, 2024) also criticized the GDC for its weak accountability measures for social media platforms, unclear participation mechanisms for multi-stakeholders in AI governance, inadequate commitments to addressing environmental impacts, and insufficient integration of gender equality principles throughout the document.

The Need for a Shift in Digital Cooperation

Hence, research suggests that digital cooperation demands a shift toward acknowledging mutual interdependencies and collective action for the common good. However, current digital narratives and strategies often prioritize competition over cooperation (Gulyas and Shahin, 2021), and the economy over sustainability. In this sense, the OECD (2023b) advocated for “risk-informed and resilient development cooperation” to harness digital transformation with social and environmental perspectives.

Digital cooperation, much like governance, is a cross-cutting aspect that interrelates with and significantly influences all pillars of digital and sustainable development.

Therefore, in the proposed Taxonomy, multilevel cooperation is also intertwined with the other pillars and domains, recognizing that digital transformation and sustainable development challenges cannot be addressed in isolation, but must acknowledge the systemic interconnectedness and the impacts of the evolving globalization on social and economic fabrics.

Certainly, Internet governance and digital disruptions transcend borders, thereby affecting all aspects of society and the economy, along with the associated threats they bring. This makes effective governance of risks and opportunities particularly challenging due to inadequate global and regional cooperation mechanisms.

Particularly, controlling and mitigating transboundary risks and spillovers demand not only robust governance but also effective diplomacy, which is often lacking. The absence or the inadequacy of global cooperation frameworks can exacerbate vulnerabilities, cyber-threats, and digital divides, further worsening the already harmed status of human rights and environmental degradation.

Weak cooperation mechanisms could also enable unethical behaviours to bypass legal jurisdictions. This underscores the urgent need to strengthen global cooperation structures and mechanisms in the digital realm. Effective digital cooperation is essential to comprehensively address these challenges across borders.

Therefore, to address the described defies and opportunities brought by digital transformation at both global and local scales, the partnership for global cooperation pillar encompasses the following domains: global digital cooperation and diplomacy architecture and agenda with robust mechanisms; multi-stakeholder alliances and communities with an inclusive, convivial, and plural focus; and multilateral programs specifically designed to embed regenerative sustainability within digital transformation cooperation mechanism.

The detailed substantiation of the respective domains within the proposed Taxonomy for SRDT is provided as follows.

5.6.1. Multilevel Digital Cooperation and Diplomacy

This section addresses the multilevel and global digital cooperation architecture, cooperation mechanisms, as well as the challenges and opportunities of digital diplomacy.

Digital Cooperation Architecture

The Partnership Pillar for global cooperation must address the challenges that the multilevel and global cooperation and diplomacy architecture face, along with the need for forging and sustaining multi-stakeholder alliances, and multilateral programs designed to embed regenerative sustainability within digital transformation efforts.

Certainly, a robust global digital cooperation architecture is essential for managing transboundary risks and impacts. Strengthening mechanisms for collaboration between governments, international organizations, the private sector, and civil society is critical to mitigating cyber threats, protecting Human Rights across value chains, and promoting inclusiveness in the digital realm.

As previously discussed, digital impacts often transcend borders, affecting the environment, Human Rights, and security. In particular, aspects such as illegal e-waste trade, raw material extraction, and transboundary GHG emissions derived from digital development, require reinforced international cooperation, as argued by UNDP (2024). Furthermore, the UNCTAD “Digital Development Report” (2021b) underlined that dealing with data disparities within key digital infrastructures, along with varying regulatory approaches among the major economies, require a global governance framework to ensure effective data-sharing, privacy, and security.

Current efforts in cybersecurity have focused on innovation and capacity building, but a cohesive global strategy remains lacking. Recent initiatives aim to address these cybersecurity risks, like the “Paris Call for Trust and Security in Cyberspace,” the “Global Forum on Cyber Expertise,” the “Global Commission on the Stability of Cyberspace,” the “Contract for the Web,” and the “Global Commitment on Digital trust and Security” (IGF, 2024).

Regulatory cooperation is also relevant when addressing governance challenges in digital trade. In this regard, Ahmed (2019) emphasized the need to reinforce global principles while considering national priorities to enable smooth digital trade operations across jurisdictions.

Furthermore, the global nature of the digital economy has led to political divisions and policy discord, increasing fragmentation risks. According to Weymouth (2023), rising restrictions on cross-border data flows could hinder innovation and inclusive digital development. According to WSIS and IGF, the Internet has also become a global critical facility which necessitates global governance enabled by cross-border cooperation.

The digital economy also has spillover effects on environmental pollution, requiring global cooperation to manage transboundary impacts. Jones and Adam (2023) argued that cross-border flows of digital products and carbon emissions present significant regulatory challenges that demand new international policy responses.

In addition, coordinated multinational and national systems are necessary to ensure secure digital identities, cross-border trade records, and health data sharing. Thus, global collaboration is essential for addressing challenges in data governance, cybersecurity, and digital trade (OECD, 2024).

Ethical governance is also a key concern, with global value chains showing vulnerabilities such as Human Rights abuse, unethical use of technologies, and environmental damage. International cooperation is essential to ensure that digital advancements are ethical and sustainable. New technologies, particularly data and AI platforms, could heighten geopolitical tensions, inequalities, and global power imbalances.

Considering these challenges, building a robust global cooperation architecture with strong multilateral and pluriversal mechanisms is critical, but thus far is lacking. The digital transformation landscape is complex and requires a comprehensive and coordinated approach across multiple dimensions and involving all the relevant stakeholders. Indeed, effective multilateralism depends on robust collaboration among stakeholders to integrate technology, regulation, social contracts, and sustainable business models, thereby driving progress.

Proposals for a new "Bretton Woods" initiative aim to modernise multilateral institutions with secure, inclusive digital platforms. Nevertheless, despite evolving international standards, a cohesive global network strategy for digital cooperation remains underdeveloped, as argued by Lysenko et al. (2024). This circumstance together with the prioritisation of competition over cooperation is hindering the potential of multilateralism.

Prominent frameworks addressing digital global cooperation, include the GDC (UN, 2024b), the OECD’s “Development Cooperation Report” (2021a; 2023b), the UN’s “Our Common Agenda” (UN, 2021), the UN’s “Roadmap for Digital Cooperation” (UN, 2020), along with the ITU’s “Global Digital Regulatory Outlook” (ITU, 2023), among others. These frameworks underscored the requirement for a more coordinated global approach. Indeed, four key global agendas underscored the need for action: global data standards and governance, digital inclusion, fair taxation of the digital economy, and digital solutions against corruption.

Overall, digital cooperation is vital for equitable access to technology, promoting sustainability by responsibly managing transboundary spillovers, safeguarding human rights in global value chains, strengthening cybersecurity, reinforcing technological cooperation, and fostering ethical governance.

The future of digital transformation hinges on the development of robust, multi-stakeholder, and decentralized cooperation mechanisms, alongside a more effective multilateral architecture.

Strengthening multilevel digital cooperation through inclusive structures will help to address the multifaceted and complex challenges posed by digital disruption and global crises, thereby contributing to regenerative sustainability for all individuals and nations. For that purpose, global digital cooperation must ensure the participation of all nations and stakeholders, and address not only the risks but also ensure a fair distribution of digital opportunities by reinforcing the principles of justice and solidarity.

Furthermore, global cooperation should promote a conducive environment for investments, knowledge sharing, technology transfer, and international partnerships.

Overall, reinforcing global digital cooperation, supported by robust mechanisms, effective partnerships, and a renewed multilateral architecture, is essential for guiding the ongoing triple transition and ensuring a sustainable, inclusive, and regenerative digital future.

Despite current shortcomings, knowledgeable multi-stakeholder institutions such as WSIS and the IGF have the potential to unite people and resources, fostering more effective cooperation for the triple transition at a global scale.

Digital Cooperation Mechanisms

Current digital cooperation mechanisms largely function on a national or regional level. However, the interconnected nature of digital technologies and the global scope of digital risks and opportunities demand enhanced international measures. The Internet Governance Forum (IGF, 2024) advocated for more inclusive, effective, and coordinated cooperation approaches within this increasingly complex digital landscape.

Existing cooperation structures face significant challenges, including insufficient political prioritization, limited inclusiveness, overlapping structures, sectoral fragmentation, and a general erosion of trust. Many stakeholders, especially from less-represented sectors, find it challenging to have their voices heard in the decision-making process.

Besides, improving these structures depends on agreeing upon shared values and operational principles centred on inclusiveness, transparency, and the global public interest.

There exist well-known global forums addressing digital cooperation, including the Internet Governance Forum (IGF, n.d.), the UN's High-Level Panel on Digital Cooperation (UN, n.d.), the Digital Cooperation Organization, the World Summit on the Information Society (WSIS, n.d.), the AI for Good Summit, the UN's International Telecommunication Union (ITU, n.d.), and the European Union Global Gateway (EU, n.d.), among others. The "Global Commitment on Digital Trust and Security" (IGF, 2024) aims to strengthen norms for responsible technology use, enhance cybersecurity capabilities, and build resilience against misinformation.

In digital transformation for sustainable development, the Coalition for Digital Environmental Sustainability (CODES, 2022) also plays a pivotal role. Nevertheless, as previously discussed, efforts from these mechanisms are not sufficiently translating into a cohesive global action.

The UN's "Roadmap for Digital Cooperation" (UN, 2020) underlined the urgent need for coordinated global action to address cyber threats, protect critical infrastructure, and maintain trust in the digital domain. These objectives should be achieved through restored cooperation mechanisms, supported by multi-stakeholder dialogue and flexible regulation, including international standards. The UN's High-Level Panel on Digital Cooperation has also proposed actions to accelerate global cooperation with input from diverse stakeholders.

Concerning the sustainable development realm, the recent Global Digital Compact (UN, 2024b) emphasized the relevance of a cooperation framework promoting system-wide sustainability and contributing to the realization of the SDGs. In this regard, cross-border collaboration in data sharing, AI knowledge exchange, information integrity, infrastructure development, open and interconnected Internet, cybersecurity, and innovation are particularly emphasized.

Certainly, the GDC envisions a "Global Digital Commons," focusing on the development and governance of digital technologies in alignment with international principles, national policies, and practices, along with a "Digital Cooperation Forum" to support multi-party initiatives, monitor commitments, and foster transparent dialogue. Nevertheless, this has been strongly criticized for undermining multi-stakeholder oversight, as previously noted.

Digital Diplomacy

As previously introduced, the transboundary nature of digital transformation poses significant governance and geopolitical challenges that require diplomacy efforts. This complexity is compounded by inadequate global cooperation mechanisms and growing geopolitical tensions. In this regard, Ghica (2024) emphasized that, despite geopolitical uncertainties, digital technologies are essential for global development strategies. Therefore, digital diplomacy emerges as a crucial tool for advancing international cooperation and managing digital risks and opportunities that surpass national borders.

Digital diplomacy is a flexible concept, that often refers to the use of technology for dealing with foreign policy objectives and addressing challenges such as cybersecurity and misinformation. Bjola and Holmes (2015) emphasized its role in international relations and crisis management through platforms like social media. Certainly, the digital age has redefined diplomatic norms and practices, particularly concerning the interactions between nations and technology companies. For instance, the European Union often uses digital diplomacy to safeguard its strategic interests, while advocating for a human-centric digital transformation.

In this context, research is incipient and fragmented. For instance, Frey (2024) explored how AI and social media influence modern diplomacy, while Manby and McConnell (2024) examined the impact of digital technologies on diplomatic practices at the UN Human Rights Council.

Diplomacy and global cooperation in the digital sphere are particularly relevant for addressing geopolitical tensions, thereby fostering regional stability, and promoting prosperity without exacerbating divides. Digital diplomacy is expected to facilitate inclusive approaches to global challenges such as cyberterrorism, illegal e-waste trade, unethical practices in global supply chains, conflicts over critical materials, the spread of misinformation, and climate change's impact on infrastructures and ecosystems.

Okano-Heijmans and Vosse (2021) argued that the European Union should intensify its digital cooperation efforts in Asia to tackle emerging geopolitical issues. In addition, initiatives like China's Digital Silk Road, and the conflicting development policies for technology between different nations, raise concerns that could be managed by suitable diplomacy efforts.

According to the World Economic Forum (2023), "tech diplomacy" has been gaining traction, becoming essential for fostering international cooperation and stakeholder engagement. Besides, it plays a crucial role in addressing workforce displacement and enhancing digital inclusion in the global value chains.

Overall, digital diplomacy serves as a mechanism for promoting enhanced international cooperation towards equitable solutions, global resilience, and sustainability. However, several critical areas require reinforcement, such as establishing robust global agreements for improved e-waste management, enhancing cybersecurity to address cross-border risks associated with technologies like AI, and advancing data flow governance. Addressing these issues demands coordinated global responses, which are currently inadequate and allow the malicious use of digital solutions.

5.6.2. Multi-Stakeholder Communities and Alliances

Both digital and sustainable development agendas underscore the importance of multi-stakeholder partnerships in addressing global challenges (UN, 2021; CODES, 2022). Enhancing global alliances and building communities focused on sustainable digital transformation and the triple transition are, therefore, paramount. However, existing cooperation efforts often suffer from inadequate design, insufficient financing, and barriers to participation. In addition, sustainability often remains overlooked in this context.

Building multistakeholder alliances and communities with an inclusive, convivial, and pluralistic focus is vital for reinforcing global cooperation in the digital age. These alliances or partnerships should involve stakeholders from various sectors, regions, and backgrounds to ensure that digital transformation efforts are representative, and address diverse needs, including the ecological aspects, along with the voices of the vulnerable local communities and actors.

Enhancing the engagement of civil society, academia, and local communities is crucial for the effectiveness and legitimacy of these cooperation mechanisms. In this matter, the Partnership Pillar within the proposed Taxonomy aims to provide awareness about the relevance of fostering global participation, co-creation, and collaboration among all relevant actors and contexts. Without the genuine contribution, conviviality, and ownership of all communities, neither the 2030 Agenda nor the Digital Agenda would realize their ambitious goals.

The concept of “conviviality” offers a unique perspective for enhancing cooperation. Caire (2008) described conviviality as promoting social cohesion and fostering interactions that enhance cooperation within communities. As argued by Beinsteiner (2020), in the digital realm, conviviality involves openness, democratizing technology, and preventing power imbalances.

Despite the existence of numerous alliances in both the digital and sustainability domains, inclusive global cooperation for sustainable digital transformation has not yet been achieved and is often ignored in global strategies. Significant participation gaps persist, especially among stakeholders from less developed countries, civil society, and academia, often due to intrinsic barriers, along with the persisting dominance of major players (UNDP, 2024). Civil society and NGOs play a critical role in empowering individuals and reinforcing their co-responsibility in the triple transition.

Therefore, further efforts are needed to reorient current and future partnerships towards ensuring a legitimate contribution and participation of all voices, and across nations and disciplines, thereby advancing a sustainable and inclusive digital transformation for the triple transition.

5.6.3. Multilateral Programmes for Integrating Regenerative Sustainability in Digital Cooperation

Considering the challenges ahead, the lack of integration of regenerative sustainability in the digital realm, and the substantial resources required to achieve the goals of both the digital and sustainable development agendas, specific multilateral programmes for this matter are essential. The GDC draft proposes a "Global Fund for AI and Emerging Digital Technologies for Sustainable Development" (UN, 2024b), but further global efforts are necessary to overcome the current intention-action gap.

According to experts, the multilateral programmes for global cooperation should focus on building digital and sustainability capacities, creating open digital public infrastructures, promoting data governance, and ensuring that digital transformation efforts align with environmental sustainability, social equity, resilience, and regenerative development. Integrating digital transformation with regenerative sustainability principles will help support both SDGs and the objectives of the Digital Agenda.

Furthermore, given that in less developed contexts, vulnerable actors often lack the resources and capacity to manage digital challenges and navigate the triple transition alone, specific measures and interventions should be considered to bridge current divides.

Disadvantaged actors frequently face exclusion from global discussions due to resource constraints, hindering genuine multistakeholder dialogue and cooperative solutions (UNCTAD, 2024). Reorienting development finance support in these regions is crucial for building resilience and ensuring sustainable digital development.

Another relevant aspect to reinforce is the scientific and technological cooperation, which certainly, has a long tradition of attracting talent, promoting knowledge creation and transfer, and mobilizing resources across diverse actors and countries to address social challenges. This cooperative spirit should also underpin and inspire more effective global cooperation for digital cooperation and beyond for the triple transition.

Indeed, technological cooperation for knowledge exchange and technology transfer across geographies is essential for capacity building and for expanding the benefits of innovative digital solutions for sustainable development. Therefore, programmes for global cooperation in the digital realm should be reinforced to further support science and technological cooperation.

Additionally, another area requiring reinforced global cooperation is the lack of awareness about digital transformation risks and opportunities. Promoting programmes devoted to raising awareness and educating the public and society on the implications of the triple transition is critical to mobilising action and enhancing cooperation.

This domain provides remarkable opportunities, but it remains underdeveloped in both research and practice. Moreover, policy efforts have largely overlooked environmental sustainability and have only marginally addressed social aspects. Therefore, further research and policy development is needed to establish suitable multilateral programmes that facilitate progress towards a sustainable and regenerative digital transformation.

5.6.4. Reflections on the Partnerships Pillar

Global and multi-stakeholder cooperation is essential to address the cross-border challenges posed by digital transformation. Current unilateral domestic or regional actions are insufficient, and a more cohesive global cooperation architecture, with efficient multilateral efforts and pluriversal partnerships, is required to overcome existing challenges. Robust digital cooperation mechanisms, inclusive multistakeholder alliances, and dedicated multilateral programmes for sustainable digital transformation are crucial for advancing global equity, resilience, and social and environmental regeneration.

As the digital cooperation landscape remains immature and fragmented, further research and policy development at a global level is needed to develop methodological frameworks, metrics, and incentives to support the described domains more effectively.

Overall, there is an urgent need for a systemic vision to enhance global digital cooperation by mobilizing cross-geographic alliances and programmes. The international community has a crucial opportunity to revitalize outdated structures and mechanisms, embedding eco-social values into global cooperation for digital transformation and the triple transition. Effective global digital cooperation also demands genuine commitments to regenerative sustainability, resilience, and inclusivity, moving beyond superficial references to the SDGs.

Only through multi-stakeholder engagement and a regenerative vision, can society reorient digital cooperation towards building a regenerative and resilient future for all.

An outline of the domains within the Partnership Pillar, as well as their alignment with the SDG goals, is provided in Table 5.11.

Table 5.11. Domains within the Partnership Pillar and their Alignment with the SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PARTNERSHIPS (MULTILEVEL COOPERATION)	Digital Cooperation and Diplomacy	SDG16, SDG17
	Multi-Stakeholder Communities and Alliances	SDG16, SDG17
		All SDGs
	Multilateral Programmes for Sustainable and Regenerative Digital Transformation and Cooperation	SDG16, SDG17 All SDGs

5.7. The Preparedness Pillar for the Triple Transition

The pursuit of digital and sustainable agendas demands transformative shifts, emphasizing the critical need for readiness to embrace change and adapt resiliently. The capacity to deal with global crises and build resilience to unfolding disruptions is crucial, whether they are digital, socioeconomic, or environmental.

Therefore, the “Preparedness Pillar” proposed within the Taxonomy for SRDT is central to both digital transformation and sustainable development, as it represents the capacities, means, culture, and conducive settings to achieve the triple transition. Notably, it relies on three axes: readiness, resilience, and response to crises. Together, these elements foster the capacity to face global disruptions, supporting the UN’s 2030 Agenda and broader digital transformation initiatives.

The COVID-19 pandemic demonstrated how critical digital infrastructure and technological adaptability are for fostering resilience during disruptive events. This unprecedented situation catalysed the rapid development of digitalisation worldwide. Additionally, it emphasized the interconnection between environmental well-being and human health, underlining the need for rapid response, resilient recovery, and regeneration. In this regard, the proposed Preparedness Pillar is multifaceted since it aims to address the complexities of the digital, environmental, and socially just transition.

In this regard, according to the Cambridge Dictionary (2024), preparedness refers to the “state of being prepared for a particular situation”. In the digital realm, preparedness is often interpreted as “the condition of readiness for digital transformation” (Cavallini and Soldi, 2021), closely linked to digital maturity. Thus, digital preparedness encompasses effectively managing DT, defined as the “transformation of all sectors of the economy, government, and society based on the large-scale adoption of existing and emerging digital technologies” (Randall et al., 2018).

While no universally agreed-upon definition of preparedness exists in the context of the triple transition, some of its components, are frequently considered in most relevant digital and crisis management frameworks (e.g., natural disasters and climate change events). Indeed, preparedness is a cornerstone to both DT and crisis management, involving the possession of the necessary capacities, resources, organisational culture, and governance to harness digital opportunities for addressing unfolding challenges.

It is also closely linked to the concept of “digital readiness,” which reflects an organisation's capacity to leverage digital technology for operational enhancement and overall performance (Chwiłkowska-Kubala et al., 2023; Silva et al., 2022; Srinivas et al., 2023). Indeed, “digital readiness” represents a critical cornerstone of the digital realm, strongly supporting the rest of digital and broader preparedness factors.

Relevant frameworks offer approaches to the assessment of digital readiness, along with indicators, namely: the Digital Government Readiness Assessment (DGRA) by the World Bank (2022b), the Network Readiness Index (NRI) by the World Economic Forum (WEF, 2016), the Network Readiness Index by the University of Oxford (2023), the International Telecommunication Union (ITU) report on Measuring Digital Development (2023).

However, these digital-oriented frameworks face limitations and are focused mainly on narrow aspects, often disconnected from sustainability and inclusiveness values.

In this regard, Nasution et al. (2018) emphasized that preparation and readiness are essential elements for successfully integrating digital technologies in an organisation. However, the lack of a reliable model for measuring digital readiness hampers the accurate assessment of such an integral component of DT.

Similarly, James (2008) argued that composite indexes of digital preparedness (e.g., Networked Readiness Index, Digital Opportunities Index) create confusion by mixing inputs and outputs. This scholar suggested separate indexes for means and ends to better understand their relationship in terms of productivity.

Along the same line, Cavallini, and Soldi (2021) emphasized the importance of improving the measurement of “Digital Preparedness and Readiness” (DPR) data to accurately assess DT progress, particularly for SMEs. Current data gaps in areas such as e-government services, ICT human resources, connection quality, ICT usage, e-commerce, and cybersecurity are hindering the potential of creating comprehensive insights at regional levels.

Considering digital readiness, as the backbone of digital-driven preparedness, the concept remains insufficiently understood (Soomro et al., 2020; Nguyen et al., 2019). Existing literature presents digital readiness in a fragmented manner, with diverse proposals about its foundational factors or attributes. For instance, Soomro et al. (2020) emphasized digital readiness as a critical theme which encompasses four success factors: digital agents and skills, digital tools and applications, digital systems and infrastructure, and digital ecosystems and culture.

Similarly, Nguyen et al. (2019) underlined the importance of digital readiness for successful digital transformation and improved performance in the corporate realm, and proposed a construct that includes digital assets, digital capabilities, and digital commitment.

Other recent studies, such as Pingali et al. (2023) explored the digital readiness of small and medium enterprises (SMEs) in emerging markets, recognizing its critical role in helping these resource-constrained businesses stay competitive. These scholars identified five key themes influencing SMEs' digital readiness and proposed a multi-item measurement scale characterized by technological sensemaking, agility, and implementation. Despite its importance, there is limited understanding of digital readiness in these markets,

In addition to these caveats in the digital realm, no comparable framework has been identified either in the sustainability domain or at the intersection of digital and sustainability fields.

Certainly, despite its relevance for sustainable development, preparedness is notably absent from sustainability frameworks and the 2030 Agenda. Although the current SDG framework includes five ICT-related indicators focused on broadband connectivity (fixed and mobile) and basic skills, these indicators only address narrow aspects of digital readiness, disconnected from other critical domains. Therefore, current frameworks do not fully capture the comprehensive scope needed for advancing a sustainable digital transformation and driving the triple transition forward.

Therefore, further research is needed to reach a consensus about the key domains of digital readiness and their value for broader preparedness, as well as for embedding this crucial dimension also into sustainable development frameworks.

Additionally, as previously discussed, preparedness is a pivotal concept in crisis management, emergency governance, and the realms of environmental response (e.g., natural disaster preparedness) and development cooperation. In this context, digital transformation presents significant opportunities for enhancing crisis management and emergency preparedness through tools such as early warning and forecasting systems (ITU, 2024; Oketch and Wamae, 2021).

These tools play a critical role in preventing, managing, and mitigating the impacts of crises, including social upheavals, pandemics, and natural disasters, particularly those exacerbated by climate change. For example, modern societies' heavy reliance on electricity, water, and digital infrastructures means that any breakdown in these systems could severely disrupt societal functioning. Thus, digitalization strengthens crisis preparedness by offering valuable tools and augmented capacities that enhance response and recovery capabilities.

Furthermore, the synergies between these realms extend into corporate contexts and everyday life activities. As argued by Leo et al. (2023), digital transformation reinforces employees' crisis preparedness by enhancing their life satisfaction and customer orientation. According to Adamik and Nowicki (2018), an organisation's preparedness for digital transformation greatly influences its competitive advantage.

According to Salmona et al. (2023), organisational preparedness includes institutional capabilities for DT and a well-crafted execution strategy. While many organisations have a vision towards DT, there is often a gap between aspiration and actual preparedness, which can impede future competitiveness. Thus, digital-driven preparedness is also intimately linked to organisational governance, strategy, and digital literacy.

Therefore, preparedness augmented by digital capabilities equips both organisations and individuals to navigate challenges and uncertainties, while strengthening their resilience and adaptability to a rapidly evolving world.

This research emphasizes the critical importance of extending the concept of preparedness beyond the digital and crisis management domains to encompass social and ecological transitions, thereby advancing a more integrated and holistic framework for resilience and regeneration within the triple transition. Readiness is positioned in this dissertation, as a multifaceted concept, focused on preparing the whole society to navigate the unfolding and interconnected digital, social, and ecological challenges.

Nevertheless, digital readiness remains a cornerstone of this framework, by underscoring the significance of universal and meaningful connectivity connected to inclusiveness and responsibility, secure and sustainable digital structures, and digital literacy and capacities. Yet, connectivity, digital infrastructures and services rely on other enabling infrastructures such as electricity, water, logistics, and space systems. Therefore, a more integrated approach to readiness is of the utmost relevance.

The broader perspective of preparedness in this research fosters a harmonious convergence of digital transformation and regenerative sustainability, which not only supports meaningful digital development, agile response, and resilient recovery of disruptions but also paves the way towards regenerative and sustainable development.

When it comes to the concept of “meaningful connectivity” is worth mentioning that it goes beyond the traditional vision of access to Internet and broadband services (A4AI, 2021; ITU, 2024). Indeed, it is a multifaceted domain strongly connected to equity and inclusiveness, as well as to responsible, secure, and safe delivery and use of digital services.

In this dissertation, the domain of universal and meaningful connectivity also encompasses the affordability of digital services such as the Internet and devices, the accessibility to relevant and reliable content free from disinformation and cyber threats, as well as the safe access and responsible use of user-friendly platforms and services for all individuals, regardless of their potential limitations. These elements are essential for fostering a more widespread and equitable adoption, and safe and meaningful usage of digital technologies across diverse communities.

In addition to meaningful connectivity, having digital and sustainability literacy and advanced capacities, as well as resilience-based skills is critical for driving the triple transition. Building these capacities and raising awareness about the relevance of a sustainable digital transformation, can empower and engage all stakeholders, including civil society, to responsibly leverage digital opportunities across all sectors of society.

Equally important for preparedness is fostering a transformational leadership supported by a responsible and agile culture, characterized by ambidexterity and a strong commitment to advancing both digital and sustainability transformations.

Furthermore, being supported by a conducive environment and ecosystems is crucial for successful digital and sustainability transformations. This entails a supportive business setting granting access to technologies and services, a stable legal and regulatory framework oriented towards innovation, trustworthy institutions, social cohesion and quality of life, and forward-looking digital and sustainability policies. Additionally, it encompasses a favourable environmental setting, with suitable access to natural resources, indispensable for the functioning of the digital infrastructures.

The crisis preparedness and emergency response domain are focused on the capacities and resources needed to effectively navigate uncertainties and complexities. This involves having the education for emergencies, the supporting infrastructures, and systems, along with the strategies and multilevel governance frameworks to swiftly manage and mitigate the impacts of any kind of disruption, ensuring resilient recovery and regeneration in the face of challenges.

Therefore, the domains within the "Preparedness Pillar" for the triple transition proposed in this dissertation, encompassing the three axes of readiness, resilience, and swift response to crises, are presented as follows: (i) universal and meaningful connectivity; (ii) secure, resilient, and sustainable infrastructures and systems; (iii) secure, robust, and interoperable data infrastructures; (iv) digital and sustainability literacy and advanced capacities, and resilience-based skills; (v) transformational leadership, a culture of responsibility, and ambidexterity; (vi) a conducive environment, including legal, institutional, political, financial, environmental, and social settings, alongside supporting ecosystems; and (vii) capacities and systems for robust crisis management, emergency response, and resilient recovery.

Together, these domains support sustainable digital transformation and the triple transition, ensuring that technological advancements align with broader ecological and social goals. Also, the Preparedness Pillar seeks to address both risks and opportunities, by reshaping existing frameworks, capacities, and settings to align with regenerative sustainability.

In conclusion, integrating a sixth pillar of preparedness in the Taxonomy is justified by its critical and multifaceted nature, its foundational role in DT and crisis management, and the need for building readiness and resilience to navigate complex global challenges as the triple transition.

The proposed Preparedness Pillar encompasses digital and sustainability readiness and resilience in their broadest sense, providing the foundation for a conducive environment and well-equipped society capable of reacting proactively and resiliently in response to disruptions.

This integrated approach addresses not only digital transformation but also ecological and socially just transitions, paving the way for a regenerative and resilient triple transition, thereby fostering the realization of the ambitions of both digital and sustainable agendas.

A detailed explanation of the proposed domains, and their integrating thematic factors within the Preparedness Pillar of the Taxonomy, is provided in the next sections.

5.7.1. Meaningful and Universal Connectivity

Achieving universal and meaningful connectivity is a cornerstone and maximum priority for both digital transformation and sustainable development. According to ITU (2023), despite global Internet use increasing from 35% to 67% between 2013 and 2023, digital divides persist, particularly in Least Developed Countries (LDCs). Certainly, connectivity is also crucial for sustainable development and should be attained responsibly and inclusively by respecting societal and environmental values alongside users' needs.

As previously introduced, meaningful connectivity is a multifaceted domain aiming to provide all individuals with the ability and means to safely and effectively utilize digital resources for social and economic development (ITU, 2024; A4AI, 2021). This entails affordable and regular Internet access by high-speed and reliable broadband connections, safe use of appropriate and accessible devices, and affordable data plans and platforms that ensure continuous and unrestricted usage (A4AI, 2021).

In this dissertation, meaningful connectivity encompasses affordable and safe access to the Internet and relevant digital services and devices, significant and reliable content, and data free from disinformation and cyber threats, and accessible and user-friendly platforms and services for everyone. This holistic approach ensures that all individuals, regardless of their location, gender, disabilities, age, or socio-economic and cultural status, can effectively and safely participate in digital development and benefit from related technological advancements.

Achieving meaningful connectivity allows society to address the current disparities in accessing digital services, data, and reliable information, across demographics and geographies to fully realize the potential of the digital transformation (ITU, 2024; A4AI, 2021).

Therefore, meaningful connectivity is also connected with inclusiveness, security and safety and should promote societal opportunities. It is also linked to environmental sustainability since connectivity relies on digital and enabling infrastructures and systems with significant environmental and social impacts, which should be guided by sufficiency, eco-design, and circularity principles, as described in Chapter 3.

Sustainability should be an integral part of the connectivity domain, as the information and telecommunication infrastructures and systems that enable access to digital services and the Internet depend on sustainable practices for their development, operation, and long-term viability. Nevertheless, this aspect aligns better with the domain of infrastructures, thus it is explained in the next sections.

This critical domain is relatively well-covered in relevant digital frameworks, such as the Digital Economy and Society Index (DESI) by the European Commission (2023; 2024), the Network Readiness Index by the University of Oxford (2023), and the ITU Connect 2030 Strategy (ITU, 2024), among others.

However, these frameworks often overlook relevant sustainability demands, such as inclusiveness and environmental sustainability, and many remain focused on technological aspects. Furthermore, existing sustainability frameworks, including the UN 2030 Agenda, only cover this aspect partially through elementary indicators for broadband access and basic skills.

Hence, these caveats underline the need to reorient connectivity with a more inclusive and sustainable perspective, within both digital and sustainability agendas, to foster sustainable and inclusive opportunities that benefit both people and nature.

5.7.2. Resilient, Secure, Sustainable Infrastructures and Systems

Achieving preparedness strongly relies on resilient, secure, and sustainable digital and enabling infrastructures and systems. This domain includes ensuring suitable Internet speed, and network coverage, along with robust data centres, cloud storage, and access to digital devices. These infrastructures and systems support crucial technologies such as IoT, BDA, Blockchain, AI, and HPC.

In this regard, one critical aspect of infrastructures and systems is ensuring cybersecurity. As argued by Szalkowski (2024), cybersecurity is crucial for protecting digital assets and promoting societal resilience. Effective cybersecurity measures involve awareness, training, and protocols to mitigate potential digital vulnerabilities.

In terms of sustainability, digital infrastructures and systems must be environmentally protective, by integrating sufficiency, eco-design, and circularity principles as previously examined in the Planetary Sustainability Pillar. This approach ensures resource optimization and helps to mitigate unintended impacts while promoting opportunities.

However, current frameworks in this field, including the Global Cybersecurity Index (ITU, 2020) and the DESI Index (European Commission, 2023), focus mainly on technological and governance aspects, ignoring sustainability facets.

Moreover, digital infrastructures often introduce social challenges, such as digital gentrification, akin to urban gentrification. The deployment of data centres and telecom networks can affect local energy resources, creating "energy gentrification" (Libertson et al., 2021). This phenomenon often marginalizes less privileged groups and alters the social fabric of local communities. Thus, an inclusive and democratic perspective of the governance of digital infrastructures is necessary to address these challenges. Besides, research on digital gentrification must explore its socio-economic impact on communities, thereby informing strategies to balance digital development with community support.

Other critical aspects within this domain are related to Digital Public Infrastructures (DPIs), which have been also examined in the "Peace Pillar" for mindful governance due to their relevance for e-government services. In the "Preparedness Pillar," the focus is different and more oriented to the physical infrastructures and systems, and their related security, operation, and sustainability.

Notably, DPIs play a key role in delivering secure and inclusive digital services. This concept includes the platforms for digital identification, payment systems, and data sharing, thus forming an intermediary layer within digital ecosystems. In this context, principles like inclusivity, interoperability, scalability, cybersecurity, and sustainability are crucial for the optimal development of DPIs, according to the World Bank (2024). The current gaps in DPIs, such as fragmented data and undervalued non-traditional data sources, need to be addressed to support effective decision-making in sustainability.

Furthermore, environmental sustainability is a significant aspect of DPIs, yet often overlooked. Relevant institutions like UNEP (2024c) emphasized the role of DPIs in enhancing information accessibility related to sustainability.

Promising applications for DPIs in sustainability include open data for environmental monitoring, data markets for sustainability-related information, and AI for environmental decision-making. These technologies enhance transparency, support data-driven policies, and promote a circular economy.

However, key aspects for ensuring environmental sustainability and social impacts are not sufficiently explored and managed in existing frameworks. Further research and policy development is needed to ensure the embedding of sustainability principles in digital infrastructures and systems, to ensure their sustainability and resilience in the long term.

Considering the relevance of sustainability, this aspect is further elaborated below.

Sustainability Aspects of Digital Infrastructures

Sustainability in digital infrastructures, particularly data centres, is critical to ensure a mindful and environmentally protective digital development. Achieving sustainability in this field relies on continuous investment in technology and innovation, along with capacity building, standardization, and regulation.

In this regard, the World Bank (2021) underscored the importance of sustainable financing models and international cooperation to maintain the digital infrastructures and systems over time, crucial for achieving the SDGs and ensuring equitable, inclusive, and sustainable development.

Certainly, the increasing demand for digital services has emphasized the need for sustainable data centres, which are critical to supporting contemporary digital needs. As society moves towards a more interconnected world, managing and reducing the environmental impact of data centres becomes paramount. There exist varied strategies to enhance the environmental performance of these infrastructures, primarily by focusing on energy efficiency, security, and innovative technologies such as “Green Tech” (e.g., renewable energy sources, and sustainable cooling technologies).

Hence, one of the principal strategies for enhancing the sustainability of data centres, and digital infrastructures in general, is the integration of renewable energy sources to reduce their reliance on fossil fuels, thereby decreasing their carbon footprint. In this regard, Chen et al. (2016) proposed that integrating renewable energies coupled with power storage, sustainable cooling facilities, and dynamic pricing into data centre operations, could significantly enhance overall efficiency and sustainability in data centres.

Furthermore, Ganesan et al. (2020) argued that virtual machine consolidation within real physical cloud infrastructures can reduce energy consumption and GHG emissions in these infrastructures. This strategy involves optimizing the use of physical servers by consolidating multiple virtual machines onto fewer servers, thereby reducing the overall energy required to operate the data centre.

The use of Internet of Things (IoT) technologies can further enhance this process by providing real-time data on energy usage, allowing for more precise and efficient management of resources. Besides, Broo and Schooling (2021) suggested that data and Digital Twins can revolutionize smart infrastructure by facilitating climate-conscious and sustainable decision-making throughout the life cycle of digital assets.

Similarly, Pedram (2010) claimed that digital infrastructures must be adaptable, energy-efficient, and environmentally friendly. This involves designing data centres that can easily adapt to changing technological demands while maintaining high levels of energy efficiency. Such adaptability ensures that these assets remain relevant and effective in supporting digital needs without compromising sustainability. Environmentally friendly practices, such as using eco-friendly building materials and implementing waste reduction measures, further contribute to the overall sustainability of digital infrastructures.

Nevertheless, research and practice have been excessively focused on carbon footprint and energy efficiency aspects, overlooking other relevant factors. As Lykou et al. (2017) stressed, there is an imperative need for a more holistic approach to evaluating data centres' sustainability. Notably, existing metrics often focus on energy use but fall short in assessing overall sustainability, which involves environmental preservation, economic viability, operational efficiency, and social responsibility.

These scholars introduced a new methodology for a comprehensive sustainability assessment based on five major quantifiable elements, proposing a sustainability scoring model to evaluate environmental impact and operational efficiency comprehensively.

In this regard, Molla et al. (2011) proposed a “Green IT readiness framework” to nurture sustainability within ICT management. This framework emphasizes the importance of organizational readiness to adopt and implement green IT practices. By fostering a culture of sustainability, organizations can ensure that their digital operations align with broader environmental goals.

There is an increasing focus on establishing robust environmental standards to foster more sustainable and responsible digital infrastructures. Organizations such as the ITU are actively providing guidelines and standards in this area, while institutions like the European Commission are advancing efforts to develop regulations and incentives for data centres and other digital infrastructure. The standardization and regulation of these infrastructures are essential to drive their evolution toward greater environmental sustainability.

Furthermore, security and privacy are critical components of sustainable data centres. According to Hussain et al. (2023), secure and privacy-preserving infrastructures are relevant to ensure reliable reporting of sustainability data. This aspect is essential for combating greenwashing, where companies may exaggerate or fake their environmental efforts. By implementing robust security measures, data centres can protect sensitive information and provide transparent, accurate data on their sustainability practices. This transparency not only builds trust with stakeholders but also encourages continuous improvement in sustainability.

In conclusion, the sustainability of digital infrastructures, particularly data centres, is a multifaceted challenge that requires a combination of innovative technologies, secure infrastructures, proactive management practices, and suitable regulation and incentives. Hence, by integrating green technologies, ensuring secure data practices, reducing energy consumption through virtual machine consolidation, and leveraging Digital Twins, data centres can significantly reduce their environmental and social impact. In addition, fostering a culture of sustainability within ICT management is crucial for achieving long-term success.

As the demand for digital services continues to grow, these strategies will be essential for building sustainable and efficient digital infrastructures that meet contemporary digital needs while protecting the environment.

5.7.3. Data Infrastructure, Data Availability, Quality, Interoperability, and Openness

Data infrastructures are a cornerstone for digital transformation, crisis preparedness, and sustainable development. Their effectiveness hinges on ensuring data availability and quality, accessibility, openness, and usability, along with integration capabilities, such as interoperability. These aspects are particularly relevant for environmental metrics and sustainability-focused repositories (UNEP, 2022a).

The success of digital transformation largely depends on robust data governance, which includes data collection, analysis, and harnessing technologies such as Big Data Analysis and Artificial Intelligence to convert data into actionable knowledge for better decision-making.

In this regard, the UN called for a "Network of Data Innovation Networks" to coordinate global efforts, ensuring that data systems adapt to new challenges (UN, 2014).

Furthermore, as data governance is critical for sustainable development, the UNSTATS underscored the necessity of oversight mechanisms, such as Data Governance Officers (DGOs) and Data Stewardship Teams (DSTs), to maintain data quality and interoperability (UNSTATS, 2018).

The most relevant components of data infrastructures are further explained as follows.

Data Architecture

Data architecture plays a critical role in building trustworthy and interoperable data infrastructures. According to Allian et al. (2021), designing a data architecture involves key drivers such as authentication, data access control, privacy, traceability, and compatibility of physical devices, data, and services. Sinan et al. (2022) noted that data architecture has evolved to meet the demands of current data-centric settings, focusing on security aspects encapsulated in the "confidentiality, integrity, and availability (CIA)" triad. This evolution aims to address vulnerabilities while ensuring the systematic use and reuse of data.

Data Availability

Data availability refers to the extent to which data can be accessed when needed. This accessibility is crucial for timely decision-making and efficient operations, especially in the policy realm. The World Bank (2021) pointed out the importance of data availability in tracking progress toward the SDGs and enabling targeted interventions. For example, Broo and Schooling (2021) draw attention to how data, in conjunction with digital twins, can improve the lifecycle management of smart infrastructures and drive sustainable, climate-conscious decision-making.

Data Quality

High-quality data is essential for making informed decisions and ensuring effective management of resources, particularly when it comes to minimizing environmental impacts and enhancing operational efficiency. Quality data must be accurate, complete, reliable, timely, and relevant, by adhering to international standards and best practices (World Bank, 2021).

Both the UN (2014) and the OECD (2019d) underscored the need for clear standards, quality assurance frameworks such as audits and data classification, along with standardized practices to maintain data integrity. This involves meticulous data collection, regular updates, and strict validation mechanisms. Besides, proper data quality enhances the ability to manage resources effectively, guiding policies and practices toward more sustainable outcomes.

Data Interoperability

Interoperability refers to the ability of different systems and organizations to exchange, interpret, and use data cohesively. This is crucial for efficiently integrating diverse data sources, thereby enhancing their utility. It is especially important in crises and climate change responses that require coordinated action.

For example, the European Union's Open Data Directive promotes interoperability by setting standards for data formats and metadata, facilitating cross-border data flow and collaboration (European Union, 2019). Also, Kadadi et al. (2014) emphasized that data integration and interoperability as significant challenges in Big Data implementation, which requires a comprehensive approach. Improving interoperability allows seamless integration of diverse data sources, enhancing information integrity and utility.

Moreover, Pagano et al. (2013) underlined that interoperability remains a complex challenge due to its varying perceptions across different communities. Effective interoperability may require developing global research data infrastructures.

In this regard, Sibenik and Kovacic (2020) suggested that improving data exchange between domains like architectural design and structural analysis can be achieved by establishing interpretation rules and new certification processes, significantly improving data interoperability and design quality.

Thus, interoperability is central to producing high-quality information. Both the UN and World Bank also stressed the adoption of common standards and protocols for seamless data exchange between systems and organizations (UN, 2014; World Bank, 2021).

In addition, the UNSTATS (2018) emphasized that data management should be driven by business needs rather than IT, with interoperability facilitated by governance frameworks. Collaborative governance approaches involving multiple stakeholders enhance adaptability and support initiatives for data partnerships, which can also enhance interoperability.

A well-structured data architecture enhances the systematic use and reuse of data. The World Bank (2021) stressed that establishing robust data collection, storage, and sharing frameworks can support interoperability and facilitate the integration of diverse data sources, thus adding value to development purposes. Additionally, the UN's "A World That Counts" iconic report, advocated for data to be both technically and legally open, ensuring it is accessible to non-technical users (UN, 2014).

Overall, data infrastructures that prioritize elements such as availability, quality, interoperability, and openness are instrumental for sustainable digital transformation. These elements ensure that data can be effectively used to support economic, social, and environmental sustainability. For example, in smart cities, integrated data systems enable efficient resource management, reducing waste and carbon footprints, as argued by Pedram (2010).

Data Openness

As previously introduced in the Peace Pillar for mindful governance, open data is fundamental to ensure inclusivity, democratic participation, trust, and accountability across all domains. When data is freely accessible for use, reuse, and distribution, it promotes transparency, user engagement, and innovation.

The UN's "Data Revolution for Sustainable Development" report underlined that open data could drive sustainable development by enhancing governance, service delivery, and economic growth (UN, 2014).

Furthermore, Ducuing (2020) called for more granular, context-specific legal regimes for data-sharing in network industries to foster innovation while benefiting market operators and third parties.

The UN advocated for publicly funded data to be "open by default", with exceptions only for security or privacy concerns (UN, 2014). This openness includes making data available in machine-readable formats and under licenses that permit unrestricted use and re-use.

In summary, open data initiatives can foster innovation, enhance transparency, and empower citizens (World Bank, 2021), therefore are crucial for sustainability.

Hence, robust data infrastructures, driven by principles of quality, availability, interoperability, and openness, are vital for sustainable digital transformation. They ensure that data can be leveraged to support economic, social, and environmental objectives, ultimately driving a more equitable and inclusive digital future.

These integrated approaches, supported by institutional frameworks and governance, facilitate a data revolution that aligns with the global goals for sustainable development, transparency, and global cooperation.

Beyond technical aspects such as connectivity, infrastructures, and systems, when it comes to promoting preparedness, human capacities, along with a suitable culture play a critical role, as described below.

5.7.4. Digital, Sustainability, and Resilience-oriented Capacities, and Awareness

A key domain of preparedness for both digital transformation and sustainable development, involves building literacy, and capacities at both individual and institutional levels, along with raising awareness about the relevance of sustainability, regeneration, and resilience for the triple transition.

This domain is critical to ensure that digital transformation supports the triple transition towards a more sustainable and regenerative society. Additionally, it ensures that all stakeholders are equipped with the digital, sustainability, and resilience-oriented skills, along with a deep awareness of sustainability values, needed to foster a responsible and inclusive digital future. Therefore, strengthening digital and sustainability education, awareness-raising, and capacity-building programmes to include both digital and sustainability aspects is critical for a successful triple transition.

In this regard, first, it is important to define digital literacy, which, according to the National Digital Inclusion Alliance (NDIA) and the American Library Association refers to "the ability to use ICTs to find, evaluate, create, and communicate information, requiring both cognitive and technical skills". This includes understanding the relationship between technology, privacy, and learning, as well as utilizing these skills to access information, communicate, and actively participate in society (NDIA and the Department of Education of the UK government, 2019).

Furthermore, digital capacities (or skills), cover a broader range of competencies beyond basic literacy, such as programming, distinguishing misinformation, and ethically using digital tools like Generative AI. These skills are essential for accessing the opportunities that digital transformation provides, including e-participation, which contributes to societal resilience. Promoting digital skills through academic curricula and lifelong learning programmes is essential for reducing digital divides, enhancing inclusion, and empowering communities as argued by Lee-Geiller (2024).

In addition, education on sustainability is critical to changing current behaviours and promoting mindful patterns of production and consumption, as recognized by SDG12 and SDG13 within the 2030 Agenda.

Achieving a holistic approach to this matter relies on integrating both digital and sustainability literacy and capacities within education and professional training, thereby ensuring that all individuals are equipped to navigate the triple transition and address contemporary challenges. Reskilling and upskilling strategies are particularly important to mitigate the social risks of digital transformation, such as job losses due to the automation of industries, as already underlined in the labour domain within the "Prosperity Pillar."

Existing frameworks, such as the Digital Economy and Society Index (DESI) by the European Commission (2023), the Digital Government Readiness Assessment (World Bank, 2022), the Digital Skills Gap Index (Wiley, 2021), as well as ITU and the World Bank databases, integrate metrics on digital literacy and skills.

However, they often overlook the inclusion of sustainability capacities and awareness. This gap hinders the realization of a sustainable and regenerative digital transformation. Supporting the triple transition requires building sustainability awareness, green skills, and digital abilities all together while fostering crisis response capabilities. To bridge this gap, education, and capacity-building frameworks and programmes should be reoriented to address the intersection of digital and sustainability capacities, thus supporting the triple transition.

Building sustainability awareness in the digital realm involves promoting behavioural shifts among practitioners, governments, and users to ensure the responsible deployment and use of digital technologies. This approach not only enhances individual adaptability and resilience but also supports a more sustainable and adaptive society, capable of driving a digital transformation aligned with social and environmental goals.

In conclusion, promoting digital and sustainability literacy, advanced capacities, and awareness is crucial for ensuring a sustainable digital transformation that advances the triple transition. This ambition requires reinforcing the integration of digital and sustainability matters in lifelong learning, raising sustainability awareness, fostering behavioural changes, and promoting a responsible approach to deploying digital systems.

A renewed focus on education and capacity-building programmes that embed the intersection of digitalisation and sustainability will contribute to building resilience, inclusion, and a regenerative future.

5.7.5. Transformational Leadership, Responsible and Agile Culture

Building the appropriate organisational mindset, culture, and commitment to fully leverage digital and sustainability opportunities, is a crucial aspect of preparedness for advancing both a sustainable digital transformation and the triple transition.

Therefore, it is essential to embrace a responsible and agile culture, coupled with change management, ambidexterity, commitment, and a proactive attitude towards digital and sustainability transformations.

Certainly, research corroborated that a suitable organizational culture is a significant factor in digital transformation. As Zaoui and Souissi (2020) highlighted, digital organizational culture can significantly enhance performance. Similarly, Martínez-Caro et al. (2020) asserted that agility and ambidexterity are necessary to effectively manage the triple transition. In addition, Hartl and Hess (2017) stated that digital transformation initiatives often fail due to an unsuitable organizational culture, which can act as a barrier.

Firican (2023) explored digital culture attributes, suggesting that it is both a premise and an outcome of digital transformation. Indeed, digital culture encompasses various factors such as collaboration, flow of information, responsiveness, agility and adaptability, innovation, risk-affinity, customer-centricity, learning orientation, readiness, and data-driven decision-making.

Other relevant organisational attributes are being “data-driven” and ready to quickly adapt to changes. Martínez-Caro et al. (2020) found that organizations with a strong digital culture perform better, as they can swiftly adapt to new technologies and market demands. Indeed, agility and ambidexterity are necessary for organizations to navigate the triple transition and global disruptions (Nyagadza, 2022).

This involves being able to balance and integrate these transitions to optimize performance and sustainability, by the coexistence of exploration and exploitation (Peng et al., 2019). A proactive approach to change management ensures that organizations are prepared to address and leverage new opportunities and be resilient to crises as they arise. Nevertheless, research demonstrated a gap regarding change management pathways and ambidexterity in achieving a sustainable digital transformation (Pacoli, 2022).

Hence, the role of organizational culture and a mindful mindset is critical, serving either as an enabler or a barrier to achieving sustainable digital transformation. These aspects are also considered within the “Peace Pillar” for mindful governance but with a different nuance. While in the Preparedness Pillar, culture and leadership aspects belong to the internal organizational dimension (micro level), in the Peace Pillar, mindful leadership and CDR pertain to the external dimension (macro level), focusing on how organizations interact with external stakeholders and the broader community.

Considering the existing assessment frameworks, several indices and guiding reports cover aspects related to organizational culture in the digital realm, including the Digital Government Readiness Assessment (World Bank, 2022), the Networked Readiness Index (WEF, 2016), the Global Digital Regulatory Outlook (ITU, 2023), and the Digital Development Compass (UNDP, 2019).

However, these frameworks fall short in integrating sustainability aspects. To fully leverage digital transformation for long-term success, it is crucial to embed sustainability principles at the core of the organizational culture, alongside digital aspects. This may entail having specific policies and adhering to widely acknowledged principles and certifications in the sustainability domain.

Fostering a proactive, responsible, and agile organizational mindset, culture, and commitment is a vital domain driving digital and sustainability readiness for the triple transition. In addition, embracing change management, ambidexterity, and sustainability is beneficial to organizations in their digital transformation efforts, while building competitiveness and resilience.

By integrating these cultural attributes, organizations can better manage the triple transition and the global crises, leading to improved performance and sustainability in the long term. While existing frameworks highlight the importance of these cultural factors, continuous efforts are needed to ensure that sustainability aspects are fully embedded in organizational practices to support a successful and regenerative digital transformation.

After examining the integrating domains within the readiness concept, which form the backbone of this crucial pillar, the next section explores the relevance of the enabling environment and supporting ecosystems, as well as the domain related to crisis preparedness and emergency response.

5.7.6. Conducive Enabling Environment and Supporting Ecosystems

Another significant domain of preparedness involves being supported by a conducive and favourable environment for digital and sustainability transformations. This domain encompasses having appropriate legal, business, political, social, institutional, and environmental settings, and conditions to leverage the available opportunities of the triple transition while mitigating potential risks.

Therefore, a conducive environment includes several components and conditions, namely:

- (i) A dynamic and appealing business setting and ecosystems characterized by ease of doing business and inclusive incentives for sustainable technology; supply and demand conditions such as consumer capacity to engage and the ability to attract and retain talent.
- (ii) A stable and trustworthy political environment with effective public administration, alongside strong support for digital and sustainability transformations.
- (iii) Robust legal conditions and an efficient regulatory framework to ensure the protection of rights and digital assets.
- (iv) Societal support and interest in digital transformation.
- (v) Favourable environmental conditions, with the availability of natural resources and quality access to supporting infrastructures such as renewable electricity, quality water, and logistics.
- (vi) A robust and efficient institutional setting with digital and sustainability capacities.

Most of these components overlap with the governance and socioeconomic dimensions represented by the respective Pillars of Peace and Prosperity. However, collectively, they are also critical for ensuring “preparedness,” and relevant frameworks assign this area to the related “readiness” dimension as well.

As argued by Tufts University (2017) a conducive institutional setting is characterized by transparency, the rule of law, and regulatory quality. These elements are fundamental in building trust and providing a stable foundation for digital initiatives.

Achieving high regulatory quality is essential for creating policies that support innovation, and sustainable development, and provide social protection to stakeholders and users from potential risks associated with digital transformation.

In conclusion, being supported by a conducive favourable environment is a critical domain of preparedness for pursuing a sustainable and inclusive digital transformation.

A supporting setting entails ensuring the appropriate legal, business, political, social, institutional, supply and demand, and environmental conditions to leverage the opportunities of digitalization and the triple transition while mitigating all the potential risks and challenges.

Fostering a dynamic and attractive business environment, ensuring access to high-quality infrastructure and natural resources, cultivating societal support, and maintaining political stability are all crucial factors for navigating the triple transition. Additionally, preserving a robust legal framework and offering targeted incentives for sustainable research, development, and technology empower organisations and society to adapt, innovate, and thrive, thereby supporting long-term resilience and regeneration.

5.7.7. Crisis Preparedness and Emergency Response

The Preparedness Pillar also integrates a relevant domain focused on crisis preparedness and emergency response, as crucial aspects for promoting resilience and regeneration, in tackling the complex and wicked challenges that humanity and the Planet face.

Crisis preparedness encompasses the ability to navigate uncertainties effectively, involving robust resources, infrastructures, capacities, and strategies. In this context, digital transformation provides outstanding tools, particularly for addressing natural disasters. For instance, the DGRA by the World Bank (2022) considers emergency response as a crucial component of readiness for digital transformation.

As Fleming (2022) argued, crisis preparedness strategies are crucial not only for ensuring resilience during disasters or crises, like the COVID-19 pandemic or growing climate-related disasters but also for promoting long-term sustainability and competitiveness.

Indeed, proactive crisis preparation allows organisations, individuals, and nations to anticipate and prepare for potential problems and disruptions, leveraging crises as opportunities to strengthen environmental, social, and economic practices. Effective preparedness hinges on reinforcing leadership to drive innovative and inclusive strategies, which integrate seamless response and recovery efforts to foster organizational resilience.

Besides, by integrating sustainability goals into crisis preparedness strategies, organisations and nations could align their goals with broader societal needs, traversing uncertainties effectively while building enduring resilience.

As the climate crisis intensifies and its impacts become more frequent, causing widespread disasters, effective crisis response becomes even more crucial than ever, also within the sustainability domain. Modern challenges in this realm include increased environmental hazards, heightened vulnerability, and anthropogenic environmental degradation, necessitating robust preparedness to prevent substantial damages.

According to Alexander (2021), disaster and crisis preparedness involves proactive measures aimed at mitigating or reducing the impact of major risks and disasters, thereby enhancing resilience. Thus, crisis preparedness activities encompass long-term strategies, such as structural, semi-structural, and non-structural measures (e.g. planning), along with short-term strategies, such as optimizing resource allocation during acute crises.

In this matter, nature-based or ecological adaptation measures can enhance the natural capabilities of the ecosystems to mitigate disaster impacts. This is strongly aligned with the idea of regeneration. Moreover, recovery from disasters also represents an opportunity to enhance safety through resilient reconstruction strategies, commonly referred to as "build back better."

Digital solutions offer exceptional capabilities for enhancing crisis management and emergency response. These include early warning systems, geolocation services, augmented predictive capacities, and alternative virtual means for delivering critical services such as education and medicine. By leveraging digital technologies, communities can better anticipate, prepare for, and respond to disasters, thereby improving resilience and ensuring continuity in essential services.

Notably, digital solutions enable enhanced data gathering and analysis through real-time data collection via sensors, IoT devices, and data-driven predictive analytics. These capabilities augment human capacity and enhance early warning systems for better management of natural disasters or any other crisis. They also facilitate communication and coordination among stakeholders, providing channels to disseminate information, coordinate rescue operations, and mobilize resources swiftly (Poblet et al., 2024).

Additionally, smart infrastructures can support more resilient systems by simulating and detecting vulnerabilities, allowing readiness and training in response plans. During crises, digital solutions support business continuity. Finally, digital technologies facilitate post-disaster recovery and "build back better" strategies. Nevertheless, once again, technology is not a universal solution, and additional factors are needed to ensure robust preparedness for the triple transition and global challenges.

In this sense, education in emergencies (UNESCO, n.d.) and capacity building for all individuals, particularly policymakers, as well as robust, multilevel, and coordinated emergency governance and resources, are of utmost relevance. Education and capacity building in this context need to consider the need to enhance digital and sustainability literacy and awareness, while also curbing disinformation against sustainability efforts (e.g., climate change).

Furthermore, it is essential to provide multichannel opportunities to ensure that no one is left behind, and everyone has access timely to relevant emergency information. This aspect also underscores the inequalities between nations and actors, since the most vulnerable contexts lack the digital means and capacities needed to build robust preparedness systems.

In this context, Fekete and Rhyner (2020) examined the interrelationship between social vulnerability and critical infrastructure amid the ongoing digital transformation. They underlined the growing interdependencies between critical infrastructures and social vulnerability as digitalization progresses, proposing the integration of digital vulnerabilities into risk management through early detection and crisis coordination. Challenges in human-digital interdependencies call for reevaluating human-environment interaction to advance sustainability and disaster risk reduction in the digital era.

Similarly, Sakurai and Shaw (2022) emphasized the urgency of reinforcing community adaptability and preparedness to achieve SDG11 through digital solutions. They emphasized Japan's "Society 5.0" strategy, which aims to align human-centred digital innovation to tackle societal disparities and sustainability. These scholars proposed that digitally enabled disaster education should engage civil society in disaster risk efforts to raise awareness and change behaviours while enhancing community resilience. Therefore, integrating digital solutions into disaster management fosters inclusive, safe, resilient, and sustainable communities, aligning with societal well-being and the SDGs.

Moreover, the UN's handbook "Integrating Disaster Risk Reduction" accentuated the increasing frequency and intensity of natural and human-made disasters exacerbated by climate change.

It also outlines the responsibilities of “Resident Coordinators” in supporting governments to develop and implement disaster risk reduction (DRR) strategies. This includes ensuring cross-sectoral support, incorporating DRR in Humanitarian Response Plans (HRPs), and promoting multisectoral risk analysis.

In this regard, the UN’s Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015) is the main global reference in the field. The key principles of the Sendai Framework include proactive risk management, resilience building, inclusivity and engagement, and sustainable development integration within DRRs.

Furthermore, the proposed Taxonomy advocates for embedding regeneration as a fundamental element of preparedness and crisis management. By mainstreaming regenerative and restorative strategies, preparation and recovery efforts can achieve more sustainable and resilient outcomes. This holistic approach focuses on long-term resilience and recovery, encompassing societal, environmental, and economic dimensions. Consequently, crisis preparedness is vital for achieving regenerative sustainability, and digital transformation plays a crucial role in facilitating this approach.

Overall, integrating disaster risk reduction into broader governance, digital, and sustainability development efforts is essential for building resilient communities capable of enduring the increasing threats posed by natural and human-made disasters. Digital transformation is indispensable for enhancing crisis preparedness and sustainability by leveraging advanced technologies to mitigate risks, improve response capabilities, ensure business continuity, and promote environmentally sustainable practices.

Digital preparedness not only strengthens resilience against disasters but also supports long-term sustainability goals, ensuring communities and organizations can thrive even in the face of escalating challenges posed by climate change and global crises.

5.7.8. Reflections on the Preparedness Pillar

Preparedness is a critical pillar for navigating the triple transition, serving as the foundation for aligning digital transformation with sustainability goals. Within this pillar, three interconnected axes - readiness, resilience, and response to crises - function as the gears that drive the preparedness engine.

Digital and sustainability readiness, supported by universal and meaningful connectivity, robust infrastructures, data integration, capacity building, leadership, and responsible culture, conducive enabling settings and ecosystems, combined with a proactive approach to crisis preparedness, work together to foster a regenerative, sustainable, and inclusive digital future that serves both humanity and the planet.

To fully harness the potential of digital transformation for societal and environmental benefits, it is essential to integrate this pillar into existing and future frameworks. This integration must be guided by principles of sufficiency, conviviality, circularity, regeneration, and resilience. Such alignment ensures that digital and sustainability infrastructures, systems, capacities, and enabling ecosystems contribute effectively to economic, social, and environmental goals.

Hence, the preparedness pillar represents both the heart and engine of digital transformation and the triple transition. Embedding regenerative sustainability into every domain of preparedness is essential to renovating current frameworks, addressing both the risks and opportunities inherent in a sustainable and regenerative digital transformation.

In essence, the Preparedness Pillar offers a holistic approach to tackling present and future challenges, bridging current misalignments and gaps, and driving forward the regenerative triple transition for a resilient and inclusive future.

In conclusion, the domains of the Preparedness Pillar, as well as their alignment with the SDG goals are outlined in Table 5.12.

Table 5.12. Domains within the Preparedness Pillar and their Alignment with the SDGs
(Own elaboration)

PILLAR	DOMAINS	ALIGNMENT WITH THE SDGs
PREPAREDNESS <i>(Readiness, Resilience, and Response to Crises for the Triple Transition)</i>	Meaningful and Universal Connectivity: Access, Affordability, Relevant Content, Accessibility, and Usability for All	SDG 4, 5, 10, 9, 11, 17
	Resilient, Secure, and Sustainable Infrastructures and Systems	SDG 9, 11, 16, 17
	Data Infrastructures, Data Availability, Quality, Interoperability, and Openness.	SDG 9, 17
	Digital and Sustainability Literacy, Capacities, and Awareness	SDG 4, 5, 12, 17
	Leadership, Responsible and Agile Culture, and Ambidexterity for the Triple Transition	SDG 9, 12, 17
	Conducive Enabling Environment and Supporting Ecosystems	SDG 4, 8, 9, 16, 17
	Crisis Preparedness and Emergency Response	SDG 4, 9, 11, 13, 16, 17

Having substantiated in detail the six pillars within the proposed Taxonomy, along with their respective domains, the resulting framework is presented in the following section.

5.8. Resulting Taxonomy for SRDT and the Triple Transition

This section presents the results derived from the development of the Taxonomy for SRDT and the triple transition. This first version was then refined and validated by an expert elicitation process, as explained later in Chapter 6.

The proposed Taxonomy provides a structured approach to categorizing the intertwined and multifaceted relationships and factors for aligning digital transformation and regenerative sustainability, focusing on the key aspects of this intersection to advance the triple transition. It offers a panoramic perspective of both potential risks (and subsequent impacts), as well as opportunities related to the long-term regeneration and resilience of societal and environmental systems in the digital age.

In this way, the Taxonomy organizes existing knowledge to empower informed decision-making and raise awareness about critical aspects of digital transformation and the triple transition, which require further research and reinforced policy development. Additionally, it provides valuable insights into the risks and opportunities that digital transformation poses for regenerative sustainability, thereby, guiding better governance by developing more suitable and efficient policies, practical actions, and research agendas. Indeed, the taxonomical framework enables the identification of critical intervention areas for a Sustainable and Regenerative Digital Transformation.

Considering the construction, as previously introduced, the resulting Taxonomy for SRDT is structured into three levels, encompassing six pillars, divided into thirty-six domains, and further dissected into 273 thematic factors. These three levels represent a simplified depiction of the complex and multifaceted intersection between digital transformation and regenerative sustainability, for supporting its understanding and governance. This structure provides comprehensive coverage of the complex phenomena underlying all dimensions of SRDT.

However, as with the SDGs in the 2030 Agenda, the taxonomical pillars, domains, and thematic factors are not isolated dimensions, rather they are strongly interrelated and can be mutually beneficial if managed conveniently.

In addition, this framework is aligned with both the 2030 Agenda and the digital transformation frameworks, such as the Digital Development Compass (UNDP, 2021) and the Digital Global Compact (UN, 2024b) and aims to bridge the current misalignment between these realms towards fostering the triple transition.

Furthermore, these levels together provide a systemic, integrative, “pluriversal,” and multistakeholder perspective, reflecting the needs of all relevant actors, stakeholders, and contexts. While this approach presents challenges in balancing the needs of different contexts with varied levels of development, it is flexible and adaptable enough to be tailored to the priorities of the varied local contexts.

The implementation and localization of the Taxonomy can be effectively supported by complementary tools. Similar to the 2030 Agenda, the Taxonomy offers a “glocal” approach, universal and global in its principles but designed to be translated into actionable measures at the local level, thereby bridging the gap between global ambitions and local realities.

In this context, the People Pillar, covering the social and just transition dimension, reflects the needs and voices of societal actors, particularly civil society. The Planetary Sustainability Pillar, representing the environmental transition, incorporates nature as a key stakeholder in sustainable development, represented by environmental-related stakeholders.

The Peace Pillar, focusing on mindful governance, integrates the perspectives of governmental actors, but also emphasizes a whole-of-government and whole-of-society approach, including all stakeholders.

Finally, the Prosperity pillar, reflecting the socioeconomic dimension, underlines the priorities of economic and corporate actors, along with all stakeholders as users.

Finally, the Preparedness Pillar encompasses the voices of all actors and stakeholders, particularly the digital sector, recognizing their essential role in driving a regenerative and resilient triple transition. This is accomplished by building literacy, enhancing digital, sustainability and resilience-oriented capacities, raising awareness, and providing the means to adapt to the dynamic changes brought about by digital and sustainability transformations.

Thus, integrating the perspectives of digital, environmental, and social actors, allows the Preparedness pillar to serve as a critical enabler of the triple transition.

The proposed taxonomical structure is comprehensive, holistic, and inherently multidisciplinary, embracing diverse fields and perspectives to foster a deeper understanding, effective articulation, and proactive management of sustainable and regenerative digital transformation. This approach supports and accelerates the triple transition, ensuring alignment across social, environmental, and digital dimensions.

In this way, the fields of digital transformation and regenerative sustainability are integrated into a cohesive and unified framework that encompasses all relevant dimensions and actors in the context of the regenerative triple transition. Although these fields are currently misaligned and often in conflict, the taxonomical framework facilitates the alignment of priorities, terminology, and narratives across both domains, steering them toward the triple transition. Within this context, the five pillars of the 2030 Agenda serve as a reference point for adapting their respective dimensions to support a sustainable and regenerative digital transformation approach.

Similarly, the Preparedness Pillar, through its axes of readiness, resilience, and crisis response, integrates established digital factors such as digital readiness, while reorienting and extending them to embed sustainability and regeneration perspectives.

This mutual convergence between the digital and sustainability realms creates a more integrated and holistic framework that bridges current disconnections. It also fosters a unified and compelling narrative that is not only reactive but also proactive to prepare society to advance the triple transition,

Hence, the Preparedness Pillar is essential within this intricate framework, as it serves as a critical connector between digital and sustainability transformations and acts as the engine behind the triple transition. It moves the interconnected gears of digital, social, and environmental transitions while addressing cross-cutting priorities such as mindful governance, purpose-driven prosperity, and multilevel cooperation. This pillar complements and reinforces the other pillars with unique attributes that are not sufficiently emphasized in either the current digital transformation agenda or the 2030 Agenda.

As previously described, digital transformation is currently underrepresented and weakly integrated within sustainability frameworks, leading to insufficient visibility and relevance. This gap results in missed opportunities and overlooked risks.

Similarly, sustainability within the digital sphere has been largely neglected, as it has not been prioritized to date. This fragmentation, lack of integration, and limited visibility mean that these priorities are inadequately addressed in both digital and research agendas, causing stagnation, and hindering progress in both domains.

In this dissertation, preparedness holds a distinct role, as it is built upon the most critical elements of existing digital transformation and crisis management frameworks while also incorporating the essential preparation required for the triple transition, fostering readiness, resilience, response to crises and regeneration. Therefore, to unlock its transformative potential, preparedness demands a well-defined and prominent position, with increased visibility and dedicated resources, rather than being diluted across other dimensions.

Nevertheless, as previously introduced, the proposed Taxonomy for SRDT must be complemented by additional tools to facilitate its practical implementation and ensure the actionability of the insights gained. To address this need, this research proposes, on the one hand, the development of Strategic Objectives to mobilize change, which are detailed in Chapter 7; and on the other hand, future research avenues, such as the creation of a Report Card Framework with concrete metrics to monitor progress.

These tools could support the operationalisation of the Taxonomy and enhance its applicability across real-world contexts. These aspects are further elaborated in the subsequent chapters.

Furthermore, acknowledging the crucial role of innovation in advancing the triple transition and SRDT, this research examined how the insights derived from the Taxonomy can be leveraged to reorient the innovation landscape and reinforce stakeholder collaboration toward this mission.

It also explored the interconnected relationship and potential joint application of the proposed 6HIM model for the regenerative triple transition and the Taxonomy. Notably, the 6HIM model and the Taxonomy are deeply aligned and interconnected, jointly contributing to achieving the vision of the regenerative triple transition. Thus, this research identified strategies to promote regenerative innovation, underscoring its synergy with digital transformation and sustainability.

This alignment also facilitates the development of ecosystems that support experimentation with SRDT initiatives, thereby enhancing their scalability and ensuring a lasting and transformative impact.

In conclusion, this research proposes the first Taxonomy addressing the interplay between Digital Transformation and Regenerative Sustainability for advancing SRDT towards the triple transition, bringing a significant foundational contribution to this nascent research field.

The alignment with the priorities of the 2030 Agenda and digital agenda, combined with the integration of the Preparedness pillar addressing resilience, readiness, and response to crises, underscores the relevance to global challenges and sets a compelling narrative for advancing the triple transition.

Nevertheless, further research and complementary tools are needed to enhance its actionability and implementation in real-world contexts.

Having described the resulting taxonomical framework and its significance, Table 5.13 and Figure 5.2 outline the pillar and domain levels of the Taxonomy for SRDT.

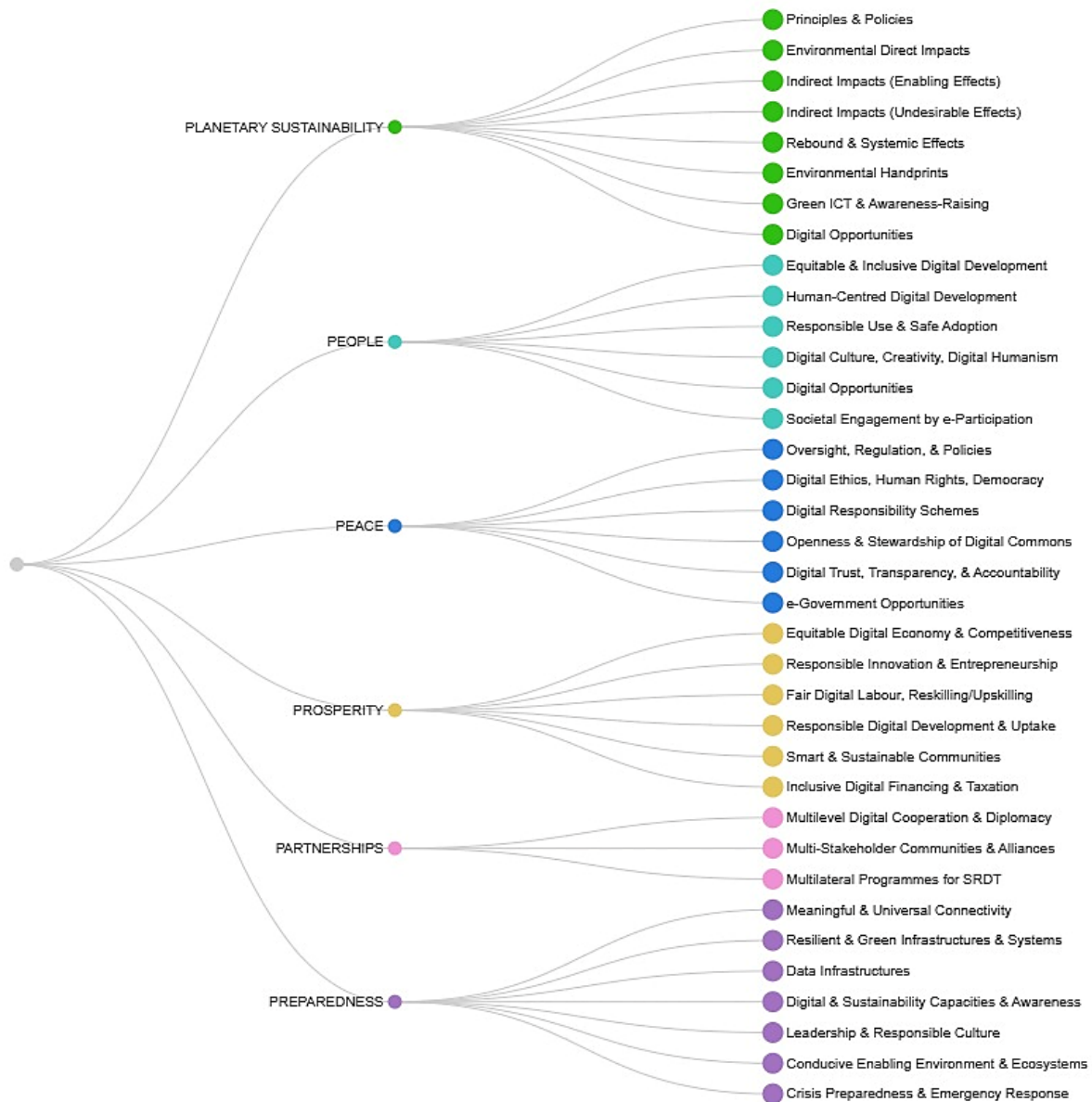
Additionally, Annex II provides the complete and validated version of the Taxonomy for SRDT, structured across three levels (pillars, domains, and thematic factors). It includes a detailed table that condenses the categorization of the determinant features of Sustainable and Regenerative Digital Transformation into three levels: six pillars, thirty-six domains, and 273 thematic factors.

These visual representations provide a comprehensive and hierarchical depiction of the Taxonomy structure, offering a clear and organized overview of the respective components and their interrelationships. Thus, this visualisation enhances the understanding of the complex phenomenon of Sustainable and Regenerative Digital Transformation (SRDT).

Table 5.13. First Version of the Taxonomy for SRDT (domain and pillar levels)
(Own elaboration)

PILLAR LEVEL (Dimension)	DOMAIN LEVEL
PLANETARY SUSTAINABILITY <i>(Environmental Sustainability Dimension)</i>	Planetary Sustainability and Regeneration Principles and Policies
	Environmental Direct Impacts (First-Order Effects – Footprints)
	Indirect Impacts (Second-Order Desirable Enabling Effects: Optimisation, Substitution).
	Indirect Impacts (Second-Order Undesirable Effects: Induction, Obsolescence).
	Rebound and Systemic Effects (Unintended High-Order Effects, Societal Effects)
	Environmental Handprints (Net-Positive Effects Within or Beyond the ICT Sector)
	Green ICT (Mitigation Strategies) and Awareness-Raising
	Digital Opportunities for Regenerative Sustainability and SDGs
PEOPLE <i>(Social Sustainability Dimension)</i>	Equitable and Inclusive Digital Development
	Empowerment, Shared Responsibility for Digital Human Rights and Human-Centred Digital Development
	Responsible Use and Safe Adoption of Digital Solutions (Digital Well-Being, Social Acceptance)
	Digital Culture, Creativity, and Digital Humanities
	Digital Opportunities and Empowerment for Social Resilience/Regeneration
	Societal Engagement by Inclusive e-Participation
PEACE <i>(Mindful Governance Dimension)</i>	Responsible and Agile Oversight, Regulation, and Policies
	Digital Ethics Governance for Human Rights, Sovereignty, and Democracy
	Mindful Leadership and Digital Responsibility Schemes
	Openness and Stewardship of Digital Commons
	Digital Trust, Transparency, and Accountability
	Inclusive, Accessible, and Secure e-government Opportunities for Regenerative Governance
PROSPERITY <i>(Purposeful and Regenerative Economy Dimension)</i>	Equitable Digital Economy and Competitiveness, Commerce and Trade for Regenerative Development across Value Chains
	Responsible Digital Innovation and Entrepreneurship Ecosystems
	Fair Digital Labour, Decent Work, Reskilling, and Upskilling
	Responsible Digital Development and Uptake for Regenerative Prosperity
	Smart and Sustainable Communities and Ecosystems
	Inclusive Digital Financing and Taxation
PARTNERSHIPS <i>(Cooperation Dimension)</i>	Digital Cooperation and Diplomacy
	Multi-Stakeholder Communities and Alliances
	Multilateral Programmes for Sustainable and Regenerative Digital Development and Cooperation
PREPAREDNESS <i>(Readiness, resilience, and response to crises for the Triple Transition)</i>	Meaningful and Universal Connectivity: Access, Affordability, Relevant Content, Accessibility, and Usability
	Resilient, Secure, Sustainable Infrastructures and Systems
	Data Infrastructures, Data Availability, Quality, Interoperability, and Openness.
	Digital and Sustainability Literacy, Capacities, and Awareness
	Leadership, Responsible and Agile Culture, and Ambidexterity
	Conducive Enabling Environment and Supporting Ecosystems
	Crisis Preparedness and Emergency Response

Figure 5.2. Dendrogram Diagram illustrating the pillar and domain levels of the Taxonomy for SRDT
(Own elaboration, domains are summarised by tags for the sake of visual clarity)



5.9. Concluding Reflections on the Taxonomy for SRDT

Digital transformation and sustainability must be reconciled and evolved to address the novel challenges and opportunities emerging from the regenerative perspective and the triple transition.

However, current governance structures lack the systemic perspective needed to pursue this evolution. In addition, existing assessment frameworks for digital transformation overlook sustainability, while sustainability frameworks fail to fully account for the risks and opportunities posed by digital disruptions to societal and natural systems. As a result, digitalisation continues to evolve and spread rapidly, often without the oversight and accountability mechanisms required to mitigate its negative effects and harness its potential benefits.

Thus, enhancing and adapting current research and governance landscapes to contemporary realities demands novel and comprehensive approaches capable of guiding decision-making regarding both the risks and opportunities of digital transformation within the context of regenerative sustainability.

The existing limitations also emphasize the need for improved methodologies and tools that enable a holistic evaluation of digital transformation progress, accounting for its impacts on sustainability dimensions. This requires combining technical and eco-social strategies, embedding regeneration and resilience perspectives, and moving beyond techno-solutionism and growth-centric governance.

Hence, the development of a systemic, holistic, and inclusive framework addressing the key determinant factors for SRDT has been identified as a priority. Such a framework should provide a panoramic view of the risks and opportunities inherent in digital transformation and sustainability and reconcile and reorient these domains toward the regenerative triple transition and systemic resilience.

To address this research gap, this dissertation proposes a Taxonomy for SRDT, comprising three levels, structured into six main pillars aligned with the 2030 Agenda and the digital agenda, thirty-six domains and 273 thematic factors. The Taxonomy provides a "glocal" approach by reflecting the voices of all actors, sectors, and contexts into a pluriversal and comprehensive narrative for the triple transition.

Indeed, the taxonomical framework encompasses the following pillars: Planetary Sustainability, representing the environmental transition and ecological stakeholders; People, embodying the socially just transition; Peace, advocating for mindful and inclusive governance; Partnerships, promoting multilevel cooperation and collaborative efforts; Prosperity with Purpose, reflecting the socioeconomic dimension; and Preparedness, integrating the digital, social, and environmental aspects of the triple transition.

The Preparedness pillar serves as a driving force and integrative connector between digital and sustainability transformations for the triple transition. This pillar is structured around three axes: readiness, resilience, and response to crises. It integrates established factors like digital readiness while embedding sustainability and regeneration perspectives, thereby creating a unified framework that addresses current disconnections.

The proposed Taxonomy provides valuable insights for identifying critical intervention areas, evaluating actions, and implementing effective mechanisms by integrating the key factors that define Sustainable and Regenerative Digital Transformation (SRDT).

A notable strength of the Taxonomy is its alignment with recognized frameworks in both digital and sustainability domains, which leverages synergies and ensures coherence with established global agendas, facilitating its adoption. Another strength is its flexibility, as the Taxonomy is designed to adapt and accommodate emerging trends, ensuring its continued relevance in supporting the triple transition.

Nevertheless, as a conceptual framework, the Taxonomy may face challenges in translating its insights into actionable pathways. To address this limitation, this research proposes complementary tools, including Strategic Objectives to mobilize change (described in Chapter 7), and future initiatives such as the development of a Report Card Framework with concrete metrics to monitor progress (presented in Chapter 10). These tools could enhance the operationalization of the Taxonomy and ensure its relevance and long-term impact in real-world contexts.

Furthermore, the Taxonomy is strongly aligned with the 6HIM model introduced in Chapter 4. This alignment evidences the interconnection of innovation, digital transformation, and sustainability. The synergy between these two frameworks could foster the evolution of innovation ecosystems that support SRDT initiatives, enhancing their scalability and long-term transformative impact.

The six helices of the 6HIM framework for regenerative innovation align with and contribute to the six pillars of the Taxonomy, together advancing the regenerative triple transition. These helices represent the key societal systems driving SRDT and regenerative innovation, namely: (i) Ecosphere aligns with the Planetary Sustainability Pillar, reflecting the environmental transition; (ii) Empowered Whole-of-Society aligns with the People Pillar, supporting a socially just transition; (iii) Conscious Economy aligns with the Prosperity Pillar; (iv) Mindful Whole-of-Governance aligns with the Peace Pillar; (v) Mindful and Green Digital Sphere aligns with the Preparedness Pillar, addressing the triple transition; (vi) Open Academia covers several pillars, aligning education with Preparedness and People, science and innovation with Prosperity, and community engagement with Partnerships.

In conclusion, this research presents the first Taxonomy addressing the interplay between digital transformation and regenerative sustainability to advance the triple transition. Its alignment with global priorities and the integration of the Preparedness pillar underlines its relevance to addressing global challenges with regeneration and resilience perspectives. However, further research and complementary tools are needed to enhance its practical implementation and cross-sectoral impact.

It is important to note that part of the findings presented in this chapter have been included in an article that was presented at the ICT4S 2024 Conference, with its proceedings pending publication by IEEE Computer Society Digital Library: Del Río Castro, G., Uruburu Colsa, Á., González Fernández, M.C. (2024). *Navigating the Triple Transition: A Holistic Taxonomy towards a Sustainable and Regenerative Digital Transformation*. International Conference on ICT for Sustainability. 9th International Conference on ICT for Sustainability (ICT4S 2024), 24th -28th June 2024, Stockholm, Sweden.

The next Chapter presents the process followed to refine and validate the proposed Taxonomy for SRDT and provides the definitive version of this framework.

6. Validation of the Taxonomy for SRDT

6.1. Methodological Approach: Refinement and Validation Process

This section provides the methodological approach followed for the refinement and validation of the proposed Taxonomy for SRDT and the subsequent Strategic Objectives, which has been conducted through a structured expert elicitation process, and other complementary activities, as described below. This process was intended to enhance robustness and transparency, as well as to reduce potential biases and uncertainties.

The refinement and validation phases were primarily conducted through an expert elicitation process based on semi-structured interviews. Additionally, this was complemented and enriched by the insights gained from the presentation of the preliminary results at two international scientific conferences. Additional perspectives were gathered through ongoing dialogue with experts and stakeholders within relevant international forums, working groups and research communities. This process allowed the capture of a range of perspectives, from diverse stakeholders, thereby contributing to an in-depth understanding of the research field.

The expert elicitation process is described below, followed by an overview of the activities conducted for dialogue and engagement with experts and stakeholders in the field.

Overview of the Expert Elicitation Process

Expert elicitation is a method used to gather and quantify expert opinions on complex issues, particularly where empirical data is limited or unavailable. It is widely employed across disciplines and research fields, including sustainability and digital transformation, to inform decision-making processes. It often involves a systematic process for the selection of experts with relevant knowledge and expertise, ensuring that they can provide informed and unbiased judgments. Experts typically participate in structured processes, through techniques that help to aggregate individual judgments into a collective expert opinion, often improving the reliability of decisions made in uncertain contexts.

However, such processes also face challenges such as potential biases, overconfidence, and groupthink. Hence, best practices are recommended to mitigate potential challenges, by ensuring transparency in the process, providing a diverse cohort of experts, along with finalising with a careful examination of the provided judgements.

In this regard, hemming et al. (2018) emphasized the relevance of structure protocols for expert judgment to enhance the quality of outcomes, while also acknowledging its vulnerability to biases influenced by context. These researchers advocated adopting structured elicitation protocols to counter potential challenges and enhance the accuracy and transparency of the resulting judgments. This study also introduced the “IDEA protocol” (Burgman, 2015), which integrated a four-step procedure (Investigate, Discuss, Estimate, and Aggregate), designed to encourage a broader use of structured elicitation. Besides, it allows remote participation to enhance its accessibility. The four steps included defining the problem to be addressed, providing background information to the experts, structuring the elicitation process, and collecting and aggregating individual judgments.

Similarly, Hadjigeorgiou et al. (2022) explored the use of expert knowledge elicitation methods to identify and address data gaps related to emerging risks, particularly under conditions of uncertainty and ambiguity. The research revealed the need for harmonized frameworks to systematically identify, evaluate, and compare emerging risks, ultimately improving mitigation strategies. Overall, expert elicitation serves as a valuable tool for decision-making and construct validation, especially in scenarios where traditional data sources are insufficient, such as in emerging and complex paradigms.

In this research, the expert elicitation process involved the selection of a skilled and diverse cohort of experts with balanced profiles and sound understanding of the research field, the meticulous design of a detailed questionnaire, and semi-structured interviews to capture diverse perspectives from experts across various disciplines and stakeholder categories. A total of fourteen interviews were conducted virtually, during the period from July 2024 to October 2024.

Indeed, the questionnaire (see Annex III) was carefully designed to provide background information, and to pose thought-provoking questions on controversial aspects, thereby supporting the enhancement of the proposed contributions.

The questionnaire contained eleven questions: two general questions about perceptions of the impacts of digital transformation on sustainability and the SDGs; four questions assessing the relevance and coherence of the overall structure of the proposed Taxonomy, including its pillars and domains; three questions evaluating the coherence and relevance of the proposed Strategic Objectives; one question addressing potential strategies for enhancing the integration of digital transformation and innovation within the UN's 2030 Agenda; and a final question for additional suggestions and remarks.

This structured process ensured clarity in the questions addressed and supported a more organized and informed elicitation process. The interactions with experts facilitated meaningful insights from diverse and balanced backgrounds on digital transformation, ethics, environmental, and social sustainability (see Table 6.1.).

This approach was crucial for gaining insights to better characterize and articulate the phenomena under study, as well as to critically evaluate the proposed constructs and their potential implications, leading to refined research contributions. In addition, this process enhanced the robustness of the research, ensuring that the proposed frameworks were both scientifically sound and practically actionable.

This dissertation employed a “bricolage approach” (Kvale, 2007), combining meaning-focused, language-focused, and theoretical reading analyses, guided by a pre-developed framework. This approach allowed a more flexible and nuanced interpretation of the responses while aligning with conceptual insights from the Taxonomy.

The transcripts were thoroughly read to reach a general understanding of the responses. Subsequently, the initial interpretation was documented, together with the transcripts in a data sheet. Following this initial overview, a line-by-line open coding process was conducted (Kvale, 2007), to identify recurrent themes, trends, and their meanings. The codes were derived from both the taxonomical components, and the data itself.

Once coding was completed, a narrative was formulated to connect and compare the perspectives of different experts, providing an interpretation of their responses. Then, recurrent themes raised by experts were identified, and similar segments and their associated codes were clustered, to suggest patterns of consensus and disagreements. Additionally, the transcripts and codes were reviewed, and trend analysis was conducted to identify response patterns across diverse groups of experts (e.g., stakeholder category, background, and speciality).

The insights gathered through the interviews with experts were then thoroughly analysed following the guidance from Kvale, (2007). Then, the findings were used to refine the Taxonomy, culminating in their final validation.

Table 6.1. Overview of the Experts' Profiles
(Own Elaboration)

ID	BACKGROUND	SPECIALITY	STAKEHOLDER CATEGORY	GENDER
1	Digital Transformación	Ethics and Legal Aspects	Academia	Female
2	Digital and Sustainability	Ethics, Sustainability, and IT	Academia	Male
3	Digital and Sustainability	Data Science for Environmental Applications	Academia	Female
4	Digital Transformation	Digital Technological Aspects	Academia	Male
5	Sustainability	Environmental Aspects	Academia	Male
6	Sustainability	Environmental Aspects, Air Quality	Academia	Male
7	Sustainability	Social Aspects, International Cooperation, Risks	Academia	Female
8	Sustainability	Social Aspects, Stakeholder Management	Civil Society and Academia	Male
9	Sustainability	Social Aspects	Academia	Female
10	Sustainability	Social Aspects	Academia	Female
11	Digital Transformation	Digital Innovation, Telecommunications	Public Body	Male
12	Digital and Sustainability	Industrial and Sustainability Applications	Enterprise	Female
13	Sustainability	Environmental Aspects, LCA	Public Body and Academia	Male
14	Digital Transformation	Ethics, Entrepreneurship	Academia	Male

Dialogue and Engagement with Experts and Stakeholders in the Field

Given the intricate and multifaceted interplay among digital transformation, innovation, and regenerative sustainability, the methodology employed in this research was designed to be both rigorous and inclusive, recognizing the need for a participatory approach capable of integrating diverse backgrounds and perspectives. This approach is indispensable for validating the proposed constructs, as it bridges the often-cited gap between theoretical research and practical application.

Considering diverse expert views enables a more comprehensive and nuanced perception of how digital transformation and innovation can be better aligned with sustainable and regenerative development and vice versa. It also allows us to address the relative immaturity of the field, and its fragmentation, alongside the scarcity of holistic perspectives. Thus, ensuring an interdisciplinary and multistakeholder dialogue is not just beneficial but essential for enriching the research process. For that purpose, the following activities were considered during the research.

Presentation of the Preliminary Findings at International Scientific Conferences

In addition to the expert elicitation process, another valuable approach for fostering dialogue on controversial aspects and gaining expert input on the proposed constructs was the presentation of the preliminary research results at international scientific conferences. Certainly, the research was enriched by the insights and critical feedback obtained from the participation in two of the most relevant conferences in the field: the UN's 11th International Conference for Sustainable Development (ICSD 2023) held by UNSDSN in September 2023, and the 9th International Conference on ICTs for Sustainability (ICT4S 2024) organised by the KTH Royal Institute of Technology in June 2024.

The ICT4S conference is a pioneer reference in this field, bringing together a multidisciplinary research community for discussing cutting-edge trends on the interplay between digitalisation and sustainability. Meanwhile, the ICSD conference is also a renowned international reference on sustainable development, with a dedicated track for digital aspects and their intersection with sustainability.

Therefore, two research articles summarizing the key preliminary findings of this dissertation were submitted, reviewed by their respective scientific committees, and presented at these conferences, stimulating insightful discussions that informed the subsequent refinement and validation phases.

One of the accepted articles was specifically focused on the Taxonomy, and the other article was related to it but more focused on the 6HIM model and the strategies for aligning digital, innovation and sustainability agendas. The feedback and insights from the reviewers, and expert committees, alongside exchanges with conference participants, including leading experts and researchers in sustainability and digital transformation, were valuable in refining and enhancing the research outcomes.

Regarding the article presented at the ICT4S 2024 conference, which focused on the Taxonomy for SRDT, it was praised by the reviewers for its comprehensiveness, coherence, and ambition. The reviewers emphasized the intellectual depth, richness of insights, and well-structured arguments provided. They also underlined the breadth and depth of the literature analysed and the robust and original perspectives discussed.

Indeed, the proposed research was recognized for its novelty and potential to address existing gaps, offering an innovative and thought-provoking contribution to the field. According to the reviewers, the approach tackled critical and timely issues at the intersection of sustainability and digital technology, with the resulting taxonomy providing a much-needed framework to raise awareness and mitigate risks associated with emerging technologies like AI. Overall, the research was considered highly relevant and necessary for shaping a more equitable and sustainable digital transformation.

In addition, the reviewers and conference attendees offered valuable advice to enhance the research outcomes. While the initial work presented a more comprehensive framework, including the Taxonomy, Objectives, and a preliminary Report Card Framework (RCF) for tracking progress toward the envisioned regenerative triple transition, the reviewers suggested narrowing the focus solely to the taxonomy to allow a deeper exploration and clearer communication of this core contribution. Also, they expressed disagreement with the proposal to integrate a novel SDG18, representing sustainable digital transformation, into the evolved 2030 Agenda, arguing that, while flawed, is the result of a global consensus that needs to be respected.

Furthermore, the principal recommendation was focused on clarifying the actionability and practical implementation of the Taxonomy, which was refined accordingly.

Additionally, future research directions proposed in Chapter 10 aim to further address this aspect. Specifically, it is suggested to refine the objectives with concrete metrics, develop a more detailed Report Card Framework, and apply these frameworks in real-world case studies to gain empirical insights into potential implementation challenges.

Another recommendation highlighted the importance of emphasizing the positive impacts of digital technologies to provide a more balanced perspective. Reviewers also advised defining key concepts for non-expert audiences and addressing overlaps between domains to enhance coherence.

These valuable recommendations from reviewers and attendees were carefully integrated into the refinement of the proposed Taxonomy and Objectives, and they also informed the formulation of future research avenues, which are described in detail in Chapter 10.

Concerning the article presented at the ICSD 2023 conference, the expert committee provided valuable insights for refining the proposed contributions focused mainly on the 6HIM model and the strategies for aligning the digital, innovation and sustainability agendas towards the triple transition.

The experts expressed that the proposed contributions represented an intriguing, highly ambitious, and valuable approach to aligning innovation, digital transformation, and sustainability.

Nevertheless, the experts underlined that real-world implementation might face challenges, considering the inherent challenges of bringing together diverse innovation stakeholders with varying priorities.

Therefore, they suggest complementing the model with implementation strategies to enhance and facilitate its broader applicability. In addition, they recommended making complex terms more accessible to a wider audience. This advice aligns with the reflections presented in Chapter 8, which provides strategic recommendations to enhance the implementation of the model. Moreover, Chapter 10 outlines future research directions, focusing on applying the approach to real-world case studies to gain insights into measures to address potential implementation challenges.

In conclusion, the inputs gathered during the review process and the conference presentations were also useful for validating the final design of the Taxonomy and shaping future recommendations with new perspectives from the research community. Hence, this process strengthened the research and ensured its alignment with the latest academic and practical advancements in the field.

Participation and Engagement in Communities of Practice and International Forums

Throughout the dissertation journey, the research process has been significantly enriched by ongoing engagement and dialogue with diverse experts and stakeholders in the field. This was achieved through active participation in specialized workshops, working groups, and international forums devoted to sustainable digital transformation, and sustainable development, along with research and innovation.

Notably, the participation in the following key initiatives is worth mentioning: the Coalition for Digital Environmental Sustainability (CODES) led by UNEP (CODES, 2022), the Digital Environment System Coalition (ICT4D-DESC, n.d.) headed by UNESCO, the ITU's Focus Groups on Environmental Efficiency for AI (FG-AI4EE, n.d.), U4SSC, and Virtual Worlds, the "Digitainable" project participatory workshops held by the Bonn Alliance for Sustainability Research (n.d.) from 2020 to 2022, the DG Connect "Digital for Our Planet" workshops (European Commission, 2021), the Digital4Sustainability Learning Path led by UNSSS (2023-2024), together with the participation in the WSIS and AI for Good Summits from 2019 to 2024, was valuable in shaping the research.

The involvement within these initiatives, not only facilitated meaningful discussions in cutting-edge themes but also broadened the knowledge base as the field evolved. Indeed, these interactions provided a dynamic flow of intriguing ideas, and challenging assumptions, thereby enriching the research framework. The insights gained from these engagements were valuable in refining the proposed constructs, ensuring their alignment with the rapidly changing landscape of digital transformation, sustainability, and R&I. Therefore, these complementary knowledge exchanges with experts have contributed to a more comprehensive understanding of the intricate interdependencies within this field.

In conclusion, this diverse approach ensured research results grounded in a holistic and inclusive perspective, capturing the rapidly evolving phenomena, and addressing the multifaceted nature of the interplay amid digital transformation, regenerative sustainability, and innovation.

The following section provides an analysis of the responses from expert interviews.

6.2. Analysis of Responses from Expert Interviews

This section presents the analysis of the findings from the expert elicitation process employed to validate the proposed Taxonomy for SRDT. A detailed review of the expert perspectives is provided below, along with a rationale describing how these insights were integrated into the refined definitive version of the Taxonomy.

Concerning the research approach followed, first the full transcription was broadly analysed, followed by coding line by line, based on the taxonomical elements and the research questions topics. Finally, an analysis of tendencies was performed.

Analysis of Expert Backgrounds and Perspectives

The analysis of the experts' backgrounds reveals three categories of expertise. Sustainability expertise is the main field for 42.9% of the respondents, followed by digital transformation for 35.7% of the respondents, while 21.4% of them reflect an integrated background in both digital transformation and sustainability. Therefore, this suggested a balanced representation of both disciplines, with slightly more emphasis on sustainability, ensuring that the experts' views inform both domains in a balanced manner.

Regarding the stakeholder type, the respondents are predominantly from universities, representing 71.4% of the total, which underscores a strong academic perspective. In comparison, public bodies represent 14.3%, while enterprise and civil society each account for 7.1% of the participants. This distribution suggests that, while the analysis benefits from the rigour and robustness of academic insights, there may be limited input from stakeholders focused on practical applications.

Finally, in terms of the respondents' areas of specialization, the distribution is relatively balanced, with 21.4% focusing on digital aspects, another 21.4% on ethics, and 28.6% each specializing in social and environmental aspects. This distribution implies a diverse range of perspectives, with a balanced emphasis on digital, ethical, social, and environmental aspects, which would enrich the analysis.

Considering gender representation, it is relatively balanced, with 43% female and 57% male respondents.

Analysis of Responses to Question 1: Perceptions of the Impacts of Digital Transformation on Sustainability

Based on the experts' feedback, a significant majority, 78.6% of respondents, indicated that the overall impact of digital transformation remains uncertain, while 21.4% of experts considered digital transformation to have an overall positive impact. This suggests that most experts are cautious, acknowledging that while digital transformation brings some benefits, it also presents challenges whose full impact is not yet fully understood.

Therefore, this reflects that most experts are cautious and consider that while digital transformation brings some benefits, it also faces challenges whose impact is not yet fully understood.

Analysis of Responses to Questions 2a, 2b, 2c, and 2d: Perceptions of the Impacts of Digital Transformation on the SDGs

The interpretation of responses regarding the potential impacts of digital transformation (DT) on the various SDG groups yielded the following insights.

The response scale was based on a 5-point Likert format, ranging from 1 (very positive) to 5 (very negative), enabling a nuanced and structured assessment of experts' perspectives (see Table 6.1).

- 2a. The potential impact of DT on social SDGs showed an average score of 3.29, indicating a slightly positive or neutral perception.
- 2b. The potential impact of DT on environmental SDGs presented an average of 2.93, suggesting a trend towards a neutral to negative impact.
- 2c. The potential impact of DT on socioeconomic SDGs revealed an average of 3.79, indicating a positive impact.
- 2d. The potential impact of DT on governance SDGs showed an average of 3.29, interpreted as a slightly positive or neutral perception.

These responses reflected a certain level of awareness among experts regarding the potential negative environmental impacts of digital transformation.

However, the recognition of potential negative social impacts is more limited. While most experts perceive socio-economic objectives as positively influenced by digital transformation, governance objectives are generally viewed with neutrality.

Overall, the perception of potential impacts is more optimistic than in the previous question yet remains centred around a neutral position. Nonetheless, most experts underlined that the impact of DT is not evenly distributed across goals, and individual assessments of each goal are necessary for deeper insights.

Table 6.2. Analysis of Responses to Question 3: Perceptions of DT Impacts on the SDGs
(Own elaboration)

Category	Averages (Mean)	Medians (Central Value)	Mode (Most Frequent Value)
Question 2a (Social goals)	3.29	3.0	3.0
Question 2b (Environmental goals)	2.93	3.0	3.0
Question 2c (Socioeconomic goals)	3.79	4.0	4.0
Question 2d (Governance goals)	3.29	3.0	3.0

Analysis of Responses to Question 3a: Overall Structure of the Taxonomy

The majority of experts (13 out of 14) consider the proposed approach coherent and highly relevant for integrating, aligning, and advancing together the digital and sustainability transformations. Only one expert expressed doubts about it and preferred an alternative approach by integrating the preparedness-related domains within the other five pillars. Another expert considers this pillar very relevant but has uncertainties about its coherence with the rest. Two experts believe that it is a relevant approach, although other alternative options, such as cross-cutting integration, could be also a valid option.

Furthermore, one expert underlined that the proposed approach includes elements, dynamics, and beliefs that are cohesive and consistent with the other five pillars while also inspiring philosophy and principles to prepare for the future and avoid past mistakes. According to this expert, the proposed approach offers support for integration with the other pillars, facilitates planning and decision-making, and bridges digital developments with social and environmental challenges. Most experts underscored that preparedness is essential for integrating diverse perspectives and establishing common ground.

One expert interprets preparedness as a preventive alert mechanism, though the concept refers to readiness and resilience, which means, having the resources, capabilities, cultural foundation, and enabling environment to seize the opportunities of the transition and adapt to it, including potential crises.

According to one expert, while the regenerative perspective is very promising and coherent, given its nascent stage, it is challenging to assess its full impact and feasibility, and further research is needed in this regard. Additionally, another expert pointed out that the approach should be generous and beneficial for all generations, emphasizing intergenerational equity.

In conclusion, the proposed Taxonomy structured based on six pillars, five of them aligned with the 2030 Agenda pillars, and the other integrating the Preparedness dimension for the triple transition, is considered by most experts, highly relevant and coherent. Therefore, the overall structure of the Taxonomy has been validated.

Analysis of Responses to Question 3b: Relevance of the Preparedness Pillar

Based on the responses provided, all experts considered the proposed approach highly relevant to align the two frameworks of digital transformation and sustainability. However, several experts indicated that moving from theory to practical implementation may be complex, given the particularities of both realms and existing resistance from the digital sector.

Experts emphasized the value provided by some contributions of the proposed approach, such as the synchronization of the digital and sustainability transitions, rooted in a common framework, terminology, and an ambitious and unified narrative. Several experts underscored that digitalisation has first progressed as an accumulation of advancements that subsequently have impacted political, social, and economic spheres, with disordered disruptions that escape to current governance mechanisms. Therefore, novel frameworks like the one proposed are highly needed.

According to one expert, the proposed six pillars must be aligned to guide strategy, objectives, and digital transformation actions. Several experts emphasize that to facilitate the implementation, objectives need to be translated into actionable and gradual steps. In this regard, this is exactly what the dissertation's contributions aim to achieve by the alignment of the proposed taxonomical approach, the connected objectives, the complementary Sextuple Helix Innovation System, and the future research lines focused on a Report Card Framework for facilitating a robust and flexible monitoring and awareness raising.

Furthermore, considering the existing challenges in this interplay, one expert suggested that maybe what needs to be reevaluated is the suitability of the current 2030 Agenda pillars. In that sense, this expert argued that the domains of "Prosperity" and "Peace" should be more closely aligned in practice, but barriers remain.

Another expert raised a highly relevant aspect about the non-binding nature of the SDGs and other global agendas, which poses a significant barrier to implementation. In this matter, one expert suggested that the lessons learned from the 2030 Agenda should be leveraged, thereby addressing its limitations to strengthen future frameworks.

Most experts recognised that, despite its caveats, the 2030 Agenda has been successful at least in creating a common language and aligning global efforts, which is not a minor achievement. Therefore, it is crucial to build upon this foundation to facilitate adoption.

Overall, experts' feedback underlines the relevance of aligning digital transformation with the broader sustainable development agenda, building on both the gained insights, as well as the emerging challenges to ensure cohesive and impactful progress.

Analysis of Responses to Question 4: Relevance of the Domains within the Preparedness Pillar

The responses from experts showed a clear consensus on the coherence and high relevance of the preparedness pillar, for supporting a sustainable digital transformation. According to most experts, the preparedness pillar is a suitable initial step and provides clarity on the foundational aspects needed to prepare society for navigating the triple transition.

Moreover, experts underlined the high relevance of the rest of the domains and their cohesive integration (robust infrastructure, human capacities, and education), as well as their significant interrelations with other pillars. Nevertheless, the experts provide some remarks and additional suggestions for enhancing the proposed Taxonomy, which are analysed as follows.

First, it is needed to clarify and emphasize that preparedness refers to “being ready” for the triple transition. It goes beyond preventive alerts, as it encompasses a holistic preparation approach, supported by robust and secure infrastructures and systems, education and capacities, a responsible culture and mindset, a conducive enabling socioeconomic environment that facilitates cohesion and transformation, including well-educated and prepared civil society, institutions, and business settings. It also includes crisis preparedness systems and capacities.

Therefore, the Preparedness Pillar represents readiness, resilience, and response to crises for tackling the regenerative triple transition.

Considering the experts’ remarks, one scholar noted that, considering that the regenerative perspective is still incipient, this aspect should be reevaluated and reinforced in the future. There exist uncertainties about the evolution of regenerative approaches in the digital sphere, therefore this could be a promising future research avenue.

Additionally, various experts raised concerns about the inequalities arising from global digitalisation, leading to unequal access to technology, and dominance of large corporations, impacting both individuals and businesses. In particular, one expert emphasized the relevance of reinforcing the social aspects related to personal prosperity, quality of living, and working environments, along with a culture of responsibility at an individual level.

In this regard, those aspects related to inclusiveness, transformational culture, personal development, and well-being are already covered in the Preparedness and People pillars, as well as a foundational cross-cutting value of the taxonomy. Notably, the People pillar is strongly focused on equality, inclusiveness, responsible use, and well-being, reflecting a just transition dimension for all the stakeholders, including individuals from civil society.

Furthermore, the Preparedness pillar included as core domain universal connectivity, capacity building, and education. In this context, connectivity refers not just to having access to digital services (e.g. broadband coverage), but also includes affordability, accessibility, relevant content in the local language, and usability or user-friendly interfaces for all individuals, especially those considered vulnerable, living in rural areas, having disabilities or belonging to specific generations or collectives, such as children, elderly, women and girls.

This is related to a remark from another expert, questioning the relationship between connectivity and usability. Both concepts are considered part of the broader “universal connectivity” concept in most digital development frameworks from the United Nations, World Bank, and OECD. Connectivity goes beyond access to infrastructures or services, as its objective is to promote inclusive access to digital opportunities for everyone, regardless of their income, language, generation, gender, place of residence, and physical or psychological conditions.

Nevertheless, considering that several experts suggested more visibility for reinforcing these critical aspects, they have been refined in the definitive version of the taxonomy.

Regarding cultural and personal development aspects, one expert suggested the integration of emotional qualities, such as empathy, a sense of hope and enthusiasm among citizens, to enhance their engagement and ownership. These aspects relate to human-centred development and resilience which are embedded in both the Preparedness Pillar (culture and mindset, education, awareness) and the People Pillar (responsible use, ownership, human-centred digital development, participation). Nonetheless, considering the crucial role of civil society and individuals in this endeavour, they have been reviewed and refined to accommodate this proposal.

Moreover, one expert proposed adding public control over communication systems and promoting open access to enhance accessibility and equity.

These aspects are already considered within the Peace Pillar since they are more related to governance than preparedness. Indeed, this underlined a prominent dilemma in literature and policy: how to balance oversight of infrastructures without compromising competitiveness in the global digital landscape. Achieving such balance is essential for ensuring sustainable use and oversight, and in this regard, good governance of Digital Public Infrastructures is critical, as substantiated within the Peace Pillar.

Another expert recommended addressing disinformation (e.g. fake news) and the role of algorithms in undermining the diversity of thinking and accurate information, along with the need for legislation in this matter. This aspect aligns more naturally with governance, which is already included. In addition, connectivity also includes security and relevant content aspects, which are related to avoiding disinformation and what the literature termed “data pollution.”

Additionally, this aspect relates to building capacities and raising awareness to detect disinformation, under the Preparedness pillar, promoting safe and responsible use of digital solutions, under the People pillar, alongside ensuring an ethical governance to regulate the misuse of algorithms for disinformation or social polarization, under the Peace pillar. These are different facets of the same problem and should be addressed from multiple perspectives: the user, the developer, and the government.

One expert also commented on the potential negative impact on employment impact, but this aspect aligns with the Prosperity pillar due to its socioeconomic dimension, and with the Peace pillar, as it involves regulation, policies, and digital responsibility schemes for labour.

Regarding the overall structure, two experts recommended further elaborating on the diverse domains for their practical application. The first point is addressed in the third level of the taxonomy, which divides the thirty-six domains into 273 thematic factors, with each domain substantiated in Chapter 5. Regarding practical application, the first step involves defining strategic objectives, which are further detailed in Chapter 7.

Furthermore, to complement this approach, a Report Card Framework with specific metrics to monitor and communicate progress is suggested as future research direction in the discussion (Chapter 8).

Finally, one expert emphasized the importance of managing interconnections and coordinating actions across pillars and domains to ensure cohesion and practicability of the framework. This aspect is already addressed in the taxonomy, as substantiated in Chapter 5. Taxonomies are designed to unify, organize, and categorise knowledge rather than analyse interrelationships.

Nevertheless, as with the 2030 Agenda, defining this network of interlinkages could provide valuable insights for policy interventions and implementation, and therefore it is suggested as a promising area for future research.

Analysis of Responses to Question 5: Relevance of the Domains within the Planetary Sustainability Pillar

All experts considered that the planetary sustainability pillar is comprehensive, coherent, and highly relevant. It is considered to bring value to understand the environmental dimension of the digital transformation, by an integrated approach with equal relevance of all dimensions and pillars. Particularly, several experts highlighted that this approach provides added value since the environmental aspects are less visible and less acknowledged in the digital domain. Thus, it contributes to identifying and clarifying the relationship between digital transformation and environmental protection and regeneration. Nevertheless, some experts made a few remarks and additional suggestions outlined as follows.

Several experts noted that the domains within this pillar are diverse and interrelated, both among themselves and with the other pillars. Indeed, the domains reflect the multifaceted nature and complexity of the intersection of digital transformation and sustainability.

The third level of the taxonomy provides more granular information on the different thematic factors that provide further understanding of this interplay. Besides, these domains are substantiated in detail in Chapter 5.

Furthermore, one expert suggested that Green ICT strategies could help to offset the environmental impacts of digital transformation as they become mainstream. This expert underlined the need for flexible thresholds when evaluating the contribution of digital solutions to sustainability, by also considering their societal benefits in areas like health and climate change.

This aligns with Hasselbalch's perspective (2022), arguing that some environmental polluting activities could be more acceptable than others based on their societal importance. For instance, an energy-intensive application that advances cancer research or climate solutions might be justifiable in the short-term, until energy efficiency and renewable integration measures are achieved. However, this also raises a controversial question with ethical implications, since prioritizing certain societal benefits over environmental health conflicts with broader sustainability goals, including human health and well-being.

In this regard, the proposed taxonomy is flexible enough to consider the different domains of application, their societal relevance, and the gradual adaptation of digital systems to comply with the environmental demands, as a genuine transitional approach. This aspect is related to the remark from another expert, suggesting a clarification about the differences between handprints and digital opportunities. In this regard, handprints are a terminology proposed to refer to "net-positive" impacts, in opposition to footprints. It is generally applied to counter negative and mainly quantifiable impacts, particularly, carbon emissions.

Meanwhile "digital opportunities" refers to a broader understanding of the use of digital advancements for sustainability benefits, which can be assessed more flexibly, but always ensuring a legitimate claim instead of current greenwashing practices. Hence, in essence, both concepts are related, compatible, and complementary since they have a different scope and applications.

Additionally, another expert emphasized that digital technologies could enable novel opportunities and sustainable business models such as "product-as-a-service" and the sharing economy. In this regard, two relevant aspects need to be clarified.

First, the potential opportunities from digital technologies on environmental sustainability are already reflected in the taxonomy in two ways, the positive indirect effects termed "enabling effects," and a dedicated domain focused, precisely, on digital opportunities for sustainability.

Second, and more importantly, there is a misconception by which digital technologies are perceived to inherently contribute to sustainability through virtualization, which is not always accurate.

The literature and practice have demonstrated that digital services and sharing economy platforms can generate significant second- and third-order environmental and social impacts, such as excessive consumption, increased emissions from logistics, and direct environmental impacts from the physical infrastructure they rely on. This is one of the most controversial environmental impacts of digitalisation and is elaborated on in detail within Chapter 5.

Considering the environmental awareness and educational aspects, several experts suggested including a domain specifically focused on encouraging sustainable lifestyles in citizens and civil society, not only in the ICT sector. In this regard, it is worth mentioning that the Planetary sustainability pillar is addressed to all stakeholders, not just the digital sector.

Second, environmental awareness is already included within the Green ICT measures. The third level of the taxonomy further dissected these mitigation strategies into several thematic factors, some of them related to environmental awareness, behavioural change, and applications for sustainable lifestyles.

Nevertheless, to provide more visibility to this crucial aspect, the related domains have been revisited and reinforced.

In relation to the environmental direct impacts and strategies, one expert suggested a domain on critical raw materials and circularity. These aspects are already included within the third level of the taxonomy. Indeed, circularity is a critical aspect of this pillar and therefore is included both as a sustainability principle and as a Green ICT mitigation strategy.

The dependency on critical raw materials is also included, both within the direct environmental impacts, as well as within the Green ICT strategies and digital applications for sustainability. For instance, aspects such as responsible sourcing, resource efficiency and sufficiency strategies, right-to-repair policies, or applications of sustainable materials discovery are included within the third taxonomical level for circularity purposes.

Moreover, one expert asked about which domain covers energy consumption for algorithm training of an AI. In this regard, the energy consumption of AI algorithms comes mainly from the related data infrastructures and systems needed for performing the tasks. Therefore, it should be placed within the direct environmental impacts. Also, the use of such algorithms could cause second and third-order effects, depending on their application.

Nevertheless, the literature and practice are underdeveloped and most LCA studies are focused on the direct impacts of specific infrastructures and equipment, instead of all the whole impacts of the life cycle of AI. Thus, further research is needed to fully characterize the environmental impacts of algorithms. This aspect is substantiated in detail in Chapter 5.

Ultimately, one expert emphasized the importance of defining specific indicators for each domain to enable effective monitoring. Recognizing the potential challenges, this expert suggested focusing on a manageable set of indicators that are easy to quantify and track over time. In this matter, following the taxonomy development, a set of six strategic objectives and thirty-six targets have been proposed as a preliminary approach, as described in Chapter 7.

These objectives are considered a first step in the complex process of setting global goals, which demands a profound dialogue with stakeholders and a proper localization to specific contexts before defining potential indicators. Indeed, the following step of the process will be to complete a Report Card Framework, along with a set of initial indicators. However, given the time constraints of the doctoral programme and the complexity of undertaking a broad stakeholder consultation and definition of metrics for such an ambitious and comprehensive framework, this aspect is out of the scope of this dissertation and will be further pursued as a future research avenue.

Considering the scope, while it is essential to keep the selection of indicators manageable, it must also comprehensively cover all critical aspects and dimensions. Otherwise, it would offer little advancement over existing frameworks, which often overlook key sustainability considerations for the sake of simplicity.

In summary, experts viewed the Planetary Sustainability pillar as a comprehensive and relevant framework for addressing the environmental aspects of digital transformation, by offering an integrated approach to give more prominence to the often-ignored environmental dimension in the digital domain. Experts underscored the importance of robust accountability measures, Green ICT strategies, flexible evaluation criteria for societal benefits, and defining "handprints" and "digital opportunities" as complementary concepts. Key recommendations include enhancing the taxonomy to reflect sustainable lifestyle promotion, and circular economy practices, alongside practical metrics, and indicators for effective monitoring.

Analysis of Responses to Question 6: Relevance of the Domains within the People, Prosperity, Peace, and Partnerships Pillars

According to most experts, the overall framework is highly coherent and relevant, along with well-aligned to digital priorities and the 2030 Agenda pillars. It is considered a comprehensive approach for integrating sustainability and future opportunities for regeneration within digital development. One expert pointed out that the structure is robust and well-designed. Another expert underscored that is relevant that all domains are approached holistically, within an integrative framework that emphasizes interconnectedness rather than isolated silos. A clear articulation of the interrelations amid domains and pillars is essential, as demonstrated by the existing overlaps.

Regulation, for example, is highly relevant within the Peace pillar but also intersects significantly with domains linked to responsibility, including culture, innovation, transparency, and accountability.

Certainly, the proposed taxonomy advocates for a coordinated, cohesive, integrative perspective to align diverse aspects toward a sustainable digital transformation. Regulation is a cross-cutting aspect, which plays a relevant role across all the domains, but it is particularly visible in the Peace pillar and its domains. In addition, the proposed approach is aligned with the existing digital frameworks. In this regard, the taxonomy has been developed with foundational principles of sustainability, inclusiveness, regeneration for creating novel opportunities, and mindful governance influencing across all the pillars and involving all stakeholders and contexts. All pillars are interconnected and somewhat overlapped precisely to facilitate their mutual synergies.

Furthermore, two experts considered that the information about the domains needs to be more detailed to fully understand their scope. In this sense, the full taxonomy version encompasses three levels (six pillars, thirty-six domains, and two hundred and seventy-three thematic factors) as shown in Annex II and is substantiated in detail in Chapter 5.

Concerning the peace pillar for the governance dimension, the experts suggested the following enhancements and clarifications. One expert raised a concern about ensuring shared responsibility and governance beyond the public sector. This shared ownership should prioritize the common good over mere efficiency or profit, promoting a lasting philosophy beyond individual projects. Therefore, according to this expert, the Preparedness pillar allows cohesion with this ambition.

Indeed, this is a relevant aspect underlined by Hasselbalch (2022), who advocated for democratic digital systems with suitable distribution of information and governance responsibilities between citizens, nations, and powerful actors. In this regard, the Preparedness Pillar complements the Peace Pillar on governance and reinforces a universal culture of responsibility, capacity building and awareness for everyone when tackling the digital transformation.

While the Peace Pillar not only affects public bodies, but all stakeholders, indeed, policies and regulations rely mainly on governments, and partially on enterprises in terms of voluntary schemes and standards. Thus, the individual responsibility belongs more to the Preparedness pillar.

Additionally, another expert noted an overlap between leadership and responsibility areas in the Preparedness and Peace pillars, respectively. While related, they have different nuances and represent diverse perspectives. In the Preparedness Pillar, the domain of responsible culture and leadership is referred to as the internal dimension within an organisation or individual. Instead, in the Peace pillar, responsibility is related to the external and normative dimension, covering soft or hard regulation, and voluntary commitments for CDR. Nonetheless, these domains have been refined to ensure that their unique characteristics are better reflected in the taxonomy.

Another expert suggested including an open Internet in this pillar. Indeed, this is a crucial aspect of governance, which is already included in the third level of the taxonomy.

A highly relevant aspect is underscored by another expert, concerning the impacts of digital technologies on peace. This expert raised concerns about the potential of digital technologies to fuelling conflict and menace peace at the global level, along with the need to address them effectively. This aspect is considered within ethical governance, digital democracy, and digital responsibility schemes, as well as in the domain of global cooperation and diplomacy within the Partnership Pillar. A more detailed substantiation is provided in Chapter 5. In essence, digital paradigms are strategic assets for governments and other agents and can be weaponized to undermine peace, destabilize democracies, and threaten societal harmony.

For that reason, both mindful governance and global cooperation and diplomacy play a key role, as well as domestic regulation, to ensure the ethical use of digital advancements for peaceful societies.

Regarding the Prosperity Pillar, most experts agreed with the proposed domains and only a few remarks have been suggested. First, to clarify the scope, the Prosperity pillar covers not only the purely economic dimension of digital transformation but also its social consequences, therefore it responds to a socioeconomic perspective with an additional nature of purpose and fairness.

Two experts emphasized the relevance of responsible innovation and frugal approaches, as catalysts for meaningful change. Indeed, the relationship of SRDT with innovation is highly relevant, as explained in Chapter 4. This taxonomy is a crucial domain since it facilitates the alignment of digital transformation and sustainability and allows novel societal opportunities and transformations.

An expert proposed to integrate the development of the technology together with uptake. This aspect is already included, but it has been refined to ensure that reflects the whole cycle of technology from design to uptake.

In addition, according to this expert, the concept of competitiveness is not sufficiently clear and suggested to rename it to “digital economy and competitiveness.” This aspect is substantiated within Chapter 5, and it is related to socioeconomic factors that contribute to the ability to compete in the market. Competitiveness encompasses productivity, efficiency, adaptability, and quality, and is also related to innovation, to improve or maintain a positive market position concerning other competitors.

When it comes to the people pillar, several experts suggested reinforcing the participation of women in all digital activities. This aspect forms part of the inclusiveness and just transition principle embedded across all the pillars of the taxonomy, especially within the People Pillar focuses on social aspects and the just transition. Also, it is specifically considered in the third level factors related to inclusive participation and responsible use. Nevertheless, as several experts suggested to give gender aspects more visibility and relevance, the taxonomy has been refined to accommodate this proposal to ensure that digital transformation benefits all demographics.

Moreover, another expert underlined the need to clarify the meaning of societal engagement by inclusive e-participation. This aspect is substantiated in detail in Chapter 5. In essence, virtual participation platforms form part of the electronic government efforts to encourage the participation and engagement of citizens and civil society in decision-making and governance. These tools have become key instruments for citizen-to-government (C2G) and citizen-to-citizen (C2C) interaction, which reinforce community bonds, empower civil society, promote awareness, and foster a more cohesive and active society. Therefore, e-participation platforms offer an opportunity for enhanced societal engagement, as argued by Vicente and Novo (2014).

With regard to the Partnership Pillar, covering the cooperation dimension, the experts proposed the following improvements and clarifications.

One expert suggested that multilevel governance needs to be integrated. In this regard, multilevel governance is already included in both the Peace Pillar (whole-of-governance approach as a general principle), as well as in the Partnership Pillar which is focused on a global and regional cooperation dimension. Governance in the digital realm takes place mainly at the domestic level, which is why it needs to be reinforced with global cooperation frameworks, such as the Global Digital Compact.

Another expert proposed that international binding commitments should be considered to address the current tendency to sidestep the responsibilities. Indeed, the unclear definition of responsibilities and the non-binding nature of the global agendas are undermining the realisation of the SDGs and sustainable digital transformation. Several aspects of the digital realm are borderless and demand global regulations and agreements that to date are lacking.

This aspect is already covered in the global cooperation and digital diplomacy domain, and it is examined in detail in Chapter 5. However, is highly difficult to establish a global binding framework in the current geopolitical scenario, particularly, in a strategic realm such as digitalisation.

Furthermore, another expert emphasized the relevance of value chains, given the significant risks that they entail for human rights and environmental health. In this sense, the risks concerning value chains are considered from diverse perspectives in the taxonomy. First, they are considered in the Prosperity Pillar, given the relevance of achieving a fair trade and a responsible corporate approach to this aspect. Second, they are also included in the Planetary Sustainability Pillar, particularly, within the Green ICT strategies (e.g. responsible sourcing and certification schemes). Finally, global value chains represent a critical issue within global cooperation and diplomacy, therefore the respective risks are integrated also in the Partnership pillar for cooperation.

Finally, another expert noted that it would be useful to map controversial digital topics. In this sense, this is exactly what the taxonomy aims to provide, a comprehensive overview of the most relevant risks and controversial areas from literature, policy, practice, and experts' views, along with a summary of the opportunities to counteract them. With thirty-six domains and 273 thematic factors, it provides a comprehensive, but still manageable panoramic of both the risks and opportunities of SRDT.

Analysis of Responses to Question 7 on the Objectives and Targets Proposed for the Preparedness Pillar

Most experts agreed that the objectives and targets under the Preparedness pillar are highly relevant, priority, and coherent and would provide significant impact, depending on how the collaboration among stakeholders is achieved. The experts recognised the approach as ambitious and necessary. In addition, the experts provided some suggestions for further enhancement, outlined as follows.

Several experts argued that there is good potential for implementation, yet this is going to depend on the awareness and commitment of civil society, governments, and the corporate sector, and it is highly influenced by geostrategic and economic factors. Reinforcing the regenerative approach in the implementation as much as possible from the outset would be useful to start with a more beneficial position in this matter.

Additionally, several experts emphasized the adequacy of connecting the different components within the pillar, with cultural and awareness aspects to build the capacities to face the transformation.

Another expert underlined the need to inspire an appealing shared sense of value and excitement, to foster public engagement and commitment, within the cultural dimension. In this regard, Target 1.5 (focused on culture) has been refined to give more emphasis to the role of citizens, the transformational culture of care and awareness, ensuring that the transformation feels inspiring rather than imposed. This also aligns with the broad scope of the regenerative sustainability perspective, as described in Chapter 2.

Furthermore, more specific indicators and a more elaborate explanation of some targets are suggested by several experts. In particular, one expert proposed to refine Targets 1.5 to 1.7 to avoid subjective interpretation and enhance measurability. Two experts also recommended clarifying objective 1.6 and making it more specific. Therefore, these targets have been refined accordingly. Also, one expert considered that the supportive environment within objective 1.6, should be originated from public policy. In this regard, objective 1.6 aligns more naturally with the Preparedness pillar since it entails cultivating readiness and resilience across society.

Having a conducive and enabling environment⁵ refers to foundational conditions, resources, and support from economic, social, and environmental systems to make effective a sustainable digital transformation. Certainly, these aspects rely on policies but go beyond them. Moreover, most digital transformation and innovation frameworks place this topic within the readiness dimension.

Following the refinement of some targets, one expert underlined the need to reinforce accessibility and inclusiveness and include the risks of disinformation within target 1.1 to avoid a uniform way of thinking and monoculture. In this regard, target 1.1 has been refined to reinforce the security, accessibility, and avoidance of groupthink, algorithmic homogeneity, echo chambers, or filter bubbles.

Regarding accountability, another expert considered that it is difficult to define indicators for some of the targets. In this regard, the targets should be as universal as possible, and the implementation will provide the context and localization to make them more specific and practical. Moreover, indicators could be qualitative, they do not have to be quantitative. There are suitable indicators for most of the targets in existing digital and innovation frameworks.

In conclusion, the feedback from experts has been considered and accommodated to refine the objective and targets within this pillar. Particularly, target 1.1 has been refined to further emphasise accessibility, usability, and secure and diverse content. In addition, targets 1.5 to 1.7 have been reworded to further clarify their ambition and components, further embed the role of citizens and stakeholders, extend the transformational culture of care, awareness, and conscious leadership to all stakeholders and individuals, and provide a more appealing and encouraging vision.

Analysis of Responses to Question 8 on the Objective and Targets for the Planetary Sustainability Pillar

Considering the Planetary sustainability objective and targets, most experts rated them as highly relevant, coherent, and with significant potential for implementation, showing a clear consensus on this matter. Most experts considered that the inclusion of regenerative principles is highly relevant and advocated reinforcing this approach in the future as a more proactive tactic for long-term sustainability. Nevertheless, some experts provided suggestions for enhancing their impact and implementation.

First, regarding implementation, several experts underlined that, despite their high relevance, the practicality of these goals is likely to be complex, in the hands of private companies, since it would depend on uneven political commitment and conflicting interests.

Another expert recognised that not all the targets may be equally realisable due to the limited and uneven commitment in the digital sector, for instance, the adoption of standards. Therefore, it should be reinforced with further awareness raising across stakeholders, particularly users and enterprises, and regulatory support. One expert highlighted the scalability potential of the proposed targets to create a broader cultural shift.

⁵ A supportive enabling environment entail institutional quality, effective governance and regulatory quality, suitable infrastructures, natural resource availability, quality of life, human capital, accessible markets and business setting, supportive incentives and ecosystems that encourage investment and entrepreneurship (Global Innovation Index by WIPO, 2024)

Indeed, several experts emphasized the need to raise public awareness about the environmental impacts of digitalisation and the pollution of digital content (e.g. data pollution), along with promoting sustainable behaviours and lifestyles among citizens in general. This has to be enabled by specific accessibility mechanisms and appealing incentives. In this regard, this aspect is already considered within the objectives, but it has been further emphasized in the refined version of the proposed framework.

Furthermore, other experts underlined the key role of public policy and regulatory support, to ensure compliance from the private sector. Government oversight is needed to monitor the sustainability efforts of companies, through binding regulations. This aspect has been reinforced in the refined version. Nevertheless, most global sustainability commitments are mainly voluntary and non-binding schemes, since regulation is considered counterproductive for digital competitiveness, except in specific regions like Europe.

Regarding accountability, several experts underscored the relevance of establishing clear and actionable indicators, along with a robust monitoring approach. In this sense, the proposed objectives and targets are a preliminary step, since they are conceived as strategic and inspirational goals, which need to be further localised to the specificities of each context. In addition, the dissertation anticipates the development of a Report Card Framework with more refined metrics adaptable to local contexts, for advanced monitoring and accountability, as the next step of future research, as described in the discussion (Chapter 8).

In conclusion, the experts expressed consensus with the proposed objective and targets, considered highly relevant and coherent, with potential complexities in their implementation. The objectives have been refined to accommodate the suggestions of the experts, mainly concerning further visibility of raising awareness among citizens and enterprises, along with binding mechanisms for compliance with sustainability requirements with government support.

Analysis of Responses to Question 9 on the Objectives and Targets under the Pillars of People, Prosperity, Peace, and Partnerships

The experts broadly agreed on the high relevance and coherence of the objectives within the People, Prosperity, Peace, and Partnerships pillars. All experts recognized their potential to support a sustainable and regenerative digital transformation. Concerning their implementation, as in the previous pillars, it is going to depend on acceptance and commitment from stakeholders, as well as on the adaptation and further elaboration of the targets to more specific indicators. Nevertheless, experts recommend some refinements, summarised as follows.

The objectives are recommended to be more the more universal as possible according to one expert, but at the same time, other experts suggested more specific and concrete goals. This is a common dilemma when setting objectives for such a complex and multifaceted global phenomenon. The approach followed in the dissertation is to provide preliminary and high-level universal objectives, to establish a common ground and mutual vision, which need to be further elaborated and adapted to specific local contexts by proper indicators during the implementation.

Considering the People Pillar, most experts rated the objective and targets under this pillar as highly relevant and saw it as fundamental for a digital transformation that is socially equitable and inclusive. Yet, the implementation of these goals would potentially conflict with economic dynamics.

Moreover, several experts recommended the reinforcement of accessibility and usability, along with inclusiveness, especially for vulnerable groups, such as children, women, and the elderly. While these aspects are already included both in the People Pillar and the Preparedness Pillar (i.e. universal connectivity) as well as in the rest of the framework as a cross-cutting principle of inclusiveness, they have been reinforced to accommodate the experts' suggestions.

In addition, one expert recommended including multichannel communication to provide diverse options for everyone. This aspect has been included in those targets related to this domain.

Another expert suggested giving more visibility to digital well-being. In response to this proposal, this aspect has been reinforced, while it was already included within the responsible and safe use of digital solutions. Finally, one expert recommended including a mention of e-government in target 3.3 devoted to digital solutions for societal purposes.

While the application of digital solutions such as e-health, relies on electronic government platforms, the focus of this domain is mainly social, oriented to digital opportunities for societal purposes, instead of e-government, which is included within one specific target for that purpose in the Peace Pillar.

Regarding the Prosperity Pillar, experts have considered highly relevant the regenerative focus and the purpose-driven promotion of innovation for social and ecological challenges. One expert particularly underlined the role of responsible innovation and cooperation in transformational change. Nevertheless, realising these targets may be complex due to the lack of commitment and regulation at the global level, suggesting the reinforcement of global cooperation and regulatory oversight.

Moreover, one expert proposed to integrate target 4.3 (development and uptake of sustainable digital solutions) within the Planetary sustainability pillar. Yet, this domain is more naturally aligned with the socioeconomic dimension, and it is mainly undertaken by enterprises and industries for socioeconomic purposes.

When it comes to the Peace Pillar, most experts considered its objective and targets as relevant and coherent, noting that, akin to other pillars, implementation may be hindered by power dynamics, and large corporations and dominant states may resist regulation. According to one expert, the governance targets imply a range of possibilities that would need further elaboration to translate into practice, from ethics to digital goods.

Furthermore, one expert suggested reinforcing the regenerative dimension of institutions and improving security. These aspects have been enhanced in the revisited version of the objectives. Another expert emphasized the relevance of transparency, trust, and ethical leadership for responsibility, which are already considered in the proposed framework.

According to another expert, digitalisation has the potential to empower citizens and promote decision-making. This is related to both the electronic government and the electronic participation domains, which are soundly interrelated. Moreover, one expert considered that stakeholder management should be more visible. In response to this suggestion, this aspect has been strengthened in the reviewed framework.

Additionally, one expert recommended defining concepts such as human values, and digital humanisms. In this regard, it is commonly agreed to refer these concepts to the globally agreed UN Declaration of Human Rights, the UN 2030 Agenda for Sustainable Development, and the UNDP's Human Development Report. Moreover, these concepts are properly described and defined within Chapter 5.

Finally, regarding the Partnerships Pillar, most experts considered its objective and targets as relevant and coherent since multilevel cooperation is crucial for driving a sustainable digital transformation. Also, one expert underlined the relevance of renewing multilateral structures and revitalising cooperation mechanisms included within the taxonomy. In addition, according to one expert, cooperation should serve to work towards a common good vision, instead of individual interests. In this sense, developing countries need specific mechanisms to strengthen their capacities and enable participation in cooperation mechanisms. In this regard, this is already considered in the Partnership pillar, nevertheless, it has been further reinforced as suggested.

Analysis of Responses to Question 10 on Strategies for Renovating the 2030 Agenda towards the Triple Transition

Based on the responses from experts, no strong preference or clear tendency is shown in favour of a single approach for enhancing the 2030 Agenda towards a more robust integration of digital transformation. Most approaches are seen as valid, albeit with specific considerations. Additionally, several experts suggested that the optimal path may lie in a combination of these approaches, which would enhance robustness and provide systemic character to the 2030 Agenda. Indeed, various experts stressed the need to build on existing frameworks rather than developing new ones that may be difficult to adopt, adding complexity and heterogeneity without added value.

While there is no dominant trend, some approaches appear to be slightly more favoured than others, as explained next.

Considering the first approach, it is viewed by most experts as necessary, primarily for addressing short-term needs and contexts with limited resources. Therefore, it is seen as a transitional approach to prepare the ground for a future agenda. However, most experts concurred that adds complexity to an already intricate agenda, and brings limited impact, while posing a barrier for resource-constrained countries.

One expert proposed to set a transitional approach for nations or stakeholders with fewer resources or those lagging. Another expert emphasized the need for simplification given the lessons learnt from the complexity of the 2030 Agenda. A third expert recommended setting gradual, revisable targets every 4-5 years, with varying paces depending on the development level, so as not to hinder developed countries or overwhelm less developed ones, where digital transformation is less mature, and ambitious approaches may be unnecessary.

Furthermore, the second approach focused on the cross-cutting nature of digitalisation, receives as many critiques as positive assessments. Most experts agreed that, by itself, it is insufficient, and its implementation requires to be combined with other strategies. One expert critiqued this approach and pointed out that, similar to the cross-cutting focus on Human Rights within the 2030 Agenda, these elements risk becoming diluted and lacking sufficient visibility to ensure effective implementation.

The third approach, consisting of integrating a novel SDG 18 specifically focused on sustainable digital transformation, is widely supported, and chosen as a priority by several experts. One expert did not support this approach explicitly. Other experts, while in favour of this novel goal, considered that may add complexity. A second expert suggested combining this novel goal with additional indicators in other SDGs where needed.

Additionally, a third expert agreed with SDG18 but considered that it should be focused on the quality of digitalisation, instead of universal access, which has largely been achieved. In this regard, it is worth mentioning that over a third of the world's population still lacks Internet access according to ITU (2023). While developed countries have near-universal access to digital opportunities, developing nations and vulnerable groups still face a severe digital divide.

Moreover, the proposed SDG18 does not centre solely on universal access to digital opportunities, but rather on achieving a sustainable and inclusive digital transformation, which is far from being achieved. Therefore, it is important to recognize the varying levels of digital and sustainability maturity in the Global North and South. Similarly, another expert proposed that a novel SDG 18 should focus on a just digital transition, which aligns with the sustainability and triple transition vision.

Concerning the fourth approach, is highly valued by most experts, and one of the most frequently selected as a priority. Only one expert viewed this approach as inadequate, arguing that simplification is needed instead of novel structures that may add complexity.

Furthermore, several experts proposed additional recommendations for enhancing this approach. One expert emphasized the relevance of these ecosystems and initiatives, like the Internet Governance Forum (IGF).

Another expert underlined the relevance of multichannel communication in innovation ecosystems to reach all stakeholders, including those experiencing digital divides. Moreover, a third expert recommended expanding or reorienting existing ecosystems and initiatives instead of creating new ones. Nevertheless, this could be challenging since most existing structures have not been created for sustainability purposes.

The approach with the least acceptance is the fifth, involving the creation of a parallel digital agenda like the Global Digital Compact.

Only one expert considered this approach a priority, while the rest see it as a complementary reinforcement, provided that it is soundly aligned with sustainability and SDG values. Several experts considered that this approach is only valuable if entails binding enforcement power.

However, neither the GDC nor any other global digital agenda currently has such capacity. Some experts do not consider it a significant addition to sustainability integration, although they understand that the digital sector may establish its agendas, prioritizing other dimensions.

Additionally, two experts do not prioritize any single approach but believe that all of them can contribute in different ways and contexts. One expert emphasized the need for a linking and facilitation element, as well as a Theory of Change and a systemic stakeholder analysis.

In this regard, Chapter 4 of the dissertation aligns with the fourth approach, by proposing a sextuple helix innovation model to implement the triple transition, integrating six key actors representing the main societal systems and transformations, and transition brokers as intermediaries and facilitators.

Thus, the proposed 6HIM model, the Taxonomy for SRDT, along with the strategic recommendations for the synergetic alignment of digital, innovation, and sustainability agendas are synchronized and aligned for this purpose.

Moreover, regarding the Theory of Change, a preliminary proposal is included in Chapter 7, along with the transformative strategic objectives for managing the transition.

Analysis of the Responses to Question 11: Additional Suggestions and Recommendations

Experts proposed a variety of additional remarks and suggestions, summarized below.

One expert suggested exploring mechanisms in underdeveloped contexts to reinforce inclusiveness through a transitional approach, acknowledging that while approaches for advancing the 2030 Agenda are essential, they are often ambitious and challenging for lagging nations and stakeholders.

This perspective is already considered in the dissertation, in which a roadmap has been proposed to guide short-, medium-, and long-term actions for reorienting the 2030 Agenda to more effectively integrate digital transformation and innovation. This roadmap is elaborated in detail in Chapter 8.

Another suggestion emphasized the critical role of policies, particularly in education and awareness, as they are crucial levers for driving transformative change. Several experts emphasized the importance of strengthening citizen awareness and civil society engagement with sustainability and regenerative principles. These aspects are integrated into the Taxonomy, as substantiated in Chapter 5.

Furthermore, one expert pointed out the potential of frugal design research. This is already addressed within the proposed taxonomy, specifically within the sustainability principles and Green ICT strategies under the Planetary sustainability pillar, and in the innovation domain under the Prosperity pillar.

Frugal innovation does not always contribute directly to environmental sustainability but can be promising when combined with sufficiency approaches, as discussed in Chapter 5.

Another expert underscored the need to strengthen interlinkages among domains and align them with the proposed objectives. This expert advocated for a general-to-specific approach, moving from broad objectives to targeted local actions. This approach supports the creation of context-specific, actionable, and measurable solutions, ensuring that broader goals effectively translate into impactful local initiatives.

This aspect is proposed as future research direction to further advance the proposed strategic objectives (Chapter 7) with a complementary Report Card Framework.

Additionally, another expert valued the research contribution, since they provide approaches to tackle global challenges effectively while promoting inclusive, sustainable, and regenerative digital development.

However, existing barriers need to be addressed, and the proposed vision may guide future policies and strategies, ensuring positive contributions at all possible levels. Indeed, this ambition supports the Taxonomy, 6HIM model, and strategic recommendations.

Accessibility and education are key concerns for one expert, who stressed its relevance within the “universal connectivity” domain under the Preparedness pillar, alongside digital competency education, which is also part of this pillar.

One of the key areas that the experts have emphasized is the need to strengthen the role of civil society in the digital transformation process. This includes establishing a more strategic view of citizenship, cultivating a culture of shared responsibility, building individual capacities, and providing an inclusive, universal approach that considers the needs and perspectives of all stakeholders.

This also includes promoting diversity of opinion to counter algorithm-driven homogeneity. One expert suggested incorporating empathy and motivation to foster shared value solutions aimed at the common good.

In response to these suggestions, those aspects related to shared responsibility, emotional capacities, individual education and awareness, and participation of the vulnerable, have been reinforced in the revised taxonomy.

In terms of sustainability, one expert argued that environmental aspects are more prominently addressed in existing frameworks than social aspects or ethics. This expert emphasized the need to give more emphasis to social aspects, while also addressing the rising GHG emissions.

However, the literature evidenced that environmental considerations are often the weakest link in both the SDGs advancement and the digital agenda. Indeed, as substantiated in Chapters 3 and 5, the environmental impacts of digital transformation are complex and significant and remain under-researched and poorly represented in policy frameworks. Therefore, both social and environmental concerns need to be better addressed.

Furthermore, digital transformation is seen by several experts as a high-speed, powerful force that is difficult to control. This calls for incentives and limitations, especially regarding social impacts. This need is already acknowledged in the Peace, Prosperity, and Partnership pillars, which cover policies, regulations, global cooperation efforts, and incentives for a fair, inclusive, and sustainable digital transformation.

In conclusion, experts' perspectives have been highly constructive in validating the proposed approach and refining it through additional clarifications and suggestions for enhancements. Most suggestions were already incorporated at the third level of the Taxonomy, as well as across other components of the dissertation contributions.

This feedback substantiates the relevance and alignment of the proposed taxonomy for SRDT with the research objectives, and their connection with the other research contributions.

Additionally, insightful novel perspectives, such as greater emphasis on citizen awareness, emotional capacities and inner transformation, shared responsibility, gender equality, and reinforced accountability have enriched the final version of the Taxonomy and the conclusions of the dissertation.

Tendencies Identified and Limitations of the Findings

The findings reveal a tendency among each group of experts to prioritize impacts more closely related to their specific field, reflecting patterns consistent with availability bias and confirmation bias. This suggests that experts are more likely to emphasize areas of impact they are most familiar with or that align with their existing knowledge and perspectives. For instance, digital experts generally focused on more technical aspects such as connectivity or security, efficiency, and socio-economic benefits of digitalisation. However, they tend to emphasize less on environmental and social risks.

Meanwhile, social sustainability experts generally prioritized aspects such as inclusion, emotional capabilities, citizen engagement, and misinformation in digital contexts. While they recognized environmental sustainability relevance, their analyses focus more on social implications.

Ultimately, environmental sustainability experts tend to emphasize long-term impacts in general and are more critical of both the potential environmental and social risks associated with digitalisation, along with accountability and technical matters.

These general tendencies aligned with the literature review findings about the perceptions of different stakeholders. However, exceptions within each group indicate that most experts recognize the need for a more balanced approach that considers both environmental and social risks and opportunities of digital transformation. In addition, the number of respondents is small, and predominantly academic, limiting the ability to draw general conclusions about the perception of each stakeholder group.

Regarding the limitations of the findings, the primary one is the limited participation from enterprise experts, whose perspectives are vital for creating actionable frameworks. The inherent complexity of the interplay between digital transformation and sustainability, demands careful reflection, and some experts found it challenging to articulate views on such a multilayer taxonomy. Therefore, for future research, a broader but streamlined consultation would be beneficial to capture more diverse inputs from enterprises, civil society, and non-European contexts.

6.3. Refined and Validated Taxonomy for SRDT

Following the expert elicitation process and subsequent analysis, the initial design of the Taxonomy was refined based on the recommendations from diverse experts, resulting in a validated version of the Taxonomy.

A summary of the modifications is provided below, and the final Taxonomy for SRDT is also outlined in Table 6.2 and Figure 6.1. The refined domains are highlighted in bold.

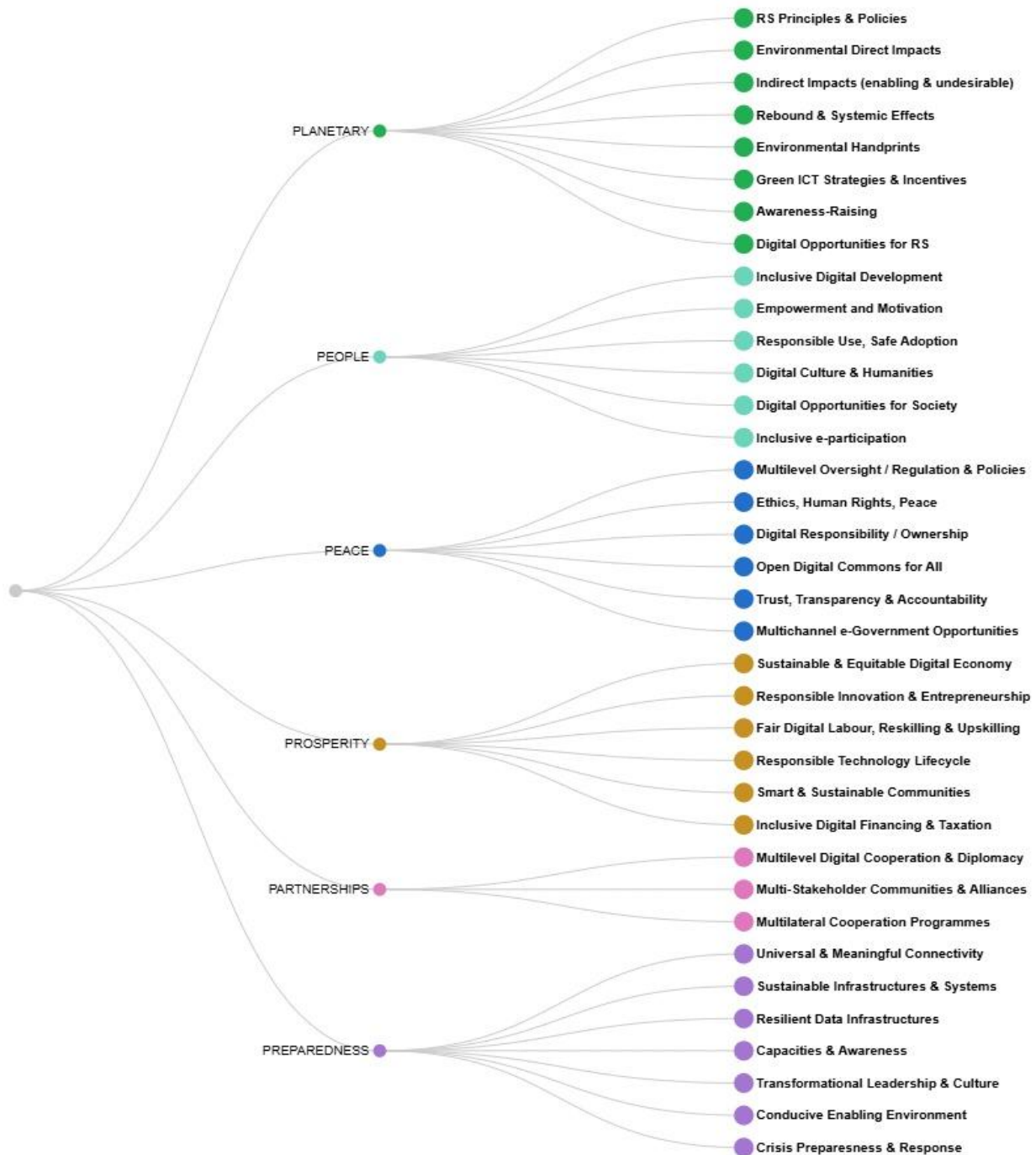
Table 6.3. Validated Pillars and Domain Levels of the Proposed Taxonomy for SRDT
(Own elaboration)

PILLAR LEVEL (Dimension)	DOMAIN LEVEL
PLANETARY SUSTAINABILITY <i>(Environmental Sustainability Dimension)</i>	Planetary Sustainability and Regeneration Principles and Policies
	Environmental Direct Impacts (First Order Effects or Footprints)
	Indirect Impacts (Second Order Effects): Enabling Effects (Optimisation, Substitution), and undesirable Effects (Induction, Obsolescence)
	Rebound and Systemic Effects (Unintended High Order Effects, Societal Effects)
	Environmental Handprints (Net-Positive Effects within or beyond the ICT Sector)
	Green ICT (Mitigation Strategies and Incentives for Greening the ICT Sector)
	Environmental Awareness-Raising Incentives and Behaviour Change among All Stakeholders
	Digital Opportunities for Regenerative Sustainability and SDGs
PEOPLE <i>(Social Sustainability Dimension)</i>	Equitable, Inclusive, and Safe Human-Centred Digital Development for Everyone <i>(including Vulnerable Groups, Women, the Elderly, Persons with Disabilities, and Children)</i>
	Empowerment and Emotional Engagement for Transformational Human-Centred Digital Development
	Responsible and Accessible Use, Safe Adoption and Self-Protection of Rights, and Digital Well-being
	Digital Culture, Creativity, and Digital Humanities
	Digital Opportunities for Empowerment, Resilience and Regeneration Leaving No One Behind
	Societal Engagement by Inclusive e-participation, Safe and Accessible Virtual Spaces for All
PEACE <i>(Mindful Governance Dimension)</i>	Responsible, Agile, and Multilevel Oversight, Regulation, and Policies
	Digital Ethics for Safeguarding Human Rights, Cybersecurity, Sovereignty, Peace, and Democracy
	Digital Responsibility Schemes, Ownership, and Shared Governance among all Stakeholders
	Openness and Stewardship of Digital Commons for All
	Digital Trust, Transparency, and Accountability
	Accessible, Secure, and Multichannel e-Government Opportunities for Everyone
PROSPERITY <i>(Purposeful and Regenerative Economy Dimension)</i>	Equitable and Sustainable Digital Economy, Competitiveness, Commerce and Trade across Value Chains
	Responsible Digital Innovation and Entrepreneurship Ecosystems
	Fair Digital Labour, Decent Work, Reskilling, Upskilling
	Responsible End-to-End Technology Lifecycle (Design, Development, Deployment, Uptake, and Adoption) for Regenerative Development
	Smart and Sustainable Cities, Communities and Ecosystems
	Inclusive Digital Financing and Taxation
PARTNERSHIPS <i>(Cooperation Dimension)</i>	Multilevel Digital Cooperation and Diplomacy for a Sustainable and Peaceful Digital Society
	Multi-Stakeholder Communities and Co-creation Alliances for Inclusive, Diverse, and Sustainable Digital Development
	Multilateral Cooperation Programmes for Sustainable Digital Development, Capacity Building Mechanisms for Vulnerable Local Communities
PREPAREDNESS <i>(Readiness and Resilience for the Triple Transition Dimension)</i>	Universal and Meaningful Connectivity: Access, Affordability, Relevant and Reliable Content, Accessibility and Usability
	Resilient, Secure, and Sustainable Infrastructures and Systems (Digital and Enabling Assets)
	Robust, Secure and Resilient Data Infrastructures, Data Availability, Quality, Interoperability, and Openness
	Digital, Sustainability, and Resilience-oriented Capacities and Awareness for Everyone
	Transformational Leadership, Ambidexterity, and Culture of Responsibility among All Individuals and Organisations
	Conducive Enabling Environment and Ecosystems <i>(Favourable Institutional, Regulatory, Business, Natural, Social and Cultural Conditions and Networks)</i>
	Crisis Preparedness and Emergency Response Capacities and Supporting Systems

Figure 6.1. Sunburst Diagram of the validated Taxonomy for SRDT (domain and pillar levels)
(Own elaboration: domains are summarised by tags for the sake of visual clarity)



Figure 6.2. Dendrogram Diagram of the validated Taxonomy for SRDT (domain and pillar levels)
(Own elaboration: domains are summarised by tags for the sake of visual clarity)



6.4. Concluding Reflections on the Validation Process

The refinement and validation of the Taxonomy for SRDT was based on an expert elicitation process involving semi-structured interviews with fourteen experts from diverse backgrounds on sustainability, digital transformation, and digital innovation, providing a balanced perspective of digital, social, and environmental aspects. This process resulted in the validation of the proposed taxonomy, underscoring its coherence and relevance for aligning digital transformation with regenerative sustainability objectives. Furthermore, the experts provided insightful refinements to further reinforce inclusiveness, public engagement and awareness, economic equity, shared governance, and ownership, and binding regulatory commitments for enhanced compliance and accountability.

In addition, the elicitation process was complemented with further expert dialogue through the presentation of the preliminary research results at two renowned international conferences, as well as through participation in international forums, workshops, and research communities in the field.

Concerning the stakeholders' perceptions of the potential impacts of digital transformation on sustainability, most experts (78.6%) acknowledged both positive and negative effects and expressed caution about the net impact, which they consider uncertain. The remaining experts were more optimistic, viewing digital transformation as a force for positive change. When it comes to the SDGs, experts were optimistic about economic impacts, neutral regarding social and governance goals, and critical of its negative environmental effects.

Regarding the overall structure of the Taxonomy (pillars, domains, and thematic factors), most experts (13 out of 14) found it relevant and coherent for synchronizing digital and sustainability transformation. Notably, the systemic integration across the six pillars was seen as highly relevant to connect the currently misaligned social, economic, environmental, and governance dimensions. Also, the alignment and coherence with already existing frameworks, such as the 2030 Agenda, were highly valued, for ensuring adoption by a shared narrative and common terminology.

Yet, experts emphasized the need to fully understand the interconnections and coordination among all the pillars for a cohesive implementation, as well as further elaborated the framework with robust metrics and monitoring methodologies. As learnt from the SDGs implementation, the non-binding nature of global agendas poses obstacles to its realisation, therefore binding global commitments were suggested, yet such agreements and complex to achieve.

The Preparedness Pillar was viewed as foundational and highly significant for both reinforcing readiness and resilience and serving as an integrative element of the rest of the five pillars. Experts suggested reinforcing the citizen preparedness and inclusion of the vulnerable groups in this pillar.

In relation to the Planetary Sustainability Pillar, experts underlined the high relevance of this dimension for enhancing environmental accountability, currently overlooked in digital policies, and encouraging stronger regulatory support and public oversight for heightened compliance, as well as environmental awareness among citizens and companies.

About the People Pillar, experts advocated for reinforcing citizen engagement by inspiring empathy and building emotional capacities that increase ownership, along with giving more prominence to the participation of women, vulnerable groups, human inner development, and digital well-being. For the Peace and Cooperation pillars, which are highly interconnected, aspects such as shared responsibility for the common good, preservation of peace, and binding commitments at both global and domestic levels, were highly emphasized.

In conclusion, the experts largely agreed with the proposed framework and provided insightful recommendations for refining the taxonomical domains.

Their perspectives were accommodated, resulting in a more robust and inclusive approach to supporting sustainable and regenerative digital transformation.

Furthermore, experts recommended complementing the Taxonomy framework with concrete and robust metrics and monitoring methodologies, alongside assessment of the interlinkages and coordination amid domains and pillars. In line with this advisement, the following Chapter 7, provides a proposal of Strategic Objectives and Theory of Change for SRDT and the triple transition. Moreover, the discussion (Chapter 8) anticipates additional strategic recommendations to address the monitoring of progress in this mission and the interlinkages assessment of these interconnected domains.

Other intriguing suggestions such as reinforcing stakeholder engagement and collaboration, as well as providing transformational approaches for inspiring change, are related to the Sextuple Helix Innovation Model, and enabling ecosystems for regenerative innovation and the triple transition, proposed in Chapter 4. This aspect is further discussed in Chapter 8.

Considering that the interviews were conducted mainly with academic experts from the Global North, a potential future research line could be extending the consultation to a broader cohort of stakeholders from diverse and pluriversal contexts, to enrich the outcomes and give more legitimacy to the consultation.

7. Proposal of Strategic Objectives and Theory of Change for SRDT

This section presents a proposal of Strategic Objectives and Theory of Change to complement the taxonomical framework. Following the validation of the Taxonomy for SRDT and aiming to translate these conceptual insights into actionable pathways, six strategic objectives based on the six taxonomical pillars have been developed to drive progress towards a sustainable and regenerative digital transformation.

Therefore, a preliminary strategic objective is formulated for each pillar of the Taxonomy, and within each objective, a set of specific targets is outlined for each domain. This framework is aligned with both the UN's 2030 Agenda and relevant approaches representing the Digital Agenda, such as the UNDP's Development Compass (UNDP, 2021).

Hence, in total, six strategic objectives and thirty-six specific targets establish the priorities for mobilizing action toward realizing SRDT and the triple transition. Additionally, a Theory of Change is proposed to facilitate the transformation process.

7.1. Introduction to Objective Setting in the Digital Realm

Establishing clear and strategic objectives in the digital and sustainability realms is crucial for guiding transformative efforts. This ensures that digital innovations not only advance technological progress but also align with broader ecological and social aspirations.

A key instrument for setting a transformative vision is the so-called "Objectives and Key Results" (OKRs) methodology, which represents a robust management tool, originally introduced by Andy Grove in the 1970s and later popularized by John Doerr in technology companies like Google (Doerr, 1999). This methodology guides organizations in goal setting, fostering collaboration, transparency, and structured objectives and outcomes.

Zhou et al. (2018) emphasized the efficacy of objective setting in performance management, since it offers relevant advantages over traditional Key Performance Indicators (KPIs), by prioritizing essential goals, encouraging innovative thinking, and aligning individual growth ambitions with the organisation's vision. Setting strategic objectives enables critical thinking, thereby ensuring that collaborative efforts drive the organisation forward (Niven and Lamorte, 2016).

Similarly, Radonić (2017) underlined that to be effective, the strategic objectives should be adaptable to the organisation's size and structure and must involve frequent evaluations, a bottom-up approach, and transparent communication. Thinyan et al. (2022) emphasized the complementary nature of objective setting, by means such as the OKRs, and KPIs. While the objectives are focused on setting a common vision and facilitating continuous improvement, the KPIs monitor the overall performance.

However, implementing strategic objectives may face challenges, including resistance to change in conventional management, implementation costs, and potential conflicts with traditional leadership styles and cultural mindsets.

Despite these caveats, setting strategic objectives represents a valuable tool, as it provides a comprehensive roadmap for organizations to achieve their visions and bridge the gap between ambition and reality, aligning individual and collective goals for evolution and continuous improvement.

Following this brief introduction, the next section describes the proposal of strategic objectives for sustainable and regenerative development in the pursuit of the triple transition.

7.2. Proposal of Strategic Objectives for SRDT and the Triple Transition

Building on the results obtained from the Taxonomy development and expert dialogue, a set of strategic objectives have been developed, and subsequently refined and validated with the input from the expert elicitation process, previously explained in Chapter 6. This process has ensured that these objectives are pertinent, coherent, and aligned with the evolving needs of sustainable and regenerative digital transformation (SRDT) in the context of the triple transition. This section introduces the preliminary proposal of objectives for SRDT and the final refined framework after the validation process.

Therefore, six strategic objectives and thirty-six specific targets, have been developed in alignment with the proposed Taxonomy for SRDT, the UN's 2030 Agenda (UN, 2015), the UNDP's Digital Development Compass (2021), and the UN's Global Digital Compact (UN, 2024b) frameworks. These objectives and targets address the most critical aspects for driving Sustainable and Regenerative Digital Transformation (SRDT) and advancing the triple transition.

The prioritization of themes for building the objectives was grounded in a detailed mapping exercise conducted during the development of the Taxonomy, in which the 273 thematic factors were scored on a 1-3 scale. The principle of parsimony guided this prioritization, ensuring that the suggested objectives and targets remain focused, meaningful, and impactful, by capturing the most significant components from the Taxonomy.

Hence, the resulting six objectives and the thirty-six targets are aligned with the priorities of the UN's 2030 Agenda and digital frameworks, while also integrating missing dimensions and regenerative perspectives into a holistic approach, crucial for the triple transition. Notably, the proposed approach combines the digital, ecological, and socially just transitions across all objectives, reflecting both risks and subsequent potential impacts, as well as the opportunities to regenerate ecological, social, economic, and governance systems for long-term sustainability and resilience.

The preliminary proposal of strategic objectives for SRDT and the triple transition was refined and validated by the expert elicitation process described in Chapter 6. As previously explained, fourteen experts in the fields of digital transformation, innovation, and sustainability were interviewed based on a questionnaire (available in Annex III), with inquiries 7 to 9 specifically addressing the proposed objectives. The questions related to the proposed objectives were questions 7 to 9. The feedback provided by the interviewees was meticulously analysed (as described in Chapter 6), and subsequently, the insights gained inform the refinement and validation of the proposed framework.

The expert elicitation process yielded insightful perspectives and recommendations, condensed as follows.

The objectives and targets for the six taxonomical pillars were largely considered relevant, coherent, and potentially impactful by the majority of experts, although their successful implementation will depend on effective stakeholder collaboration, commitment from the private sector and policymakers, as well as on socioeconomic, and geostrategic dynamics. Furthermore, the experts underlined the relevance of the cohesive, interrelated framework proposed, aligning digital and sustainability domains in an integrative and holistic manner. The experts also recommended refining the wording of three targets within the Preparedness Pillar for enhanced clarity and measurability.

Experts emphasized the need to reinforce aspects, such as accessibility, usability with a stronger focus on women and vulnerable groups, and multichannel communication, along with addressing algorithm homogeneity and disinformation. Other suggestions included raising social and environmental awareness, inspiring public engagement, and shared responsibility.

Concerning peace and governance, experts cautioned against dominant power dynamics, advocating for institutional regeneration, stakeholder collaboration and citizen empowerment. The need for regulatory support, commitments for reinforced compliance, and collaborative governance, alongside broader ownership among all stakeholders were also advised.

Regarding partnerships and cooperation, experts emphasized the need to set global binding commitments, multilevel cooperation for the common good, and capacity-building mechanisms for developing nations.

Additionally, experts also underscored the relevance of further elaborating the framework with concrete metrics and a robust monitoring system and exploring the interlinkages amid them. In this regard, the dissertation proposes the development of a Report Card Framework for context-aware metrics, as a future research step, as explained in Chapter 8.

In conclusion, the experts validated the proposed objectives and targets, recommending refinements across all pillars. Key improvements included reinforcing the accessibility of digital solutions, increasing the visibility of women and vulnerable groups, promoting shared responsibility for the common good, enhancing public engagement and awareness about social and environmental risks, and establishing binding commitments to ensure compliance and accountability.

Validated Proposal of Strategic Objectives for SRDT and the Triple Transition

Therefore, after integrating pertinent expert recommendations, the refined and validated version of the Strategic Objectives for SRDT in support of the regenerative triple transition is presented in Table 7.1.

These Objectives have been developed to mobilize action and move forward from the conceptual foundation established through the proposed Taxonomy to practical implementation. Thus, these Objectives conform to the strategic agenda for advancing towards a sustainable and regenerative digital transformation in alignment with the triple transition vision.

Table 7.1. Validated Strategic Objectives for SRDT and the Triple Transition
(Own elaboration)

PILLAR	OBJECTIVE AND TARGETS
1. PREPAREDNESS <i>(Readiness, Resilience, and Response to Crisis for the Triple Transition)</i>	OBJECTIVE 1: Achieve Universal and Meaningful Connectivity and Preparedness for the Triple Transition by 2035 to Harness Digital Opportunities for the Benefit of Humanity and the Planet. <i>Target 1.1: Ensure universal, affordable, and secure access to connectivity, accessible and usable digital services, and meaningful content free from disinformation for everyone (particularly women, the elderly, children, persons with disabilities, and vulnerable people).</i> <i>Target 1.2: Develop secure, sustainable, resilient, and interoperable infrastructures and systems for regenerative digital transformation, prioritizing sovereignty, sobriety, and eco-design.</i> <i>Target 1.3: Develop resilient, interoperable, open, and sustainable data architectures and management systems that protect and maximize their social value.</i> <i>Target 1.4: Cultivate digital and sustainability capacities, and resilience-oriented soft skills, and raise awareness about the risks and opportunities of the triple transition among all individuals and organisations, particularly women.</i> <i>Target 1.5: Promote transformative and mindful leadership, along with a culture of responsibility, shared value, and resilience that maximizes digital opportunities and mitigates risks to support regenerative development.</i> <i>Target 1.6: Foster a conducive enabling environment and supportive institutional, social, natural, policy and governmental ecosystems to enable a sustainable and regenerative digital transformation.</i> <i>Target 1.7: Develop robust crisis response, emergency preparedness, and resilience capabilities through education and sustainable digital solutions, accessible to all via multichannel strategies.</i>

PILLAR	OBJECTIVE AND TARGETS
2. PLANETARY SUSTAINABILITY (Environmental Dimension)	OBJECTIVE 2: Achieve a Regenerative, Circular, Climate-Neutral Digital Transformation within Planetary Boundaries by 2035. <i>Target 2.1: Establish sustainability binding international commitments, along with principles and policies in digital strategies across all organisations gradually, harnessing their benefits and mitigating risks to the natural environment and human health.</i> <i>Target 2.2: Establish incentives to reduce environmental footprints and promote sobriety in digital infrastructures, systems, devices, hardware, and software, fostering circular, climate-neutral, and regenerative digital development across sectors.</i> <i>Target 2.3: Develop methodologies and standards to effectively assess the direct, indirect, and rebound environmental effects associated with digital solutions.</i> <i>Target 2.4: Create open data inventories to monitor the environmental impacts and enabling effects of digital infrastructures, solutions, and systems.</i> <i>Target 2.5: Establish mandatory due diligence and accountability mechanisms for digital investments, alongside an ESG reporting standard tailored to the digital sector to promote eco-social transformations and combat misleading green claims.</i> <i>Target 2.6: Raise awareness and promote behaviour change towards sustainable consumption and production practices in the digital sector, to combat harmful practices and greenwashing among all the stakeholders.</i> <i>Target 2.7: Prioritize incentives that enable sustainable "Green ICT" practices to mitigate the negative effects of digitalisation, promoting certified eco-design, responsible sourcing, and digital sobriety among all stakeholders, including civil society.</i> <i>Target 2.8: Foster the development of mindful digital applications to advance regenerative sustainability and the SDGs, focused on biodiversity, ecosystem protection, and human health, in the face of climate change.</i>
PILLAR	OBJECTIVE AND TARGETS
3. PEOPLE (Social and Just Transition Dimension)	OBJECTIVE 3: Achieve an Inclusive, Safe, and Human-Centred Digital Development by 2035, fostering Societal Resilience and Creating Positive Opportunities for All. <i>Target 3.1: Safeguard inclusivity, equity, intergenerational justice, and human rights in all digital initiatives and virtual worlds, ensuring a human-centred digital transformation that benefits everyone (including vulnerable communities, women, the elderly, children, and persons with disabilities).</i> <i>Target 3.2: Promote initiatives to empower, equip, and encourage public engagement in advancing human-centred and sustainable digital development by inspiring individuals and communities with a sense of purpose and ownership with social regeneration.</i> <i>Target 3.3: Promote sustainable and accessible digital solutions that address eco-social challenges and foster regenerative opportunities for all (e.g., e-education, e-health, access to participatory or cultural spaces, access to social welfare opportunities).</i> <i>Target 3.4: Create accessible, open, and safe virtual spaces for e-participation that promote digital humanism, shared values, inner transformation and growth, and social regeneration.</i> <i>Target 3.5: Raise awareness about digital human rights, digital well-being and the risks of disinformation and cybersecurity among all individuals while providing accessible tools for their protection, especially for vulnerable populations, women, and children.</i> <i>Target 3.6: Protect inclusiveness, diversity, and property rights in digital art and culture, and promote human creativity and values in the face of challenges posed by Generative AI and Virtual Worlds.</i>
4. PROSPERITY (Purposeful Economy Dimension)	OBJECTIVE 4: Drive a Sustainable, Equitable, Competitive, and Innovative Digital Economy by 2035, Cultivating Regenerative and Purposeful Prosperity Opportunities for All. <i>Target 4.1: Foster responsible innovation, knowledge transfer, and purposeful entrepreneurship to deliver new digital solutions with social and ecological values, and the participation of women.</i> <i>Target 4.2: Promote equitable conditions and incentives for fair and sustainable competition in the digital marketplace and value chains, mitigating digital colonialism and power concentration.</i> <i>Target 4.3: Encourage the responsible development, deployment, and adoption of sustainable and inclusive digital technologies and multichannel solutions that address social and ecological challenges.</i> <i>Target 4.4: Promote incentives and accessible multichannel mechanisms for inclusive and sustainable financing, ethical business models for digital platforms and Fintech, and fair trade and taxation.</i>

	<i>Target 4.5: Address the future of work by promoting decent formal jobs, skill enhancement, and opportunities for equitable digital development for all, with full participation of women.</i> <i>Target 4.6: Support the creation of smart and sustainable communities that foster sectoral digital transformation with positive impacts for regenerative development, empowering people and encouraging social responsibility.</i>
PILLAR	OBJECTIVE AND TARGETS
5. PEACE <i>(Mindful Governance Dimension)</i>	OBJECTIVE 5: Promote Ethical, Multilevel, Agile, and Inclusive Shared Governance by 2035, for an Inclusive and Regenerative Digital Transformation. <i>Target 5.1: Establish strong oversight, regulatory frameworks, and international standards to ensure ethical and regenerative governance, preservation of peace, sovereignty, democracy, and human rights in the digital sphere.</i> <i>Target 5.2: Establish an efficient global framework for digital ethics that strongly integrates regenerative sustainability and pluralism, fosters mindful leadership, digital agency, and shared digital responsibility among all stakeholders, while providing incentives for its universal implementation.</i> <i>Target 5.3: Strengthen cybersecurity and human rights protection through binding global commitments, supported by national and transnational regulation, and mechanisms, to promote digital technologies for peace and social cohesion, prevent disinformation and malicious uses, and reduce polarization.</i> <i>Target 5.4: Develop policies and mechanisms to ensure ethical, inclusive, and sustainable e-governance, with strong engagement from civil society and businesses, alongside accessible multichannel administration focused on the common good, social value and regeneration.</i> <i>Target 5.5: Ensure open access and proper stewardship of digital common goods to address eco-social challenges, promoting conviviality and community.</i> <i>Target 5.6: Enhance digital trust through reinforced, equitable accountability mechanisms incentivizing transparency and mindful participation.</i>
PILLAR	OBJECTIVE AND TARGETS
6. PARTNERSHIPS <i>(Cooperation Dimension)</i>	OBJECTIVE 6: Promote Multilevel Cooperation and Diplomacy for a Sustainable and Peaceful Digital Society by 2035, through Multi-Stakeholder and Pluriversal Communities and Partnerships. <i>Target 6.1: Establish a renewed multilateral structure and universally binding policy commitment to catalyse multilevel cooperation and diplomacy efforts in addressing geopolitical challenges and promoting a sustainable, regenerative, and peaceful digital society.</i> <i>Target 6.2: Forge multi-stakeholder, multilevel, interdisciplinary, and plural communities, and partnerships to drive scientific and technological cooperation, knowledge exchange, and co-creation of context-aware and sustainable solutions for a regenerative digital transformation on both global and local scales.</i> <i>Target 6.3: Strengthen multilateral cooperation programmes, sustainable financing, and capacity-building initiatives to address the challenges of sustainable and regenerative digital transformation, ensuring accessible, safe, and resilient digital spaces worldwide, and combating unsustainable practices and cyber threats.</i>

Although the initial aim was to develop a comprehensive set of OKRs and metrics, specifically focused on SRDT, to complement the suggested approach, due to the complexity of metric-setting in this realm, along with the time constraints of the doctoral programme, led this dissertation to finally focus on establishing the preliminary foundational framework for this matter. The development of more concrete OKRs and specific metrics would be addressed as future research direction, integrating stakeholder dialogue and contextual insights, which is beyond the scope of this dissertation.

Thus, this strategic framework lays the foundation for a holistic and more nuanced understanding of the intricate relationships between digital transformation, regenerative sustainability, and innovation, facilitating more informed and targeted decision-making on the potential interventions and research directions in this research field. The proposed strategic framework offers a multi-dimensional perspective that addresses the most critical aspects for aligning current sustainability, digital, and innovation agendas towards advancing a regenerative triple transition.

Furthermore, the suggested objectives align with global efforts to shape a more harmonious digital future that promotes social and ecological renewal, and long-term sustainability and resilience.

Overall, while the proposed strategic objective framework requires further development through close collaboration with global stakeholders, it already offers a valuable direction for enhancing current digital, innovation, and sustainable development agendas, by positioning SRDT as a central driver for the triple transition.

7.3. Theory of Change for Driving the Triple Transition

This section presents the proposed Theory of Change (ToC) to complement the Taxonomy framework, and the Strategic Objectives for SRDT, aiming to enable the transformation toward the regenerative triple transition vision advocated within this dissertation. It begins with a background overview of the relevance of transformational approaches and is followed by the specific ToC proposal to support the pathway toward a regenerative triple transition.

7.3.1. Introduction to Transformational Approaches

The “Theory of Change” (ToC) is a methodology designed to mobilize action and achieve desired transformations through structured planning and evaluation. It is widely used in development and policy planning to create impactful programmes and assess their outcomes.

Additionally, the ToC methodology supports designing, implementing, and evaluating interventions across sectors, thereby enhancing their effectiveness and accountability.

It provides a framework to understand the expected results, causal mechanisms, and contextual factors that may influence change. Usual components within the ToC process include the following: (i) identifying relevant gaps and pathways for improvement; (ii) categorising required resources and activities; (iii) delivering measurable short- and long-term outcomes; (iv) establishing mechanisms for sustained impact; and (v) monitoring and refining the ToC.

This iterative approach promotes learning, improves the effectiveness of the interventions, and assists in decision-making. Therefore, robust ToCs are crucial for evaluating complex initiatives by providing a foundation for understanding the expected results and facilitating theory-driven evaluations when direct comparisons are not feasible.

Regarding the literature in this domain, Mayne (2017) introduced several criteria for constructing robust ToCs, underscoring the “COM-B” model and the importance of understanding impact pathways and causal assumptions. Similarly, Oberlack et al. (2019) discussed the role of ToC in sustainability science, identifying key components such as diagnosing causes of unsustainability and exploring suitable pathways for achieving the intended outcomes. They noted relevant aspects such as the need for resources, and the relevance of stakeholders’ willingness and open-mindedness, for a broader adoption of a ToC.

According to Bommasani et al. (2023), proposing a structured framework for assessing nascent domains, such as their “Foundation Model Transparency Index”, can be inherently transformational and an indirect form of Theory of Change, when there is sufficient uptake. Thus, by defining objectives and metrics, assessment frameworks not only guide decision-making but also promote transparency and improvement, particularly in areas that may have been previously overlooked.

As Bommasani et al. (2023) asserted, the identification of objectives begins by underlining the key areas that demand transparency, such as upstream processes (e.g., resource inputs) and downstream impacts (e.g., societal, and environmental outcomes).

These aspects are often disregarded in the absence of clear frameworks guiding their assessment. The development of metrics is central to this process since they provide measurable benchmarks to track progress and unveil gaps.

Certainly, the application of structured frameworks is particularly relevant in policymaking to better understand relevant requirements for the creation or refinement of standards, regulations or mandates, guiding decisions on where to focus the interventions. Moreover, the process itself enables continuous evaluation and improvement since the iterative adjustments can be made in alignment with the evolving demands of the stakeholders and society.

Furthermore, novel trends in this area are focused on promoting transformational ToC approaches, in which expected outcomes are firstly applied to inspire the strategy and guide systemic transformation, starting from the impact and translating it into inputs, activities, and outputs. This innovative approach has been exemplified by the MOTION project (2022).

In this regard, one of the most well-known approaches is the “Transformational Change Theory,” which focuses on deep, systemic changes that alter fundamental structures and power dynamics within organizations or societies, to promote long-term sustainability goals. This approach addresses the root causes of the key issues for driving transformative shifts.

For instance, the Multi-Level Perspective (MLP) framework, used in the MOTION Project (2022), examined the landscape, regime, and niche levels to better understand socio-technical transitions as recommended by Feola (2014) and Termeer et al. (2016). Such a framework is relevant also for achieving the SDGs through experimentation, learning, and the creation of novel pathways for change.

Feola (2014) emphasized the need for radical shifts to achieve sustainability transformations, while Termeer et al. (2016) underscored the role of governance in managing dynamic processes, specifically in climate action.

Shields (2010) explored transformative leadership for social and educational change, and Strasser et al. (2019) discussed how grassroots social innovation can disrupt established systems. Overall, as argued by Miettinen et al. (2012), the Transformational Change Theory offers a multidisciplinary approach, driven by collective learning and experimentation to foster sustainable societal progress.

Additionally, there exist many other intriguing alternative methodologies to the Theory of Change (ToC), which offer less linear thinking and may be well-suited for addressing the complexity and interconnected nature of the interplay between sustainability, digital transformation, and innovation.

First, the “Complex Systems Approach” considers that systems are interconnected and can benefit from models like feedback loops and systems maps to manage complexity. This methodology provides a holistic and dynamic understanding of problems and potential solutions, by emphasizing the relationships and interactions that exist at multiple scales. In this regard, Leeuw (2019) underlined how complex and adaptive systems embrace instability and multi-scalar interactions and encouraged the use of diverse models for understanding change.

In addition, Design Thinking is a well-known methodology focused on creativity and use-centred innovation. It involved empathy throughout the different steps from the problem definition, ideation, prototyping, and testing to develop effective and collaborative solutions that better adapt to addressing challenges.

Another intriguing approach is Theory U, developed by Otto Scharmer, which encourages deep personal and collective transformation through “co-sensing,” “co-presencing,” and “co-creating.” It also enables the discovery of emerging futures.

Moreover, according to Detel (2001), the “Actor-Network Theory” (ANT) is another methodology which analyses the relationships between human and non-human actors to understand how social and technological realities are constructed and maintained. It provides a detailed understanding of the dynamics between diverse actors in complex systems.

Similarly, the “Outcome Mapping” methodology emphasizes behavioural change in actors, focusing on the processes rather than just on the outcomes. This approach maps the path to impact through milestones and continuous adaptations, facilitating ongoing improvements.

Other intriguing methodologies specifically addressing regeneration and resilience are the following. In this matter, the “Adaptive Systems Approach” is based on the complex adaptive systems theory and recognizes the permanent change and adaptability of social and ecological systems. Thus, this approach promotes resilience and responsiveness by allowing flexible adaptation to evolving conditions and new information.

Additionally, the “Causal Layered Analysis” (CLA), developed by Inayatullah (2008) and explored by Camrass (2023), offers a multi-layered approach to understanding complex issues. Notably, the CLA approach emphasizes co-evolution between human and natural systems, using regenerative future thinking to uncover root causes and foster continuous self-regeneration. Thus, this approach is highly relevant for this research context, but complex to apply in practice.

Lastly, the “Regenerative Thinking” and “Regenerative Design” approaches, explored by Svec et al. (2012), recognized that change in one area can trigger positive impacts across other systems. Indeed, the regenerative design applies “whole-systems” theories, along with interdisciplinary collaboration, and locally tailored efforts, to enhance social, environmental, and cultural capital, for ultimately achieving net-positive impacts.

Overall, these alternative methodologies represent inspiring instruments for addressing the complex dynamics of transformative change, with a focus on adaptability, interconnections, and systemic change, thereby enabling progress in addressing sustainability and regeneration goals.

7.3.2. Proposal of Theory of Change

Considering the perspective from Bommasani et al. (2023), an assessment process like the one proposed in this dissertation, mirrors the principles of a Theory of Change, for guiding the strategies towards achieving the desired outcomes. In this context, the proposed Taxonomy not only characterizes and categorises the available knowledge but also creates a commitment to change, by informing about relevant aspects that have been so far neglected. This approach considers the contributions not just evaluative, but also transformative since they help to promote a better-informed theory and more accountable implementation.

In emerging fields, like digital transformation, organisations and policymakers often neglect certain areas just because they have not been identified as critical. Therefore, by proposing a structured framework such as an index or a taxonomy, relevant aspects of the phenomena under study can be unveiled, thereby motivating the stakeholders to address gaps in their interventions.

Indeed, this is similar to how sustainable finance taxonomies, like the European Green Taxonomy, have shaped reporting practices. The proposal of a new assessment framework can act as a catalyst for transformation, supporting the stakeholders to recognize and prioritize relevant aspects previously ignored.

In the context of SRDT and the triple transition, offering a substantiated framework that emphasizes the importance of specific dimensions can help shape future policy and research agendas, ensuring that digital, innovation, and sustainability efforts are aligned.

Eventually, such frameworks can provide a foundation for informed decision-making, driving transformation by clarifying what needs to be addressed in the pursuit of sustainable and regenerative digital futures. Therefore, the contributions proposed in this dissertation can help to identify and address critical, yet often overlooked, areas within digital, innovation, and sustainability agendas.

Nevertheless, the stronger the ToC, the better prepared is to successfully guide transformative processes. Thus, considering that this dissertation proposes a Taxonomy, along with Strategic Objectives and a future Report Card Framework to advance and monitor SRDT within the context of the triple transition, a ToC can be a highly valuable instrument to facilitate the necessary transformations. Furthermore, recommendations from the expert elicitation process corroborated this perspective.

Building on these insights, a Theory of Change tailored for SRDT was developed to provide the structured framework that connects the proposed contributions, supporting the pathways and mechanisms needed to achieve the desired long-term vision of a regenerative triple transition.

After evaluating several methodologies, the ToC emerged as the most suitable framework for this dissertation, considering its focus, efficiency, practicability, and alignment with long-term sustainability goals.

While more advanced approaches are intriguing, they are complex to implement and the ToC is widely accepted in both the sustainability and the digital realm as evidenced in the literature (e.g. Digital Development Compass by UNDP, 2021; Digital Governance Readiness Assessment by the World Bank, 2022b). Nonetheless, exploring more advanced and transformative approaches, such as regenerative design, could be a promising future research direction for this research field.

Accordingly, the proposed ToC is outlined in Table 7.2, presenting the key components and pathways for driving change in the context of SRDT and the triple transition.

Table 7.2. Theory of Change for SRDT Towards the Regenerative Triple Transition
(Own elaboration)

GAP	INPUT/RESOURCES	ACTIVITIES	OUTPUT - deliverables	OUTCOME - measurables	IMPACT	MECHANISMS FOR CHANGE
Lack of understanding and awareness about digital impacts on sustainability	Scientific literature on digital and sustainability transformation measuring schemes and features	Analysis of literature, topic modelling, qualitative analysis, comparative analysis of frameworks	Taxonomy for a panoramic understanding of sustainable and regenerative DT features (UNDERSTANDING CONTEXT)	Enhanced Awareness of digital transformation impacts on sustainability and opportunities for regenerative sustainability	Promoting a sustainable and regenerative digital transformation , towards a triple transition	Novel Narratives of regenerative approaches and systemic integration
Lack of suitable measuring frameworks to assess sustainable digital transformation	Grey literature on digital and sustainable transformation frameworks	Expert elicitation: consultation and interviews with stakeholders	Report Card for enhancing monitoring and raising awareness about sustainable and regenerative DT (MONITORING PROGRESS)	Enhanced monitoring and assessment frameworks for sustainable DT	Engaging stakeholders in the pursuit of a triple transition towards a pluriversal view	Engagement with stakeholders
Lack of convergence and missing alignment amid sustainable and digital transformations	Expert elicitation	Analysis of strategies for enhancing DT and SD agendas	OKR for agile governance towards pursuing a triple transition and a future SDG18 (PROMOTING TRANSFORMATION)	Better integration and alignment of digital and sustainability agendas	Building capacities and alliances for a triple transition	Building capacities and raising awareness
Lack of awareness among policymakers, practitioners, and civil society	Stakeholders' views	Case studies	Development of case studies to identify barriers to implementation	Science-informed policies and frameworks with whole-of-society and whole-of-government approach	Alignment and systemic integration between digital and sustainability policies and frameworks	Building recommendations
Lack of practical tools for agile governance of sustainable DT and innovation	Relationships and networks	Formulation of the Taxonomy for SRDT	Development of recommendations based on expert input: strategies for enhancing the 2030 Agenda, Digital and Innovation Agendas	Enhanced integration of sustainable ambitions and regenerative approaches in digital and sustainability agendas	Alignment of stakeholders	Practical tools for easier adoption, monitoring for continuous dialogue and improvement
Lack of integration of regenerative approaches and eco-social transformations		Formulation of the Report Card Framework	Integration of eco-social transformations and RS in ST strategies	Better understanding between stakeholders, pluriversal approaches	Better accountability	Policy advocacy and alignment with SD agendas
Breaches amid disciplines and stakeholders from digital, innovation, and sustainability realms		Formulation of the strategic objectives for SRDT and the triple transition			Future directions for the Agenda 2030; cohesive strategies in digital and SD agendas	Novel models encouraging collaborative governance and knowledge exchange

7.4. Concluding Reflections on the Strategic Objectives and Theory of Change

This research direction aims to complement the proposed Taxonomy for SRDT, to facilitate and reinforce its practical implementation, by establishing a preliminary framework of Strategic Objectives to mobilize action toward SRDT and the triple transition. Furthermore, based on the recommendations from several experts during the elicitation process and the expert dialogue, defining concrete objectives and sound metrics was considered critical for translating theoretical aspirations and visions into actionable interventions.

The process of defining objectives related to sustainable development requires extensive dialogue with stakeholders, which is challenging to address within a doctoral programme. Additionally, it requires context-sensitive and transformational approaches capable of motivating real change. This dissertation has taken an important but preliminary step, in establishing the foundation of these objectives integrating the input from existing literature and experts across diverse disciplines.

However, these objectives should evolve into more specific OKRs, adapted to specific contexts. In this regard, balancing universal goals with local implementation is highly complex, as demonstrated by the 2030 Agenda itself, particularly in the digital domain where digital divides between diverse actors, and nations of the Global North and Global South remain significant. Thus, the foundational contribution from this Thesis paves the way for more elaborated approaches, as promising future research direction.

Considering the validation process, the experts showed a clear consensus and broadly agreed with the proposed framework, considering it coherent, integrative, and highly relevant. They suggested a few improvements, including more precise wording for some of the Preparedness Pillar targets, more visibility for women and vulnerable populations, stronger integration of environmental awareness among citizens, accessibility in digital solutions, and control of disinformation.

Moreover, they also recommended promoting shared common good, binding commitments, and emotional motivation for driving transformational efforts. Experts also emphasized the need for concrete metrics and localization, which may be complex for some targets, echoing the challenges of balancing global and local agendas, and different levels of digital development. Lastly, one expert underscored the importance of stakeholder management and transformative frameworks for driving change. Indeed, stakeholder dialogue and transformational change theories based on regenerative approaches emerge as promising areas for future research.

In conclusion, the proposed Strategic Objectives were considered coherent, consistent, and highly relevant. Following refinement based on expert advice, the framework was validated. Nevertheless, further research is needed to tailor the objectives to specific contexts and to develop metrics for effective monitoring and impact assessment of progress and suitability. Additionally, a Theory of Change has been proposed to facilitate the transformation process. More ambitious transformational processes focused on regenerative design are suggested as a future research direction in Chapter 10.

The next Chapter presents the discussion regarding the research results and contributions achieved in this dissertation. It also provides a discussion about potential strategic recommendations for enhancing the alignment and facilitating the co-evolution of the digital, innovation, and sustainable development agendas towards the vision of the regenerative triple transition.

8. Discussion

This section provides a profound discussion of the key findings achieved in the Thesis and their interpretation in the respective research contexts. Furthermore, it also proposes several strategic recommendations for co-evolving, enhancing, and synchronizing digital transformation, innovation, and regenerative sustainability agendas towards advancing the triple transition.

General Discussion about the Research Context

At a time when ecological, social, and governance global crises converge, the concept and frameworks for sustainability face unprecedented challenges. While the Sustainable Development Goals have provided a global blueprint and compass for this purpose, their implementation is fragmented, growth-centred, and limited in their ability to address contemporary complexities. Concurrently, the pervasive influence of digital transformation is reshaping nearly every aspect of society. Digital advancements present a dual nature, as their powerful potential to drive innovation and connectivity conflicts with the environmental and social impacts arising from the often undisciplined and unregulated solutions. This misalignment between digitalisation, innovation, and sustainability jeopardizes efforts to advance towards an inclusive and sustainable future.

This dissertation asserts that digital transformation holds the potential to advance regenerative sustainability and generate benefits for both nature and society, provided that its potential adverse effects are prevented and mitigated.

However, the first step in this journey is to recognize and address the varied risks that digital transformation poses to planetary health, human well-being, and global peace. These risks must be systematically identified, mitigated, and managed to ensure that digital progress aligns with the principles of equity, ethical responsibility and long-term resilience and sustainability.

The integration of regenerative principles into the digital sphere remains limited to date. The digital landscape is still swiftly evolving, largely unregulated and often disconnected from sustainability and human values. In line with D4S (2023), this dissertation emphasizes the need to enhance and synchronize digital transformation, innovation, and sustainability frameworks to address the pressing contemporary challenges. Notably, to fully capitalize on digital and sustainability opportunities, a comprehensive understanding and systematic categorization of the interplay between these fields, alongside a precise conceptualisation of Sustainable and Regenerative Digital Transformation (SRDT) are indispensable.

Furthermore, the research findings exposed the limited convergence of DT and sustainability agendas, surrounded by techno-utopian narratives, misleading green and ethical claims, and a lack of awareness regarding impacts and opportunities. This dissertation has unveiled the inadequacy of current assessment frameworks and metrics in accurately capturing the impacts of digital transformation on sustainability aspects. Consequently, this research advocates for a shift from fragmented and siloed thinking to a holistic and pluriversal approach, which integrates digital, environmental, and social perspectives to support genuine and meaningful sustainability efforts.

The emergence of the triple transition, encompassing the unfolding digital, environmental, and social metamorphoses, calls for a paradigm shift toward regeneration and long-term resilience. While sustainability and regeneration should be foundational values guiding all activities, findings from this research revealed a significant gap in acknowledging, understanding, and measuring progress toward a SRDT, with only limited advancements made thus far.

This gap underscores the pressing need for a more comprehensive conceptual approach, alongside practical tools to raise awareness, guide decision-making, and foster pluralistic dialogue. Such efforts are crucial to effectively navigate the broader impacts of this promising interplay and to further operationalise the regenerative triple transition.

In this research context, the pervasive force of digitalization emerges as a transformative influence, reshaping behaviours, organisational structures, consumption, and production patterns, and learning processes. Recently, the surge of enthusiasm surrounding Generative AI capabilities has reignited fears of dystopian futures, once consigned to the recesses of societal collective memory. While vibrant discussions in international forums and pioneering communities, such as ICT4S, CODES and DESC, offer valuable insights, a significant gap remains in both the literature and practical applications concerning the integration of digital transformation and innovation within the sustainable development agenda, and vice versa.

This persistent lack of awareness and accountability regarding the environmental and societal impacts of digitalization, combined with naïve narratives and techno-utopian ideals, has exacerbated these challenges. Also, the insufficient scientific understanding of "net impacts", including indirect and rebound effects driven by digital transformation, underscores the urgent need for a more robust and comprehensive assessment framework.

This dissertation asserts that achieving genuine regenerative sustainability hinges on a systemic and holistic alignment of digital, sustainability, and innovation agendas, alongside the ecosystems and actors they encompass. Central to this alignment is the seamless integration of digital, environmental, and social perspectives, coupled with the reinforcement of mindful governance and collaborative efforts. Such integration fosters the convergence of ideas, capacities, networks, and resources, driving transformative and meaningful change.

Furthermore, adopting a pluriverse approach, grounded in diversity, inclusivity, and active participation of multiple stakeholders across regions, is essential to ensure no one is left behind in the pursuit of digital and sustainability objectives. This vision demands robust collaboration across actors, disciplines, sectors, and geographies, creating a unified framework that supports equitable and regenerative progress.

The evolution of digital transformation and innovation has often been constrained by unrealistic notions of dematerialization and efficiency, fostering an illusion of sustainability. However, this vision is far from reality. Therefore, it is crucial to recognize the limitations of existing frameworks and narratives surrounding digital innovation, which may, whether inadvertently or intentionally, mask its true environmental and social impacts.

Digital initiatives are frequently labelled as "green" based solely on their potential to deliver efficiency gains while disregarding broader societal and ecological implications. This narrow perspective overlooks critical factors such as rebound effects and spillovers, underlining the pressing need for a more comprehensive approach to assessing the sustainability of digital transformation efforts. Such an approach must be panoramic across disciplines, sectors, value chains, and nations, to enable a truly systemic and inclusive evaluation of impacts.

In this context, the rise of the triple transition provides a crucial opportunity to establish regeneration and resilience as the new standard. This shift requires a balanced recognition of both the risks and opportunities that digital transformation presents for revitalizing social and ecological landscapes. This novel perspective reframes the transition, as an ongoing evolution toward a more regenerative, sustainable, and resilient society, one that not only mitigates threats but also leverages opportunities to thrive in an ever-evolving world. Hence, regenerative sustainability must become the core value guiding current and future generations.

However, bringing this vision to life requires bridging the existing gaps in understanding and evaluating sustainable digital transformation through the lens of regeneration and resilience.

In embarking on this inquiry, this research turned to the wealth of literature and existing frameworks to gather insights into the potential realization of a sustainable digital transformation with a regenerative lens. Yet, a key question arises: *What lessons can these frameworks teach society about the trajectory of the world's collective journey towards a sustainable digital future?*

While diverse experts from various fields have offered perspectives on how to steer digital transformation more consciously, their voices have not been universally selected. Meanwhile, a stark reality emerged, where regulation remains elusive, digital rights are barely endorsed, greenwashing permeates all sectors and actors, and environmental and social impacts of digitalisation are inadequately understood and ineffectively tackled. All these caveats are aggravating the ongoing planetary and social crises.

A central question then surfaces: *Can society gather the audacity to craft a sustainable digital transformation paradigm to address global challenges?*

As the world approaches the remaining 6 years to meet the 2030 Agenda's deadline, having already passed its halfway point, with a compass laden with poorly developed targets and indicators, other essential enquiries emerge: *Does society possess the necessary strategic goals, metrics, capacities, and means to succeed in this endeavour? Should sustainable and digital transformations be managed together or separately? Is it feasible to promote a triple transition that is digital, ecological, and socially just, or is it an unrealistic ideal or utopia?*

All these questions remain unanswered in the existing literature, sparking lively debates, without reaching a consensus or a clear research and policy pathway.

Therefore, a profound understanding of the hallmarks of sustainable and regenerative digital transformation (SRDT), along with clear and actionable directions to achieve them, is urgently needed to bridge extant gaps and illuminate a pathway that prioritizes the well-being and revitalization of both humanity and the Planet.

Amidst this debate, the UN's Pact for the Future was adopted on 22nd September 2024 in the UN's Summit of the Future.⁶, thereby reinforcing the global commitment to sustainable development, science and innovation, alongside providing a novel blueprint for digital cooperation and governance, the Global Digital Compact (UN, 2024b). In this context, a growing number of experts (Clark et al., 2022; Luers et al., 2020) advocated for a novel SDG dedicated specifically to fostering a sustainable digital transformation.

Despite the extensive global discussions shaping the 2030 Agenda, a cohesive goal addressing SRDT has yet to be proposed and agreed upon. Such an ambition represents a complex endeavor, considering the polarized geopolitical landscape, and the prevailing economic hurdles. This raises another critical question: *Does society truly require a new SDG 18 or a parallel Agenda for SRDT? or should the priority be to enhance and refine existing goals and metrics to better align with emerging trends and contemporary realities?*

Whether established as a new global pact, integrated as a novel SDG, or merged across existing goals, digital transformation for and with sustainability must be profoundly embedded within current and future sustainable development and innovation agendas.

⁶ UN's Summit of the Future 2024: The Pact for the Future includes a Global Digital Compact and a Declaration on Future Generations (A/RES/79/1), covering a broad range of themes, including a more transformative view of sustainable development, climate change, digital cooperation, human rights, gender, future generations, and global governance.

Hence, this research has been built on previous efforts to understand and delineate the contours of the unfolding sustainable and regenerative digital transformation, while providing a more nuanced, comprehensive, and inclusive conception of this intricate relationship. The ambition was to contribute to the ongoing efforts and catalyse further discussions to navigate the complexities of sustainable and digital transformation, with holistic, plural, and regenerative perspectives, thus far ignored in the literature.

To address the unveiled gaps in the literature, policy, and practice, this research engaged with experts to gain in-depth insights into the dynamic landscape of digital transformation and its repercussions on the sustainability arena. The focus was placed on identifying the key determinant factors of the interplay between digital transformation, innovation, and sustainability, and evaluating their potential implications with a forward-thinking approach. Furthermore, by integrating diverse views from different stakeholders, this research seeks to bridge the salient gaps between disciplines and across science, policy, and practice, fostering a more inclusive narrative and realistic categorization of risks and opportunities.

Therefore, this research has navigated the rapidly developing and multifaceted field of the triple transition, keeping pace with evolving trends, understanding their implications, and enabling the formulation of supporting frameworks and strategic directions to more effectively integrate digital, sustainability, and innovation agendas in advancing the triple transition.

Building on this general reflection, the next sections provide a more focused discussion of the findings, emphasizing the relevance and limitations of the contributions. Additionally, strategic recommendations are proposed to advance the alignment and co-evolution of the digital, innovation and sustainability agenda. The structure of the discussion is outlined below.

This dissertation aims to bridge existing gaps and misalignments between digital transformation, innovation, and sustainability while embedding novel perspectives rooted in regeneration and resilience within these critical domains. To achieve this, the research introduces the Taxonomy and Strategic Objectives for Sustainable and Regenerative Digital Transformation (SRDT), and the Sextuple Helix Innovation Model (6HIM). These frameworks are designed to address this critical interplay offering actionable pathways to align these agendas more effectively towards the advancement of the regenerative triple transition. Also, the dissertation provides directions to pave the way for future implementation.

First, this discussion explores the limitations that the SDGs, and sustainability in general, face concerning their ability to integrate digital and innovation challenges and opportunities. The evolution of sustainability frameworks also suggested integrating regenerative perspectives and effective measures for tackling these challenges systematically.

Subsequently, the interplay between digital transformation and sustainability is discussed, emphasizing that it brings both risks and opportunities. In this context, the proposed Taxonomy for SRDT and Strategic Objectives for its operationalisation are discussed as a guidance framework to structure existing knowledge and facilitate decision-making on the complex interplay between these domains.

Then, the needed evolution of innovation models, policies and ecosystems towards regenerative approaches adapted to the triple transition is discussed. This includes a reflection on the significance of the proposed 6HIM model, its connection with the Taxonomy for SRDT, and the opportunities and challenges of the unfolding evolution of digitalisation, innovation, and sustainability. This novel model advocates for a more inclusive and plural, systemic, and collaborative approach to encouraging regenerative innovation by facilitating the engagement of all actors and stakeholders in the creation of knowledge, multi-capital, and inclusive ecosystems to jointly address the complexity of contemporary challenges.

Finally, this dissertation underscores the critical need for synchronizing, reconciling, and co-evolving digital, innovation, and sustainability agendas to bridge gaps between these fields and support a systemic triple transition. It reflects on both the contributions presented and the practical challenges that may hinder their implementation, offering a comprehensive perspective on advancing this complex interplay.

Overall, this discussion calls for reflection and action to reorient digital transformation, innovation, and sustainability toward a regenerative and resilient future, where social, natural, technological, and governance systems co-exist in full harmony and balance.

The Imperative Evolution of Sustainability Towards Regeneration

While sustainability has been a cornerstone of global governance, today it confronts scepticism and controversies that undermine its ability to address contemporary complexities. As some experts argued, the misunderstanding and misuse of the sustainability notion, coupled with excessive emphasis on its normative dimensions at the expense of intrinsic motivation, have led to the erosion of its significance and the proliferation of green hypocrisy.

Even when the concept requires renovation to adapt to contemporary needs, this dissertation asserts that sustainability remains an imperative for humanity, offering structured and valuable approaches. The current trend of discrediting sustainability risks further promoting green hypocrisy by adopting an elastic and harmful interpretation that follows the path of least resistance.

Sustainability is an ancestral notion rooted in the connection between human and planetary needs. Regeneration, therefore, emerges as the paradigm shift following a "sustainability winter", representing a return to its original essence. Thus, the triple bottom line must evolve to embrace a more dynamic vision aligned with a regenerative triple transition.

Although some experts suggested that sustainability transformations are hindered by insufficient capacity, this dissertation posits that it also lies in deficient awareness and lack of collaboration among stakeholders, as no single actor can address the global challenges alone.

Regeneration offers hope for a renaissance of genuine sustainability efforts, driven by a collective recognition of its value, a reorientation of the existing frameworks to contemporary realities, and a concerted and transformative collaboration among all actors, including society and nature. Furthermore, this research advocates for positioning the triple transition as a central strategy to harmonize the interconnected digital, environmental, and social transitions, fostering an integrated approach to tackling global challenges.

The current disconnect between social and environmental disciplines must be addressed, with the recognition of their intrinsic interconnectedness. Recent global events such as the COVID-19 pandemic and the tragic impacts of climate change on human lives have evidenced that without a healthy environment, human well-being and progress are also compromised. Without nature, humanity cannot flourish, therefore, environmental concerns can no longer be relegated to the bottom of the agenda but must be considered as relevant as socioeconomic or technological aspects.

The worsening triple planetary crises and the breaching of planetary boundaries should serve as a wake-up call for society to reconsider its future trajectory, thereby shifting toward realistic ambitions that acknowledge the limitations of finite systems.

As long as socioeconomic priorities continue eclipsing environmental imperatives, and society keeps lacking a systemic vision, true progress in sustainability will remain elusive. Moreover, the degradation of natural and social systems has reached a point where mitigation is not sufficient anymore.

Therefore, natural, and societal systems require restoration and revitalization, which can only be achieved by regenerative sustainability perspectives.

Indeed, sustainability is hindered by numerous challenges, including inaction, delays, greenwashing, disinformation, resistance to change, and even denial of pressing issues such as climate change. While policy and regulation are often viewed as the fit-for-all solution, the critical role of civil society must not be overlooked.

Without the active participation of society, progress toward sustainability and regeneration will remain unreachable. Shared responsibility, collaboration among stakeholders, and inclusive approaches are essential, alongside awareness-raising and education to equip all stakeholders with the capacities needed for the unfolding triple transition.

This dissertation emphasizes that transformation must involve all voices and perspectives, including those of citizens, by adopting a multi-stakeholder and pluriversal approach to decision-making and implementation.

Opportunities and Challenges of the 2030 Agenda for Sustainable Development

The Sustainable Development Goals were conceived as a universal framework to tackle interconnected global challenges and represent a significant milestone towards a universal and goal-oriented agenda. However, they were the result of a political commitment instead of a science-based process, therefore, their design and implementation present severe shortcomings and barriers that hinder their transformative impact.

Despite the challenges, the SDG framework is an unprecedented compass for sustainable development, which has achieved global consensus and established a common language, creating momentum that must be maintained, improved, and gradually increased in ambition.

Following the pandemic, there has been a radical shift in SDG implementation policies, and socioeconomic factors have been prioritised at the expense of environmental ones. Consequently, environmental goals, akin to equality-based ones, face significant risks of not being achieved and, in many cases, are even regressing.

Since the signing of the Paris Agreement in 2016, global emissions have risen by 8%, and by 2024, global temperatures have surpassed 1.5°C above pre-industrial levels for the first time. Climate-related disasters have become increasingly evident, causing unprecedented human tragedies and significant economic damage in both developed and developing countries. Despite these alarming signs, the global community continues to neglect the urgent actions required to reverse environmental degradation and address the erosion of the social fabric.

The SDGs lack sufficient ambition in relevant areas of ecology and human rights since the economic discourse predominates at the expense of environmental protection and social equality. Furthermore, there is a notable absence of narratives that genuinely promote transformative change.

In Chapter 2, the challenges of the SDG framework were categorised into seven clusters that could benefit from digital advancements: the systemic nature and understanding of interlinkages; design shortcomings and imbalances; implementation and whole-of-governance hurdles; monitoring and evaluation difficulties; truncated adoption and uneven progress; unclear roles, responsibilities, and limited cooperation; and untapped innovation, technological development, and knowledge management.

These challenges underscored the pressing need for a cohesive, inclusive, and innovation-driven approach to align governance, innovation, digital transformation, and enhanced collaboration across all levels for achieving sustainable development.

One of the principal shortcomings of the SDGs lies in their fragmentation. Although they were designed to be interconnected, efforts to implement them have been approached in isolation, leading to a lack of synergies among economic, social, and environmental dimensions. The disconnection and lack of ambition in terms of ecological and social priorities are aggravated by the absence of clear responsibilities and binding commitments, leading to inconsistent and often superficial application of the Goals.

Furthermore, the inadequacy of metrics to capture the complexity of global challenges, and the lack of effective monitoring mechanisms pose a significant barrier. Indeed, critical ecological aspects and the protection of human rights are disregarded, and development indicators often prioritize outdated and narrow metrics such as GDP (Gross Domestic Product). This growth-focused approach in a world where most planetary and social boundaries have already been trespassed is not sustainable. Despite its original aspiration, the 2030 Agenda is unintentionally contributing to an unbalanced perspective that fails to reflect the priorities of genuine sustainability, and it also falls short in integrating the perspectives of resilience and regeneration, along with the opportunities provided by digital innovations.

The SDGs also face significant implementation issues, as they must adapt a global agenda to local contexts with varied levels of development. Establishing global goals that meet the needs of both the Global North and South is very complex. Also, metrics and data are insufficient, and the custodian agencies for these metrics are reluctant to update them with novel indicators and data sources, due to the required efforts.

Yet, most experts agree that harnessing the digital era is crucial to overcoming the limitations of current accountability and data systems. However, resistance to change persists, and indicators and metrics are often chosen for their ease of measurement rather than their representativeness. This approach leaves significant gaps, hindering the understanding of interlinkages and limiting effective policy guidance and decision-making. Such “cherry-picking” leads to harmful prioritization, frequently neglecting goals related to inequality and environmental sustainability.

Achieving preparedness to face this transformation also requires the development of more robust accountability frameworks, and assessment methodologies, along with pertinent metrics and quality data, that truly reflect the sustainability priorities across dimensions, and make it possible to evaluate progress, rather than what is politically convenient or easy to measure, as to date.

Undoubtedly, the greatest challenge in this area lies in studying the interrelationships among the SDGs. The existing literature remains highly fragmented, and all methodologies face inherent limitations, rendering them insufficient for evaluating causality or effectively informing policy and decision-making.

After examining the existing literature on interrelationships among SDGs, this dissertation concludes that quantitative approaches are significantly constrained by the global-local dilemma, alongside persistent data gaps and delays. Similarly, qualitative approaches are prone to biases, limiting their reliability. Therefore, integrating methods into hybrid methodologies is essential.

Nonetheless, this dissertation concluded that novel advances in causal machine learning and novel data sources, in combination with expert judgment for interpretation, offer promising opportunities to open new pathways for research and foster a deeper understanding of these complex interrelationships.

Furthermore, the agenda requires a genuine multi-stakeholder approach, yet responsibilities remain poorly defined, leading to issues such as "free riding" and the "tragedy of the commons". Existing alliances are insufficiently inclusive, often overlooking nature-related stakeholders and civil society as active participants. Partnerships tend to focus primarily on public-private collaborations for infrastructure and financing, both of which remain inadequate to meet the scale of the challenges.

Therefore, this dissertation concludes that fostering more inclusive multi-stakeholder cooperation through equitable alliances with clear and complementary roles and shared responsibility must become a cornerstone of sustainable development agendas. Frameworks such as those proposed in this research can serve as inspiration for creating pluriversal and genuinely inclusive stewardship to drive the triple transition effectively.

A critical challenge in implementing the SDG framework lies in the inherent weaknesses of global governance systems. The global cooperation architecture continues to erode, with the United Nations facing mounting criticism. Moreover, the governance system lacks equity, with most decisions remaining non-binding, further undermining its overall effectiveness. In both sustainable and digital development, new "shining" agendas seem to emerge every 10 to 15 years, often echoing their predecessors with minimal and cosmetic changes—well-intentioned rhetoric that falls short of delivering ambition, actionable mechanisms, or meaningful social engagement.

The benefits and costs of the three transitions - digital, environmental, and social - must be equitably distributed, to prevent dominant actors from perpetuating neo-colonialism and "winner-takes-all" narratives.

This dissertation concludes that a radical shift in the global governance architecture is essential. Effective structures must enable genuine, inclusive participation from all nations and actors while incorporating ambitious goals, robust accountability, and capacity-building mechanisms to drive truly sustainable progress.

Therefore, a more inclusive, responsible governance shared among all stakeholders, with both individual ownership and collective stewardship, is highly needed and should be fostered through binding commitments that ensure consistent compliance and effective implementation.

Another significant challenge is the disconnect between the SDGs and the promising advances in technology and innovation. While innovation and digitalization have emerged as particularly promising drivers for sustainable progress, they remain insufficiently integrated into the agenda, lacking both focus and visibility. The rapid and often chaotic evolution of digital transformation, along with its societal and environmental disruptions, has not been adequately considered in the global goals.

This gap perpetuates the misalignment between digitalisation and sustainability, hindering efforts to harness technological opportunities to address complex challenges and support ecological and social transitions. In many cases, emerging technologies are deployed in unregulated or unethical ways, exacerbating environmental and social risks and perpetuating "green hypocrisy."

This dissertation argues that a sustainable development agenda unable to deeply integrate two of the most relevant and transformative engines for eco-social change, digital transformation, and innovation, is destined to fail. Therefore, both digital transformation and innovation opportunities must be fully embedded within the sustainable development agenda, while ensuring they are utilized responsibly and sustainably.

Thus, evolving the existing sustainability agenda is imperative. Achieving this requires moving beyond traditional perspectives to embrace a regenerative narrative. This shift requires adopting a systemic approach that prioritizes the restoration and balance of natural, governance, and social ecosystems while fostering resilience.

Regeneration not only seeks to reduce harm but also to create the conditions to allow all societal systems and nature to co-exist and thrive in harmony. This approach, aligned with the triple transition, recognizes that current sustainability challenges are closely interdependent, thus they require holistic and systemic solutions. Indeed, restoring and revitalizing all societal systems, including governance, is essential to rebuilding trust in institutions and policies, fostering peaceful societies amid geopolitical tensions, and restoring integrity and faith in democracy.

Therefore, this dissertation emphasizes that traditional frameworks, including the SDGs, must evolve to embed the regenerative and resilience perspectives, alongside responsibly leveraging innovation and digital transformation as drivers of change. This vision demands the concerted effort and participation of all actors, including civil society, towards a regenerative triple transition for long-term sustainability, equity, and resilience.

Overall, the notion of sustainability and the sustainable development agenda must evolve to respond to the challenges of the 21st century. This evolution requires overcoming the current limitations of the concept, improving the design and implementation of the 2030 Agenda, and adopting a regenerative approach that addresses the complexity of digital, ecological, and social transitions in an integrated and transformative way that ensures sustainability, equity, and resilience of both natural and societal systems.

With this approach, it will be possible to leverage powerful drivers of transformation, such as innovation, digitalisation, education, and mindful governance, in a truly sustainable manner.

In conclusion, this dissertation emphasizes the pressing need to evolve the 2030 Agenda into a truly regenerative, inclusive, and systemic agenda, which contributes to the triple transition. To achieve this ambition, multiple gaps need to be bridged in governance, cooperation and collaboration among stakeholders, accountability mechanisms, inclusive participation, and responsible and sustainable use of digital and innovation advancements. This vision demands collective action, capacity-building, and commitment to co-create a harmonious world for present and future generations.

Opportunities and Challenges of the Interplay between Digital and Sustainability Transformations

Digital transformation has become a foundation of contemporary societies, and an engine for innovation, impacting all aspects of the economy and human life. However, its intersection with sustainability is marked by tensions and contradictions. While digitalisation holds the potential to facilitate sustainable transitions, it also poses significant risks to social, ecological and governance objectives, intensifying and perpetuating divides and inequalities. Akin to any other technological advancement, devoid of responsible reflection and oversight of its inherent risks, digital transformation becomes a runaway force advancing rapidly and unpredictably.

Indeed, digitalisation has begun as a collection of enabling technologies designed to improve efficiency and optimize processes, but it has evolved into a disruptive force, for better and for worse, that permeates every domain of society. The rapid and transformative spread of digitalization has outpaced governance systems, leaving them unable to effectively address its wide-ranging impacts, like the natural ecosystems are unable to cope with the anthropogenic climate crisis.

The integration of sustainability into the digital domain encompasses two inherently interrelated dimensions. The first is ensuring the sustainability of digital transformation itself, which involves assessing and mitigating the societal and environmental impacts of digital paradigms on social communities and natural ecosystems. The second is leveraging digital transformation as a strategic tool to drive sustainability.

Digital solutions have the potential to significantly advance most of the SDGs, as examined in Chapters 2 and 3. They have revolutionized education and access to information, making it accessible to anyone with Internet access. These technologies have driven progress in resource efficiency and sustainable agriculture through innovations such as smart grids, smart water, and smart agriculture systems. Additionally, digital technologies have been enabling groundbreaking advances in medical research, sustainable materials discovery, climate modelling, and biodiversity protection. Furthermore, they have enabled ubiquitous communication and streamlined e-administration processes.

Modern life can no longer be conceived without digital technologies, and during moments of disruption, essential systems such as banking, energy, transport, and healthcare become entirely dependent on them. However, in the wrong hands, digital technologies become a weapon capable of undermining social stability, eroding democracy, and peace, and damaging environmental well-being.

As literature and expert dialogue unveiled, this critical nexus between digital transformation and sustainability presents a dual nature, with challenges and opportunities, for addressing the complexities of the 21st century. Therefore, it must be deeply understood and mindfully governed with the utmost responsibility. Also, the interplay between digital transformation and sustainability confronts several fallacies and dilemmas.

First, prevailing naïve narratives about digital transformation perpetuate the fallacies of dematerialization, efficiency, technological neutrality, automatic progress, free services, and green growth. The fallacy of dematerialization promotes the false idea that digital solutions are intrinsically sustainable. Instead, they are inherently tied to infrastructures and systems with a significant environmental footprint. Behind the virtual applications on the cloud there exist large data centres that consume energy on a scale comparable to that of entire nations. The semiconductor industry, a cornerstone of ICTs, produces massive amounts of waste, much of which is illegally dumped in landfills in the Global South. In these regions, vulnerable groups, including children and women, often work in unsafe and unsanitary conditions, further exacerbating social and environmental injustices.

Moreover, efficiency often leads to rebound effects, increasing overall consumption and subsequent impacts, rather than reducing them. Also, technology is not neutral, as it is developed within specific socio-political contexts. Digitalisation does not inherently drive progress, and digital services are never truly free as they depend on the commercial exploitation of users' data.

Considering the so-called "Greentech," digitalisation cannot become "green" simply by installing photovoltaic panels in data centres or by promoting second-hand platforms. Indeed, the growing energy demand for data centres cannot be supplied with renewable energy alone, and second-hand platforms also induce rebound effects.

To address these systemic problems, an in-depth critical re-evaluation of digitalisation and its sustainability claims and misconceptions is needed, along with regulation, education, awareness-raising, and behaviour change. This prevailing lack of awareness regarding the adverse environmental and social impacts of digitalisation is driving uncontrolled impacts difficult to manage, contributing to rising carbon emissions, the mining of critical materials, competition with green technology sectors essential for the energy transition, and human rights violations within both physical supply chains and the virtual flow of data and information.

Another significant dilemma concerns the “regulation versus competitiveness and innovation” debate. Traditionally, digitalisation has been treated as a strategic sector, and thus, few countries have dared to regulate it. Only the European Union has adopted a cross-national AI standard, which has even faced criticism for its lack of ambition and insufficient consideration of environmental aspects. Akin any technology, its impact depends on both responsible use and regulation, and, currently, regulation is nearly non-existent.

Moreover, another dilemma lies in reconciling the needs of the Global North and the Global South, with two different speeds of digital and sustainable development, and cultural disparities.

In the most developed and industrialized regions, digitalisation raises concerns about its impact on mental health, the disinformation that accelerates social and political polarization and erodes democracy and peace, and the implications for climate change and international policies. Additionally, there are pressing issues regarding the massive consumption induced by e-commerce, the management of growing electronic waste, the scarcity of water and renewable energy to meet the demand from data centres, the automation of jobs, the gentrification of infrastructures, and the disruption caused by unethical platforms.

Instead, in the developing world, the challenges are different. As with climate change, it is the less-developed countries that bear the brunt of mining, labour exploitation under abusive conditions, alongside human rights abuses. They also face educational gaps, limited access to infrastructure, neocolonialism, and illegal waste storage. Many of these nations also endure oppressive regimes, censorship, and violations of freedom of expression. The inequalities in the physical world have thus carried over into the virtual realm.

In the developing world, the challenges are different. As with climate change, less-developed countries disproportionately bear the burden of mining raw materials, labour exploitation under abusive conditions, and human rights violations. They also struggle with a lack of digital literacy, limited access to infrastructure, neocolonial practices, and the illegal dumping of waste. Additionally, many of these nations face oppressive regimes, censorship of the Internet, and infringements on freedom of expression. As a result, the inequalities present in the physical world have seamlessly extended into the virtual realm.

Notably, the environmental and social issues associated with digitalisation are significant, and the worst part is that they remain largely unaddressed, and poorly regulated, and are growing at an alarming rate. All digital technologies have a dual nature, with both positive and negative impacts, as well as their peculiarities, as examined in Chapter 3. However, the risks associated with some of them are more likely and with more severe effects, for instance, AI and future quantum technologies.

The literature has proven that the digital sector is a highly polluting industry that severely impacts natural resources and ecosystems, equity, peace, and human rights. Furthermore, the digital sector is a voracious industry characterized by a rapid pace of obsolescence.

However, thus far, governance and policy have been somewhat naive, centred around the interests of industry, mainly a small group of multinational corporations that hold the technology property and apply influence over governments. These same companies are the dominant voices in standardization committees and regulatory advisory boards, including within the EU and the UN.

Their narrow interests have undeniably influenced policy, while their publications (e.g., GESI, GSMA) continue to emphasize the benefits of digitalisation while downplaying its adverse impacts, like the Oil and Gas industry has done in the past and continues to do.

This “climate-digitalisation” analogy holds here as well. Scientifically, the environmental impacts of digitalisation remain largely unexplored. Research has been mainly focused on carbon emissions (scope 1 and 2) from software and data centres. Life Cycle Assessments (LCAs) are scarce for most digital technologies, infrastructures, and systems.

Additionally, there are no comprehensive standards or metrics to measure all relevant impacts, leaving the focus solely on carbon issues. Despite the “green pledges” of large tech companies, it is difficult to imagine meeting their demand for energy, water, and critical materials with existing renewable resources, which also increases the competition for resources needed in other sectors.

The link between digital and energy is also clear: without clean energy, the digital transition cannot be sustainable. However, the energy transition itself faces technical, financial, and societal challenges.

Similarly, the growing water demand and pollution resulting from digital infrastructures and manufacturing processes, are increasingly concerning, especially in a world already facing water scarcity problems, which are expected to worsen under the influence of climate change.

In addition to the immediate and significant direct impacts that remain unaddressed, indirect impacts are equally problematic and even more difficult to study due to their uncertain system boundaries and the lack of methodologies and empirical measures. As a result, the full potential of digitalisation to facilitate more sustainable processes without trade-offs remains unknown. This aligns with the experts’ perspectives.

Digitalisation is amplifying the impacts of overconsumption. The literature demonstrates that last-mile e-commerce drives higher consumption levels, the proliferation of multi-device usage and planned obsolescence accelerates resource depletion, and emerging digital habits foster excessive consumption and unhealthy lifestyles.

The indirect impacts also affect social issues. On a societal level, digitalisation has brought outstanding opportunities but also disruptive risks that threaten sovereignty, human rights, personal identity, and mental health. The OECD’s latest report (OECD, 2024) focuses on the mental and social issues caused by the new digital age, with unknown consequences for the next generation. Disinformation and misinformation, induce severe social polarization and are being used as a weapon to destabilize democracies.

Digitalisation is increasingly becoming a driver of inequality and exclusion. Vulnerable groups, the elderly, women and girls, people with disabilities, and those with low income or living in rural areas without access to electricity or the Internet, are often excluded from essential services like banking, e-commerce, telemedicine, and education. This disparity was particularly evident during the pandemic and in rural regions. For this reason, digitalisation should not be imposed, there must be multichannel options and the freedom to remain offline must be respected, ensuring that individuals can live, work, and learn in ways that align with their preferences and circumstances.

Algorithms are also amplifying inequality, reducing diversity, and increasing discrimination and unique thinking. In many countries, they are being used as tools for manipulating or controlling the population, as well as for human rights violations, for instance by mass surveillance. They have become powerful weapons in cyber-terrorism. In this context, most experts are calling on the public sector for control and regulation. However, while the Internet and global digital chains know no borders, regulation remains predominantly at a national level. Countries that implement regulations (e.g., EU members) risk losing competitive advantages to those that permit unrestricted digitalisation, often prioritizing profit over the common good.

As emphasized by experts and the literature, every time a potential social risk of digitalization is raised, the first proposed solution is to increase public control and regulation. However, companies often resist and fail to comply with regulations. Particularly large technological companies exploit the borderless nature of digitalisation to circumvent rules.

Moreover, as some experts have pointed out, not everything can be resolved solely through public regulation. Shared responsibility is essential, both in consumer decisions and in the democratic choices of leadership and governments. Each stakeholder must assume their role, take responsibility, and contribute within their means to a solution that balances the common good with particular interests.

Furthermore, the absence of a taxonomy for shedding light on the intricate interplay between digital and sustainability realms, the lack of suitable objectives and accountability frameworks, together with the prevalence of naïve narratives, hinder the alignment and transformative opportunities. The interdependencies and implications of this interplay demand a comprehensive and integrated approach.

Therefore, it can be said that sustainability is the missing piece in the digital debate. With the future unfolding, harmful practices such as greenwashing and ethics washing pose significant risks to humanity. It becomes imperative to establish a robust and comprehensive framework to bridge current gaps and guide digital transformation through a regenerative and sustainability perspective.

This dissertation advocates for cultivating narratives to reorient digitalisation towards a sustainable and degrowth-oriented path with pluriversal views, and a regenerative perspective. This relies on collaborative and concerted efforts from all stakeholders, linking knowledge to action.

Challenging outdated and narrow viewpoints, this research emphasizes that digital innovation, when framed through social and environmental lenses, can act as a transformative force for the regenerative triple transition. Therefore, this approach envisions sustainability, not as a mere destination but as an ongoing responsive journey, akin to the continuous evolution of natural ecosystems.

The desired regenerative triple transition depends on achieving restorative, stakeholder-centred, multidisciplinary, and holistic approaches that foster harmony among societal systems and nature, moving beyond narrow frameworks like the SDGs. However, regenerative approaches remain underexplored in the digital domain.

Current efforts are often siloed and fail to scale or achieve significant impact, underlining the need for innovative strategies that leverage digital solutions for regenerative sustainability. This dissertation argues that regeneration should align with a triple transition perspective, addressing both ecological and human needs while supporting a theory of change. The contributions proposed in this research aim to serve as tools for guiding the journey toward a regenerative triple transition.

Nevertheless, this vision faces multiple challenges and barriers that need to be addressed by a combination of measures and strategies.

One of the most prominent challenges of the interplay between digital transformation and sustainability is the lack of awareness and disconnect between the two realms, particularly their respective policy agendas. Indeed, naïve narratives and misconceptions, such as the dematerialization of digital solutions, and technocentric policies that prioritize economic and technological aspects over social and ecological facets, have been concealing the significant adverse impacts that digitalisation can pose, as described in detail in Chapter 3.

Unfortunately, research and policy have not kept pace with these harmful trends, leaving their adverse consequences insufficiently addressed.

In this matter, another critical challenge is the prevalence of "greenwashing" and "ethics washing" practices and misleading rhetorics. Many companies, and even governments, portray digital transformation as a magical wand enhancing and solving any challenge without significant harm. This phenomenon, combined with "ethics washing" practices, particularly in AI, creates a false perception of sustainable progress while sustainability impacts persist or even worsen.

This dissertation argues that both greenwashing and fake news share a common foundation: disinformation. A troubling paradox is evident, as governments that should champion sustainable practices often portray digitalisation as a panacea, downplaying its risks and allowing large corporations to dictate the terms of this asymmetrical dynamic. In response, this research emphasizes the importance of the concept of double dynamic materiality in the digital realm to enhance accountability and transparency.

The dissertation further contends that integrating regenerative approaches can significantly enhance performance and ambition. Accountability mechanisms such as robust certification schemes, supported by agile regulations, targeted incentives, and education are crucial for driving progress, improving consumer information, and fostering meaningful engagement with sustainable digital practices.

Additionally, the lack of regulatory frameworks and the unsuitability of existing methodologies and metrics to evaluate sustainability in the digital context hinder meaningful alignment of both realms. Notably, current policies tend to address technological, socioeconomic, and governance-related digital risks while ignoring sustainability and their critical interdependencies. This leads to fragmented governance that inadequately reflects reality and fails to fully capitalize on the synergies between digitalisation and sustainability. Consequently, digital risks remain insufficiently controlled, adverse impacts are not satisfactorily mitigated, and opportunities for sustainability are missed.

Therefore, agile, and flexible governance, coupled with mindful leadership, is critical for navigating this transition. This requires a deep understanding of the challenges and practical tools to operationalize the vision. Encouraging sustainable digital practices through incentives and ethical nudges is also relevant. Integrating agile methodologies and ambidexterity with sustainability principles further enhances adaptability to evolving environmental and societal demands.

Despite these challenges, digital transformation also presents outstanding opportunities to accelerate regenerative sustainability across social and environmental dimensions and contribute to tackling the SDG challenges, as described in Chapter 3 and Chapter 5.

Certainly, digital paradigms hold the potential to optimize resource efficiency, augment analytical capacities, unlock novel data sources, empower communities, and facilitate seamless communication. These transformative capacities can drive sustainability by addressing societal and environmental challenges while reducing their impacts through mitigation measures such as Green ICT.

In the social sphere, digital advancements foster connectivity, accessibility, and civic participation, creating spaces for democratic decision-making. Furthermore, digital solutions provide access to education, telemedicine, and emergency services, while grassroots innovations empower communities to address local challenges in Smart Communities. Digital tools also facilitate the monitoring of poverty, health, and food security, support people with disabilities, and enable accessible microfinance systems.

In the environmental sphere, digital solutions enhance resource efficiency, transparency, and accountability across value chains in agriculture, water, mobility, urban infrastructures, manufacturing, and energy management. They also support ecosystem and biodiversity monitoring, and climate modelling. Also, innovations in bioinformatics contribute to sustainable bioprocesses.

Concerning governance, digital platforms for electronic participation and government provide more transparency, and accessibility and allow participation, thereby facilitating democratic and inclusive decision-making. Open platforms enable access to information and solutions to improve all societal processes.

Therefore, digital transformation presents both outstanding opportunities for regenerative sustainability and significant risks, requiring a deep understanding and robust governance to ensure a net positive impact, which remains uncertain to date.

The proposal of Taxonomy for Sustainable and Regenerative Digital Transformation (SRDT) aims to address these challenges by providing a comprehensive and systemic categorization of the key determinant factors, both risks and opportunities, within this interplay. Recognizing the lack of awareness and a systemic perspective on the impacts of digitalization across sustainability dimensions, the Taxonomy for SRDT organizes and structures existing knowledge to categorise the key factors necessary to responsibly and sustainably harness the transformative potential of digitalization.

Furthermore, it is aligned with the terminology of the 2030 Agenda and Digital Agenda, while providing the flexibility to adapt to emerging trends. The Taxonomy is founded on six pillars, representing all the key dimensions of the triple transition, alongside cross-cutting dimensions such as peace (governance) and partnerships (cooperation).

Additionally, the sixth pillar, focused on preparedness, represents a multifaceted representation of the readiness, resilience, and response to crises perspectives for preparing society towards the regenerative triple transition and unfolding global challenges.

The proposed pillar of preparedness is highly relevant, as it consolidates, organizes, and makes visible critical factors for success in both sustainability and digital transformation, such as meaningful connectivity, resilient and sustainable infrastructures, quality data, and capacities. This pillar also enables coordination and acts as a bridge with other closely related dimensions. Indeed, the six pillars of the Taxonomy are strongly intertwined, much like the helices of a DNA strand.

Preparedness also means cultivating a culture of transformational leadership and responsibility, understanding risks and opportunities, and providing an enabling environment with supportive institutions, and robust crisis management systems and capacities. If individuals and organizations are prepared for change, it will be easier to agree on common, ambitious goals and reach further with the collective effort, but if not, even the most comprehensive regulations and infrastructures will be of little use in the face of a disruptive event. Therefore, creating a culture of transformation, preparation, and resilience, paves the way for overcoming resistance to change, siloed mindsets, divides, and mistrust.

Thus, the Taxonomy provides a comprehensive guide to governance and decision-making in aligning digital transformation with regenerative sustainability goals. A key aspect is its ability to bridge the gap between sustainability and digitalisation by promoting a holistic and integrated approach, which gives more visibility to ecological and social values, contemplates both the risks and the opportunities, and embeds resilience, regeneration, and response to crises perspectives into the preparedness dimension.

This approach could equip and empower stakeholders to make better decisions. Certainly, having the right information and capacities facilitates more effective governance. Nevertheless, the taxonomy must be tailored to each context. In each case, certain issues will be more relevant than others. Yet, as with the 2030 Agenda, ensuring a systemic approach is critical.

The implementation can be facilitated by more streamlined frameworks, such as a Report Card Framework, tailored to specific contexts, balancing transitional and gradual approaches, without losing ambition.

The experience from previous programmes advice to go beyond promoting disconnected projects in underrated calls, without examination of their joint societal impact. Therefore, programmes must be based on mission-oriented schemes, creating meaningful impact. Moreover, scaling is essential to move beyond the current state of scattered small projects that lack the integration needed to drive meaningful progress.

Furthermore, to unlock and scale the transformative potential of digital transformation in the context of sustainability, it is crucial to address the existing challenges through inclusive policies, binding regulatory and global commitments, robust metrics, multilevel cooperation, education, and tailored awareness-raising incentives.

The integration of digital transformation and sustainability must serve to catalyse the transition toward a regenerative mindset. However, this process is complex as it requires overcoming structural and cultural barriers, resistance to change and disconnection among key stakeholders. It also demands capacity-building, not only in technical areas but also in sustainability and resilience, along with ownership and shared responsibility in pursuing the common good.

To achieve this vision, several aspects must be strengthened: accountability mechanisms, mindful governance, collaboration among all stakeholders and regions, as well as education in digital literacy, sustainability, resilience, and core values.

In conclusion, the interplay between digital transformation and sustainability represents a strategic opportunity to redefine global development with regeneration and resilience perspectives. Nevertheless, it requires frameworks, like the proposed Taxonomy and Strategic Objectives for SRDT, to guide decision-making and research toward addressing the current caveats and promote a regenerative future, where digitalisation becomes an ally of sustainability rather than a problem.

Opportunities and Challenges of Regenerative Innovation

Innovation has historically been a key driver of social and economic progress, yet traditional models reveal clear limitations in addressing the complexity of contemporary challenges. Indeed, technocentric and growth-oriented approaches have dominated innovation systems, frequently overlooking critical interdependencies among social, environmental, and economic dimensions.

Innovation remains anchored in the past, isolated in ivory towers, lacking awareness, and marked by sterile disciplinary divides. Therefore, it must be redirected toward regenerative and sustainable innovation. Despite the rise of novel trends focused on collaborative, frugal, and socially and ecologically driven innovation, often led by grassroots and social actors, the current innovation landscape still relegates sustainability, pluralism, and the role of civil society to secondary positions, thereby hindering its potential for driving sustainability.

In this context, reimagining innovation is an imperative. This dissertation advocates for shifting from conventional and narrow models to regenerative approaches prioritizing long-term sustainability, the plurality of views, collaboration and co-opetition among all stakeholders, and systemic resilience, envisioning innovation as a driving force for the triple transition.

Concerning the evolution of the n-helix innovation models, predominant approaches, such as the Triple Innovation Helix encompassing university, industry, and government, have proven insufficient to address complex sustainability challenges in the digital era. In line with many experts, this dissertation asserts that traditional helix models have become obsolete since they exclude the priorities of society and natural ecosystems, marginalise the voices and knowledge of non-traditional actors, and do not integrate the novel challenges arising from digital transformation.

Despite the close interconnection between innovation and digital transformation, much of their synergic potential remains untapped, while aggravating social and environmental adverse impacts and divides. This narrow approach limits the ability of both innovation and digitalisation to deliver genuinely inclusive and sustainable solutions to pressing issues such as climate change and social cohesion.

Another significant issue is the fragmented and linear approach to innovation, which often lacks a systemic perspective. This approach perpetuates disciplinary silos, disconnecting social and environmental dimensions from technological ones. Additionally, the resistance to change, misconceptions, and reliance on traditional power structures hamper the adoption of more systemic, inclusive, and collaborative approaches.

Innovation keeps overly focused on short-term economic interests, and frequently outweighs long-term sustainability solutions, reinforcing growth-oriented models instead of regenerative approaches. Indeed, sustainability is often incorporated late and superficially in the technology development cycle when it is already too late to spark transformational effects.

Therefore, sustainability criteria and collaboration among all stakeholders, including nature-related stakeholders such as NGOs and civil society, should be considered alongside technical ones from the outset of the design stage.

In this landscape, regenerative innovation emerges as a transformative alternative that transcends traditional models. This approach recognizes the interdependence of social, ecological, governance, and economic systems, and aims to deliver solutions that restore and regenerate these structures in harmony.

This dissertation proposes the Sextuple Helix Innovation Model (6HIM) as a necessary evolution to address the challenges and opportunities of the triple transition while embedding a regenerative perspective and collaboration among actors as fundamental values in sustainability, digitalisation, and innovation. The six helices, or societal subsystems, which constitute the 6HIM model are aligned with the six pillars of the Taxonomy. Each subsystem must independently progress toward regenerative sustainability while simultaneously co-evolving through its relationships with the others.

Indeed, the 6HIM model comprises six deeply interconnected social subsystems, each representing essential social structures for the digital, social, and ecological transition: whole-of-government (public sector); whole-of-society (civil society); digital sphere (digital stakeholders); ecosphere (environmental stakeholder on behalf of nature); conscious economy (market stakeholders); open academia (science, education, and cooperation for society stakeholders).

The model is complemented by enabling ecosystems for its implementation, the Regenerative Digital Innovation Hubs (RegenDIHs), which embrace the 6HIM and act as transition brokers for catalysing systemic transformation and dynamization. These ecosystems could be existing initiatives, conveniently oriented, like the EDIHs, smart communities, or novel ones, and also serve as “sandboxes” to test and scale SRDT initiatives.

Furthermore, the 6HIM and its enabling ecosystems (RegenDIHs) are strongly aligned with the Taxonomy for SRDT, creating a cohesive environment for advancing the integration of innovation, digitalisation, and sustainability in support of the triple transition. Both frameworks share a common vision and principles, while their distinctive characteristics and purposes enable them to complement and reinforce one another, fostering a synergistic environment for transformative progress.

This model expands the traditional innovation framework (government, industry, academia) to include key actors representing the values and priorities of civil society, the environment, and the digital sphere, alongside transition brokers as intermediaries who dynamize this ecosystem of systems.

This comprehensive approach allows a virtuous circle for promoting knowledge creation and diffusion, with multidisciplinary and inclusive collaboration perspectives.

Analogous to the Taxonomy, the 6HIM also embodies the three transitions (digital, ecological, and social), along with the multi-capital framework, and diverse modes of knowledge. Together this ecosystem of systems facilitates new connections and alliances between actors and sectors, enabling the emergence of novel knowledge, catalysing systemic change, and supporting the scaling of regenerative solutions.

Regenerative innovation offers a wide range of opportunities to address sustainability and digital transformation challenges. This is exemplified in the Smart and Sustainable Communities, which illustrate the potential of this approach to foster regenerative digital and innovative development while encouraging societal participation and empowerment. These communities have shown their ability to empower organisations with a common cause, making them more active agents in their development and global change.

Digitalisation is increasingly applied in regenerative agriculture through “Agritech” initiatives (O'Donoghue et al., 2024). In urban settings, digital solutions support the implementation of nature-based strategies to revitalize the urban environment. Innovations, such as fungal computing (Adamatzky, 2018), illustrate the convergence of regenerative sustainability and digital innovation, opening new frontiers in this interdisciplinary field.

Moreover, the regenerative perspective facilitates alternative approaches such as frugal, catalytic, and grassroots innovation. These approaches, when combined with ecological perspectives, can prioritize affordable, inclusive, and sustainable solutions tailored to local contexts and realities, challenging traditional growth paradigms. Additionally, they promote the co-creation of solutions and reinforce local capacities and networks, becoming levers for driving systemic eco-social transformations.

Nevertheless, the 6HIM remains a conceptual approach, whose success relies on the acceptability of innovation players, along with the evolution of current digital innovation initiatives and ecosystems into accelerators and enablers of transformative change. This requires a shift towards a new development model rooted in the principles of the triple transition, collaboration, and regeneration. Translating this vision into practice could be challenging, as some experts expressed.

Certainly, implementing novel approaches that defy the status quo and aim to transform conventional structures is always highly challenging, even within the innovation realm, naturally transformative. Sometimes, simple approaches are necessary for implementation. However, if the initial approach is overly simplified and lacks ambition, then it will remain empty rhetoric, a waste of capacities and resources.

The most sceptical experts argued that collaboration among stakeholders is unlikely to succeed, given that it often fails even in simpler scenarios. However, this dissertation contends that if humanity resigns itself to avoiding collaboration and systemic approaches, it will remain trapped in the same degenerative spiral that characterized the industrial era. True social transformations are not achieved through incremental changes but through transformative shifts, where disruption becomes an opportunity for progress. The pandemic, for example, highlighted the critical role of digitalisation in maintaining communication, education, or healthcare, but it also reminded the world of the inseparable link between nature and society.

In addition, previous helix models have achieved advancements, for instance, the university's third mission emerged with entrepreneurship and social causes, while cooperatives, corporate universities, and public venture capital investment appeared similarly.

One actor interacts with another, creating a new hybrid entity, and bringing additional knowledge, collaboration, and functions that lead to the evolution of the entire ecosystem.

In any case, the model needs to be tested in empirical cases to bring theory into real-world complexity and address the implementation barriers.

Despite its promise, regenerative innovation faces significant practical challenges, such as cultural resistance to change, the complexity of coordinating multiple actors, alongside the lack of suitable methodologies and resources for collaborative innovation can jeopardize its implementation.

However, with proper mechanisms and resources, these barriers are not insuperable. Initiatives like CODES and the European Digital Innovation Hubs Network showcase the viability of creating ecosystems to drive this transformation, provided that adequate governance and incentives are provided.

In conclusion, the evolution of innovation towards a regenerative model represents a transformative opportunity to address the challenges of the triple transition and promote the alignment of digital, innovation and sustainability agendas. The proposed model 6HIM, supported by the evolution of digital innovation ecosystems, transition brokers as agents of change, and regenerative narratives, provides a solid framework for reimagining innovation as a driver of sustainability, resilience, and equity.

This approach redefines how progress is understood but also lays the foundation for a future where technology, society, and the environment can thrive together in balance. Nevertheless, the implementation will face the challenges that demand specific incentive programmes and policies, as well as education, capacity building and dialogue with stakeholders.

Reconciling Digital Transformation, Sustainability, and Innovation

Digital transformation, innovation, and sustainability represent three transformative forces crucial to addressing the contemporary global challenges and unfolding crises. However, their historical evolution has been fragmented and misaligned, lacking meaningful integration. This disconnect limits their capacity to drive transformative impact and perpetuates technocentric and linear approaches that have proven inadequate in facing contemporary complexities and wicked problems. Thus, reconciling these agendas is a strategic priority for advancing toward a triple transition.

One of the most relevant challenges for reconciling these agendas is their lack of conceptual and policy alignment. Digital and innovation strategies have prioritised technological advancements and economic competitiveness, often dismissing critical social and ecological aspects, such as social justice, human rights, diversity, and healthy natural ecosystems.

Similarly, sustainability agendas, such as the 2030 Agenda, have underestimated the transformative role of digitalisation, knowledge management, and innovation, perpetuating a limited vision of the opportunities of their interplay.

This misalignment is also evident in governance. Current policies and regulations often treat digital innovation and sustainability as separate domains, resulting in a fragmented and desynchronized landscape. This hinders the implementation of holistic strategies that attempt to address the critical interdependencies and inherent opportunities among these fields and their intersections.

Digital transformation and innovation often advance without sufficient reflection, lacking the ethical considerations and sustainability literacy required for a conscious approach that carefully balances risks and opportunities. The dynamics of Silicon Valley have fostered a business philosophy that prioritizes disruption over adherence to established norms, frequently at the expense of social responsibility.

Moreover, the lack of integrated methodologies and metrics to evaluate the influence of digital innovation impacts on sustainability reinforces this fragmentation, fuelling superficial and misleading narratives and misconceptions, along with ethically questionable practices such as "ethics washing."

This dissertation proposes innovative approaches to reconcile these agendas and bridge gaps among the three realms. First, the Taxonomy for Sustainable and Regenerative Digital Transformation (SRDT) structures key aspects at the intersection of digital transformation, including innovation, and sustainability, raising awareness of risks and opportunities while enabling strategic prioritization aligned with a regenerative approach. Complemented by Strategic Objectives and a Theory of Change, it mobilizes action toward the triple transition vision. Second, the Sextuple Helix Innovation Model (6HIM) enhances this framework through a collaborative approach, fostering synergy among key actors, knowledge co-creation, citizen participation, and the convergence of digital and sustainable agendas via intermediaries like transition brokers.

The practical implementation of both the Taxonomy for SRDT and the 6HIM model in the future will provide valuable insights into the dynamics between helices, the connections between dimensions, the collaboration among stakeholders, and the role of transition brokers in the triple transition.

Reconciling these agendas also offers an opportunity to reflect on and address the weaknesses of each realm, thereby unlocking further transformative changes. When aligned with regenerative narratives and mindful shared governance, digital paradigms and innovations can become powerful tools for restoring ecosystems and empowering communities, as substantiated in Chapters 3, 4, and 5.

However, maximizing the impact of this interplay requires overcoming barriers such as regulatory fragmentation, and the predominance of technological determinism and techno-utopias. It also requires integrated governance frameworks and accountability mechanisms with suitable metrics to evaluate progress holistically and systemically, to counteract misleading green and social claims. Furthermore, as previously discussed, is crucial to leave behind the misleading rhetoric and fallacies that portray digital transformation and innovation as a beacon of environmental sustainability and green growth.

Therefore, despite the potential added value of the proposed frameworks, reconciling these agendas remains a complex challenge that demands a combination of measures to be tackled. Challenges such as inertia, conflicting interests among stakeholders, inadequate regulation and policies, insufficient resources, and unsuitable methodologies for fostering collaborative environments can impede the adoption of holistic approaches like these. Overcoming these barriers requires targeted policies, well-designed incentives, enhanced collaboration, and continued research to ensure that digitalisation, sustainability, and innovation work in harmony to drive balanced and regenerative development.

The reconciliation and synchronization of digitalisation, sustainability, and innovation is not merely a desirable goal but a strategic priority for addressing global challenges. Frameworks like the Taxonomy for SRDT and the 6HIM model provide a possible pathway by fostering a systemic approach that prioritizes regeneration and resilience. Nevertheless, their successful implementation will hinge on the ability of all stakeholders and actors to collaborate, overcome structural barriers, and embrace regenerative narrative and stewardship that can transform these agendas into a driver of systemic change towards regenerative sustainability.

The next sections discuss strategic recommendations for reorienting digital transformation, innovation, and sustainability agendas, based on the insights drawn from the research activities and continuous expert dialogue. First, it proposes and discusses recommendations for aligning digital transformation with regenerative sustainability principles and values. Next, it presents and discusses recommendations for embedding digital transformation and innovation into the sustainable development agenda.

Finally, the chapter concludes with recommendations for reshaping the innovation landscape to advance the triple transition.

Recommendations for Aligning Digital Transformation with Regenerative Sustainability

The research findings provided valuable insights for the formulation of strategic recommendations to advance, synchronize, and reorient the landscapes of digital transformation and sustainability towards the regenerative triple transition and long-term resilience.

First, the agendas for digital transformation, and sustainable development must be recalibrated to integrate regenerative and resilience perspectives, ensuring that they reconcile technological progress with the restoration and revitalization of natural ecosystems, society, economy, as well as governance. They also need to converge to adapt to the triple transition, which demands that all stakeholders enhance their capacities and awareness to be prepared for this complex defy. This includes understanding both the adverse impacts that digital disruptions impose on society and nature, and the outstanding opportunities that they present for nurturing a regenerative future.

A paradigm shift is needed to foster a culture of care, responsibility, collaboration, and co-opetition among all stakeholders to embark all of them on the same course for the triple transition. This entails recognizing that their diverse capabilities and perspectives are complementary rather than conflicting.

Currently, ecological, and just transitions are relegated in favour of economic and strategic priorities, especially in public-private partnerships. While conventional approaches have also neglected the role of civil society in digital transformation and innovation advancements, this dissertation argues in favour of a novel perspective that empowers citizens as full actors of the triple transition. This entails reinforcing their capabilities, encouraging shared responsibility and ownership with this common goal of the triple transition, and promoting their participation in building mindful governance and adoption of digital solutions.

Notably, both the ecological and just transitions require active participation from all stakeholders, including civil society and academia, supported by intermediaries, who play a key role in dynamizing, catalysing, and mediating transformations.

Second, accountability frameworks must evolve to reflect the complexities and demands of the triple transition. This evolution requires moving beyond naïve narratives and making meaningful commitments to ecological and social priorities. Current assessment frameworks for digital and sustainability realms need to be reimaged to fully integrate the essential aspects of the digital, environmental, and socially just transitions, all within a regenerative and resilience-based perspective. These frameworks need to achieve a harmonized balance among the three realms, decoupling prosperity from social or environmental degradation.

Moreover, they should embody principles such as equity, resilience, sufficiency, circularity, and climate neutrality, while ensuring social safety, human agency, inclusiveness, respect for human rights, and personal development. Thus, digital development and transformation must prioritize both digital humanism and the planet as core aspects.

Therefore, on one hand, accountability frameworks must provide methodologies and metrics to assess the whole life cycle, both social and environmental, including value chains, where impacts are often more significant and damaging. On the other hand, they must also account for positive aspects and rebound effects, which are currently overlooked. Thus, the role of science and academia is crucial since novel methodologies and metrics need to be developed and widely agreed upon.

Specifically, these frameworks should adopt the revisited multi-capital accounting framework presented in Chapter 4, which ensures a more balanced and comprehensive consideration of natural, human, digital, social, intellectual, and economic capitals. These capitals are often treated in isolation in existing literature and policies, while are considered part of the intertwined helices in the proposed 6HIM model.

Accountability strongly relies on robust and pertinent metrics and quality data. Transitioning from conceptual frameworks and aspirations to actionable objectives with robust and relevant indicators is essential for advancing and materialising the regenerative triple transition. This requires experimental studies and case applications to fully understand implementation barriers and, consequently, to identify the incentives, mechanisms, and capacities required in specific contexts. Therefore, the Taxonomy, Objectives, and 6HIM model proposed in this dissertation can only be fully proven when applied to real-world scenarios. Considering data limitations, further efforts are needed to leverage the outstanding potential of novel data sources and analytics capacities provided by digital advancements.

Building on these accountability frameworks, novel policies and regulations reflecting the triple transition, need also to be developed. This regulatory and policy effort will require the active participation and training of governments and public servers, in close collaboration with other stakeholders.

Implementing these policies in the private sector requires capacity building, transitional strategies, and specific and inclusive incentives, as well as behaviour change mechanisms to make them perceive this as an opportunity instead of a burden. Achieving such a transformation relies on both intrinsic motivations, such as ethical responsibility, and extrinsic drivers, like binding regulations and financial incentives linked to goals, like impact financing programmes.

These novel ideas must confront controversies and dilemmas caused by the uneven global sustainability commitment, geopolitical tensions, the borderless nature of digital transformation, and the difficulties in establishing binding international agreements.

In this process, the proposed Taxonomy, Objectives for SRDT, and the future Report Card Framework can act as levers for better decision-making and governance. A balance must be achieved in providing a streamlined approach, which ensures comprehensive consideration of the systemic impacts.

Furthermore, the enhancements in accountability should be translated into novel and improved measuring and monitoring frameworks that enable a SRDT for the triple transition, with all the stakeholders on board.

In this regard, developing a Report Card Framework (RCF) is proposed as a potential future research direction in Chapter 10. This framework will monitor progress while raising awareness towards the regenerative triple transition vision. The proposed RCF must be aligned with the Objectives and Taxonomy for SRDT and must also contribute to translating the theoretical insights gained into practical implementation pathways.

While the Taxonomy is comprehensive, the Report Card Framework must be conceived as an agile monitoring tool, capturing the essence of the SRDT notion in a way that allows a feasible and efficient implementation.

It is worth mentioning that a novel approach does not necessarily have to be more complex or impose an administrative burden. Indeed, it must be a more effective approach that enables a more agile and efficient way of mobilizing stakeholders and resources toward sustainable goals.

Third, the disconnections between disciplines, particularly digital versus ecological and social versus ecological, must be bridged. The intertwined relationship between social and environmental impacts needs to be recognized and reflected in all policies and regulations. Otherwise, progress in socio-economic goals could undermine environmental health and vice versa.

Bridging these gaps, along with the mistrust and resistance to change among stakeholders, requires novel and transformative approaches that address these intersections. Indeed, the implementation of the proposed frameworks and the advancement of the triple transition strongly rely on stakeholder collaboration and multidisciplinary multilevel cooperation. Transformational regenerative approaches are, therefore, highly needed as recognized by experts, opening a promising research avenue.

While regulation, incentives, and funding are undoubtedly enablers of change, the true transformative shift lies in education, capacity building, and collaborative innovation. This is where the link between the Taxonomy and the 6HIM becomes crucial for developing ecosystems that work towards SRDT and regenerative innovation, fostering capacities, and enabling knowledge sharing and creation.

Both frameworks are intertwined as they align with and pursue the same vision: a multistakeholder, pluriversal, and regenerative triple transition.

Therefore, education and innovation emerge as key drivers of systemic transformation. While sustainability transitions and systemic changes cannot be achieved through incremental advancements alone, a transitional path and gradual approach are essential to ensure genuine legitimacy, stewardship, and the engagement of all stakeholders.

The digital transformation agenda should integrate ecological and social risks and opportunities, while sustainable development agendas must embrace the potential of digital transformation for fostering regenerative sustainability and resilience. To achieve this, stakeholders from all sectors need to raise their awareness and capacitation in both digital and sustainability capacities, as well as in resilience-oriented skills to be prepared for the unfolding triple transition. Therefore, innovation and education should serve as enablers and transformational catalysts to drive meaningful and enduring change within this interplay.

Moreover, the establishment of a common terminology and compelling narratives is crucial for engagement and stewardship. Aspirations such as conscious prosperity, mindful and agile governance, and responsible innovation must be translated into measurable and tangible outcomes to foster meaningful and impactful change. In this regard, raising awareness of the Inner Development Goals is crucial to preparing society for this transformation, also addressing it from a sociological perspective.

The journey undertaken with the 2030 Agenda and other previous digital frameworks has provided valuable lessons for the future. To avoid failure, a compelling and ambitious narrative for promoting digital development, aligned with the principles and values of the pillars of people, planet, peace, prosperity, and partnerships, must remain at the core of all human activities.

In essence, digital transformation and regenerative sustainability should be synchronized and decoupled from environmental and social degradation. Achieving the regenerative triple transition is possible, provided all stakeholders assume their respective roles and responsibilities, working together through collective and concerted efforts toward this vision.

This journey will not be easy and will require multiple enablers, including robust regulation and ambitious policies at both national and global levels, innovative incentives, and funding mechanisms, as well as capacity-building, education, and transformational leadership across individuals and organizations. Such transformational approaches must also foster a culture of care, shared responsibility, and stewardship toward the common goal, all of which fall under the preparedness pillar, as the cornerstone of the triple transition.

In addition, preparedness stands as a key foundation for meaningful change, offering a multifaceted approach to fostering readiness and resilience across all individuals, infrastructures, institutions, and organizations. Building collective preparedness allows society to better address the challenges ahead. Moreover, preparedness serves as an integrative pillar that supports and aligns with other priorities, creating a cohesive framework for transformative progress.

In response to those claiming simplicity and reduced sustainability ambition, this dissertation asserts that, while complex approaches can risk failure, strategies without ambition cannot trigger genuine transformative change. Therefore, a balanced approach is needed, complemented by transitional pathways and suitable incentives, to progress meaningfully toward a sustainable and regenerative future.

Past discussions about the future of digital technologies have often oscillated between two extremes: a dystopian vision where technology undermines humanity and a utopian and naïve rhetoric that sells digitalisation as a silver bullet able to save humanity. None of these scenarios is the most likely, instead multiple futures are possible, depending on the choices that humanity makes today in governing the digital transition. This dissertation proposes a path that, while daring, may offer the greatest benefit for all stakeholders and the planet, while acknowledging the inherent risks and challenges.

For instance, this dissertation envisions Society 6.0 as a promising pathway for the realisation of the triple transition, since it represents the intersection of societal, ecological, and digital subsystems, fully aligned with the principles of human-centred development and the Sextuple Helix Innovation Model (6HIM). This vision seeks to harmonize in a coherent framework digital transformation with ecological restoration and societal well-being. While Society 6.0 remains an aspirational vision, rather than a reality, transitional narratives, and models like the one embedded within the 6HIM, the Taxonomy and Objectives for SRDT, provide actionable pathways to guide society toward this goal.

Nevertheless, technology is not a universal solution, and the risks of techno-utopianism must be carefully avoided. This dissertation also acknowledged that humanity and the planet encompass complexities and multifaceted dimensions that cannot be fully captured and translated into the digital realm or addressed solely through data-driven solutions.

Despite the pervasive claim of achieving a “smart everything everywhere” society, the added value of datafication and digitalisation is neither boundless nor infinite. The most relevant value of digitalisation is that it enhances human capacities and fosters collaboration, both domains are fundamental components of the preparedness pillar.

This dissertation asserts that the integration and synchronization of digital transformation and regenerative sustainability is a complex but attainable goal. The regenerative triple transition vision represents a unique opportunity to realign digital and human development with the principles of equity, resilience, and environmental protection and restoration, and therefore should be a foundational value shaping all human activities.

Yet, achieving this ambitious vision depends on bridging knowledge gaps, fostering close collaboration and co-opetition among all stakeholders, embracing shared responsibility and robust oversight, and committing to concerted efforts to drive meaningful progress and innovation.

While the path will be challenging, the lessons learned from the 2030 Agenda and other digital initiatives, offer valuable insights for navigating future complexities, with a culture of care, shared responsibility, and proactive preparedness for achieving a just, inclusive, and sustainable digital future.

To acknowledge this, two recent real-world examples are discussed as follows.

A timely study from Poblet et al. (2024), analysed the 2024 floods in Valencia (Spain) to underline the critical role of data stewardship in disaster and climate change response, identifying three key challenges: ensuring timely access to actionable data, distinguishing vital information from irrelevant noise and misinformation, and translating data signals into prompt and coordinated response actions. These authors advocated for robust data management practices to enhance community resilience in the face of natural disasters, by data accessibility, trusted data stewards to filter essential information, and systems that facilitate swift responses to emergencies.

All these aspects concerning readiness, response, and resilience are related to the preparedness pillar. They demonstrated that data-driven advancements are useless without the needed preparation of society, including their education on emergency response. This tragedy has also reminded the world about the close interconnection between climate change, water, and energy availability, alongside the reliance on digitalisation for all our daily activities, as well as the need to manage them systemically.

Furthermore, Henrysson et al. (2024) explored the impacts of crisis-driven transformation on the SDGs. Particularly, they concluded that 90% of the SDGs were negatively impacted during the COVID-19 pandemic, uncovering the vulnerabilities of global resilience.

However, the crisis also presented opportunities and benefited sixty-six targets in contexts with comprehensive policies, and inclusive leadership, where strategic decisions were made by promoting economic recovery efforts that prioritized environmental sustainability. This approach corroborates the relevance of the preparedness pillar, and the crucial role of robust policies, leadership, and inclusiveness awareness.

Notably, the pandemic-driven transformation showed the world that environmental and social issues are closely related, and also that digitalisation is critical for dealing with crises and having the opportunity to recover stronger. Certainly, digital solutions proved indispensable during the pandemic, enabling society to keep functioning amid unprecedented disruptions. Those better prepared with digital tools experienced less severe impacts and demonstrated faster, stronger recoveries.

During the first globally impactful pandemic under the digital era, technologies facilitated education, remote work, telemedicine, and enhanced data understanding and management for decision-making. However, they also amplified divides and risks, such as massive surveillance and control, and disinformation which is used as a weapon to destabilize or control nations and hinder democracy. While digital means proved essential, they could not replace the innate human need for social connection and interaction with nature.

These tragic events offer valuable lessons for the world. First, the overwhelming availability of data does not automatically translate into better decision-making. Data and technology are powerless if governance structures are ineffective, and people are unprepared. Second, society requires multichannel communication strategies to ensure inclusivity. Digital tools must augment and complement traditional communication methods rather than replace them, especially for those affected by digital divides. Third, a culture of preparedness is critical for sustainability and resilience, requiring both citizens and public institutions to be educated and prepared for crisis management and response. Fourth, crises often fuel authoritarian control, and the spread of disinformation, which exacerbates social polarization and destabilization.

Addressing these challenges demands a combination of robust regulation and widespread education to build resilience and ensure societies are equipped to face global challenges effectively.

It is often assumed that regulation is the only path to progress in sustainability and human or social rights. Undoubtedly, regulation is a critical component, but the importance of shared responsibility, education, and emotional engagement is often disregarded. In the realm of responsible digital consumption, civil society, and individuals, play a significant role in avoiding the spread of disinformation, choosing reliable providers, and adopting sustainable consumption habits.

In terms of production, companies can opt for responsible and sustainable methods that provide long-term competitive advantages. Research institutions can promote education in these values and commitment with the third mission of the university, while governments can establish policies and programs focused on education and incentives, not just regulation. Without active citizen responsibility, inclusive and sustainable digitalization will remain out of reach.

In conclusion, the triple transition is an opportunity to reimagine a regenerative and resilient future where sustainability and equity are mainstreamed, allowing societal and natural systems to coexist in harmony. Considering the critical role of digital advancements in current society, a profound transformation is needed to reconcile and synchronize digital and sustainability agendas. This transformation hinges on robust governance and regulation, advanced accountability mechanisms, concerted collaboration efforts from all stakeholders, including civil society, as well as transformational leadership and education.

The contributions of this dissertation provide both structured frameworks and strategic directions to take the first step towards building the preparedness for such an ambitious transformation.

Recommendations for Embedding Digital Transformation and Innovation within the 2030 Agenda

The recommendation to align and synchronize digital transformation and innovation with regenerative sustainability must also extend to sustainability agendas, such as the 2030 Agenda. This facilitates acknowledging the risks and harnessing the opportunities that digital and innovative solutions may bring to sustainability advancement while reinforcing a perspective focused on regeneration and resilience. This section reflects the critical insights and potential pathways identified throughout this dissertation for aligning these realms to achieve the regenerative triple transition.

The current integration of digital transformation and innovation aspects within the UN's 2030 Agenda for Sustainable Development is feeble. Indeed, the SDG framework only includes five ICT-based targets scattered across four disparate goals. These five targets encompass basic broadband connectivity and basic Internet usage (SDG9 and SDG17), mobile ownership by women (SDG5), and basic digital skills (SDG4). Electronic waste could be indirectly addressed within SDG12. This is recognized by most experts as clearly insufficient and inadequate for a mindful oversight of digital risks along with for pursuing a sustainable digital transformation.

Digitalisation, as a critical driver of transformation, cannot be superficially integrated into sustainability agendas. First, the dual nature of digital transformation may disrupt social and environmental landscapes with profound and complex effects that must be addressed and mitigated. Sustainability cannot afford to overlook one of the most disruptive forces shaping society and the economy today.

Second, sustainability challenges increasingly demand digital capabilities, data-driven insights, and interconnected innovation ecosystems to overcome present barriers. Digital solutions have the potential to significantly enhance environmental and social aspects, offering innovative ways to tackle pressing issues like resource efficiency, climate action, and social equity. However, undisciplined digitalisation could also disrupt environmental systems, undermine societal cohesion, and threaten peace.

The imperative restoration and revitalization of society, governance, and the planet will require leveraging all available knowledge, capabilities, and collaborative networks. For that purpose, once again, collaboration from all stakeholders is needed, including those in the digital sector, to align efforts and harness the transformative potential of digitalisation for a truly equitable, sustainable, resilient, and regenerative future. Hence, sustainability – particularly the SDGs - requires embedding innovation and digital transformation as core elements.

Furthermore, the literature review uncovered severe deficiencies in the formulated targets and metrics of the SDGs, as well as significant data gaps and delays in measuring progress. The current design does not fully embrace a regenerative approach, with key ecological and social aspects inadequately addressed.

Additionally, many critical facets of digital transformation influencing sustainable development are largely overlooked.

This particularly concerns digital human rights, social welfare, and peaceful societies amid disinformation and algorithm dominance, environmental impacts, divides, and inequalities caused by the digital economy, and global digital governance. As examined in previous chapters, these aspects remain insufficiently integrated into the 2030 Agenda design and implementation.

As explored in Chapter 3, many SDG caveats would benefit from digital solutions, enabling the leverage of novel data sources, advanced analytical and predictive capacities for decision-making, more informed governance and interventions, and collaborative ecosystems for innovation. However, these opportunities remain largely untapped.

For instance, the integration of novel data sources and analytical capabilities could help to address the current deficiencies in metrics, data availability, and quality. Indeed, many metrics have been chosen merely because they are easy to measure. Humanity can no longer rely solely on what is convenient to quantify. Instead, pertinent, and accurate metrics that genuinely reflect progress on sustainability priorities must be developed, and digitalisation could help in such endeavour.

Second, it is essential to acknowledge that many sustainability challenges cannot be solved by technology or innovation alone. They often require structural changes and shifts in behaviours that demand entirely different approaches and novel capacities and means of implementation. Thus, Big Data, AI, and Supercomputing are not always the solution and must be complemented by expert judgment, stakeholder collaboration, and small and context-sensitive insights to ensure relevance and accuracy. The often-applied fallacy of "techno-solutionism", must be abandoned. Indeed, numerous digital solutions that were anticipated to transform sustainability have, ultimately, exacerbated social and environmental problems.

For instance, Smart Cities and Communities have often fallen short in delivering sustainability outcomes, because they have been approached from a narrow technical perspective, attempting to address fundamentally human problems solely by technology. Another example is the digital platforms, which were intended to democratize services and make them more environmentally sustainable and socially accessible.

However, they have instead contributed to gentrification, labour and privacy rights abuses, informal and precarious jobs, the displacement of residents and traditional local businesses from their cities, and an increased environmental footprint and inequality. Social media and networks were heralded as a revolution in communication and networking, but they have become tools for disinformation, harassment, overconsumption, and eroding human values and welfare.

Hence, a cautious and balanced approach is necessary, one that harnesses the potential of digital solutions while recognizing the importance of tackling its risks and integrating other methods and perspectives to address sustainability challenges holistically and in dialogue with local stakeholders and communities.

Experts in the field have expressed diverse perspectives on how to address the evolving demands of sustainability in the digital era. However, there is a growing consensus on the need to reform the current 2030 Agenda to address its shortcomings and better integrate modern trends and priorities. The SDG framework has represented an extraordinary advancement that will endure over time, but nearly 10 years after its adoption, it has been rendered outdated to tackle emerging global challenges, such as the uncontrolled spread of digital transformation.

In this context, there is a pressing need to broaden the scope of the 2030 Agenda and its successor frameworks, exploring ways to enhance their capacity to encompass the critical trajectories of digital development, regenerative sustainability, and innovation.

This global blueprint for sustainable development must reflect, comprehensively and inclusively, the contemporary challenges and opportunities presented by digital disruptions and the unfolding eco-societal transformations.

However, two contrasting schools of thought coexist. On one hand, some stakeholders advocate for lowering ambition, even suggesting dismissing the SD agenda. On the other hand, most sustainability experts call for raising ambition to meet the scale of the challenges ahead. The current geopolitical landscape is challenging, and often prioritizes socioeconomic goals over environmental and equity commitments, thereby reversing or retarding progress on sustainability.

This approach is flawed, as environmental well-being underpins the long-term prosperity of both the economy and society. Addressing this imbalance and changing such outdated and erroneous prejudices are critical steps towards building a sustainable, inclusive, and regenerative future.

This research advocates for a more ambitious approach by placing the regenerative triple transition at the heart of sustainable development and the post-2030 Agenda, thereby harmonizing digital, ecological, and socially just transformations. These elements must be fully embedded within sustainability strategies and assessment frameworks to effectively tackle emerging global challenges. However, this ambitious endeavour is highly complex, as it demands bridging traditionally divergent disciplines, such as ecology and social sciences, while achieving global stakeholder consensus, developing novel metrics, and securing additional funding for capacity building and implementation.

Particularly, for less developed nations and actors, already struggling to monitor and implement the current SDGs, such a transformation poses even greater obstacles. Balancing the differing priorities and capacities of the global North, with its high digital maturity, and the global South, which lags in digitalisation complicates reaching a consensus on a more integrated and comprehensive agenda.

Addressing the synergies and trade-offs among global goals is crucial to achieving holistic outcomes that benefit the five pillars of the 2030 Agenda. Nevertheless, the limited understanding of SDG interlinkages and the nexus between digital and sustainable transformations adds another layer of complexity, underscoring the pressing need for enhanced collaboration, knowledge-sharing, and capacity-building to pave the way forward.

Despite these challenges, a more integrated and holistic approach to sustainability frameworks is unavoidable for the future of humanity and the planet. In response to these challenges, this dissertation examined diverse strategies for enhancing the 2030 Agenda and its successor frameworks, through a more comprehensive integration of digital transformation and innovation. This approach echoes some intriguing ideas gaining traction at international forums and original reflections. Additionally, the process has integrated insights from a specific expert elicitation process, as outlined in Chapter 6.

Therefore, a critical evaluation of the most relevant prospective strategies is presented below, emphasizing their advantages and disadvantages:

(i) Embracing Digital Transformation as a Cross-Cutting Transformation

As suggested by Sachs et al. (2019), embracing digital transformation as a cross-cutting driver acknowledges its pervasive influence across all societal domains and SDGs. While conceptually valuable, as recognized by most experts, this approach faces challenges in materializing and assessing progress due to the absence of specific metrics, which can hinder sustainability outcomes. Therefore, supplementary assessment methodologies are needed for its implementation. However, this dissertation argues that evidence suggests that cross-cutting responsibilities often become diluted, losing visibility and focus, and thus failing to achieve meaningful results.

While DT is inherently transversal, it is also a unique force of disruption that requires dedicated resources, responsibilities, and focused management to ensure its effective integration.

(ii) Enhancing Current SDG Targets for Digital Transformation and Innovation

Enhancing existing ICT targets is primarily preferred by statistical UN offices, as well as stakeholders less committed to sustainability. These groups are often reluctant to extend or substantially update the 2030 Agenda but acknowledge the necessity of revisions to keep the agenda relevant.

This approach is particularly useful for less developed contexts struggling to achieve rudimentary connectivity and basic digital skills. However, it risks overlooking critical risks and opportunities tied to sustainable and regenerative digital transformation.

For highly industrialised and emerging nations and organisations, this approach is insufficient to address their broader goals and needs. In this regard, statistical offices should not hinder or delay the progress of sustainability agendas due to inefficiencies in accountability. Instead, they must remain updated and leverage digital opportunities to enhance data availability and improve the measurement of metrics.

(iii) Integrating Additional Digital-Based Targets Across SDGs

As proposed by Fuso-Nerini et al. (2024), integrating key digital-based targets into relevant SDGs could address short- to medium-term concerns by supplementing existing frameworks. While this approach offers the potential for targeted solutions, it also introduces complexities in monitoring processes, while adding limited overall value. Consequently, it raises concerns about both efficiency and applicability. This dissertation considers it a transitional strategy, useful for developing the capacities needed to implement more ambitious and comprehensive frameworks in the future.

(iv) Establishing a Novel SDG18 for SRDT

Proposing a new SDG18 specifically dedicated to sustainable digital transformation, as suggested by Clark et al. (2022), offers a structured framework to address a wide range of risks and opportunities while enabling more granular monitoring. However, this approach faces challenges, such as the need for global consensus, which is difficult to achieve in the current geopolitical context. Additionally, it would require the development of a novel set of indicators, data systems, and statistical capacity, all of which entail substantial costs. Special attention must be given to the limited statistical and technical capacities of the Global South to ensure this approach remains realistic and attainable.

Despite these challenges, this dissertation concurs with many sustainability experts, who recognize this choice as the optimal long-term solution, particularly from 2035 onwards. Giving SRDT more prominence, focus, and dedicated resources is essential to drive the transformative changes needed to align digital transformation with sustainability goals. This novel SDG18 could be founded on the Taxonomy insights, particularly the preparedness pillars, overcoming current fragmentation and lack of visibility and focus on digital and innovation aspects.

(v) Endorsing a Parallel Agenda, such as the Global Digital Compact (GDC) (UN, 2024b)

Historically, digital agendas have overlooked environmental sustainability, and the forthcoming GDC is not an exception. Indeed, this voluntary commitment has received criticism from environmental and social researchers, due to its limited consideration of critical social and environmental sustainability concerns. First, having a parallel agenda menace perpetuating the same misalignment and neglect of sustainability aspects observed over the past two decades, where little progress has been made in protecting human rights, advancing social equity, or addressing environmental sustainability (e.g. Tunis Agenda for the Information Society, 2005).

The digital sector, by inertia and confirmation biases, tends to prioritize socioeconomic and technological development, and this trend is unlikely to change unless global agendas enforce a stronger alignment with broader sustainability goals.

This dissertation argues that this approach may hinder the development of a truly systemic perspective on regenerative sustainability, preventing the genuine integration and alignment of digital and sustainability efforts and failing to adequately manage potential risks. In addition, a parallel agenda may also exclude the sustainability community, exacerbating current misalignments, as it can obstruct communication and cooperation toward a unified mission and vision of SRDT.

While parallel agendas like the GDC will inevitably exist as representatives of the digital sector interests, it is crucial to allocate a specific space for digital transformation within global sustainability strategies, ensuring they have the same focus and are coordinated.

This research aligns with Unwind's (2024) perspective, criticizing the proposed GDC, for adopting an overly instrumental view of digital technologies, treating them as inherently beneficial, while neglecting negative impacts such as environmental damage and inequality. Moreover, this expert argued that the global digital agenda is being shaped by a few powerful "Digitals Barons", that are prioritizing self-interest over societal good, thereby undermining forums like the World Summit on the Information Society (WSIS) and the Internet Governance Forum (IGF).

Unwind also criticized the vague legal language, lack of implementation plans, and oversimplified approach to environmental sustainability within the GDC framework, advocating for a more holistic perspective, like the one proposed by the "Digital Environment System Coalition" (DESC, 2021) to address the broader impacts and prospects of digital development.

Even when the GDC and similar initiatives may not represent significant advancements compared to frameworks like the Tunis Agenda, from 20 years ago, they could still serve as incremental steps by incorporating sustainability aspirations and aligning digital development with the SDGs. It is worth noting that digital experts often favour this approach, as it offers a simpler, more manageable framework specifically tailored to digital stakeholders.

(vi) Achieving SRDT through a Sextuple Helix Innovation Model (6HIM) and related Ecosystems

As described in Chapter 4, this approach envisions the digital, ecological, and social transitions as interconnected societal subsystems driving transformation within a sextuple helix ecosystem, emphasizing the role of innovation, stakeholder relations, and knowledge creation and transfer.

By reorienting digital and innovation actors, ecosystems, and initiatives toward fostering sustainable and regenerative digital transformation (SRDT), this model has the potential to catalyse policy formulation, capacity building, solution scalability, and the creation of novel networks.

While promising, this approach requires further empirical research and extensive stakeholder dialogue to address potential implementation challenges. It serves as a valuable medium-term strategy that complements existing frameworks. The 6HIM serves also as a "sandbox" environment for experimenting and building the capacities and relationships needed to scale SRDT, bringing together the digital, innovation, and sustainability communities, with the support of transition brokers.

This innovative model presents a unique opportunity to explore and refine pathways for integrating SRDT into broader sustainability frameworks, driving the triple transition while fostering interdisciplinary and multistakeholder collaboration and transformation.

(vii) Society 6.0

Another potential strategy aligns with the evolved concept of **Society 6.0** (Žižek et al., 2021), which builds on the Japanese **Society 5.0** framework for creating a human-centred digital society. Society 6.0 shifts the focus towards a sustainability-centred society, leveraging advanced digital solutions to tackle complex ecological and social challenges in a responsible, resilient, and sustainable manner.

While this approach is conceptually intriguing and inspiring, it remains aspirational. Translating this vision into actionable goals will require the development of specific targets and metrics. Also, its implementation may face significant challenges, making it more suitable as a long-term strategy rather than an immediate solution.

In addition to the previously discussed approaches, this dissertation agrees with Luers's (2020) view on the need to formulate a new social contract to ensure that digital technologies benefit society, as well as to promote collaboration among stakeholders and educate in the risks and opportunities of the digital era. Indeed, these aspects are fully embedded within the proposed Sextuple Helix Innovation Model, as well as in the Taxonomy and Strategic Objectives for SRDT to promote a mindful transformation for and with sustainability.

Additionally, this dissertation strongly aligns with Fuso-Nerini et al. (2024) who advocated for raising ambition and extending the SDGs framework beyond 2030, by updating indicators, better integrating digital paradigms such as AI, and shifting towards net positive approaches to more effectively address global sustainability challenges and opportunities. Thus, clearer, and better measurable indicators and accountability mechanisms are needed, aligned with scientific advancements and global ambitions, to ensure long-term success. Furthermore, global governance, particularly binding commitments, should be reinforced to deliver solutions, while this is highly complex in the current geopolitical landscape.

For that purpose, periodic consultations with stakeholders and a truly accessible and inclusive global forum to maintain relevance would be far more effective than consulting every 15 years, like today. All these aspects are fully aligned with the contributions proposed in this dissertation, as well as with the experts' views.

Overall, the 2030 Agenda requires a fundamental rethinking to better integrate digital and innovation opportunities and challenges, along with perspectives on regeneration, resilience and strengthened crisis response, all considered within the preparedness pillar of the proposed Taxonomy.

To achieve this, novel objectives and indicators, stronger and mindful governance, education, and capacity building, along with suitable accountability and financial mechanisms are needed, particularly to mitigate the risks and leverage the opportunities posed by digital solutions for sustainable, regenerative development, and resilience, as already mentioned in the previous section.

This approach is further strengthened by the need to deepen the knowledge of the SDG interlinkages to identify optimal policy interventions, that so far are limited by unsuitable metrics, data availability and quality issues, and fragmented literature on suitable methodologies.

Additionally, the development of innovative metrics and methodologies, powered by digital technologies like Earth Observation Data, IoT, Big Data Analytics (BDA), AI, and advanced computing, will be pivotal in advancing and monitoring these goals. These tools will enhance the understanding of interlinkages and spillovers, improve reporting processes through advanced analytics, and enable more timely and actionable decision-making, ensuring greater accountability and transparency.

Also, this dissertation emphasizes that novel metrics must go beyond the mitigation of negative impacts, and proactively promote the regeneration of natural, social, economic and governance systems.

For example, by addressing aspects such as biodiversity restoration, climate resilience, circular models focused on sufficiency, digital well-being and Inner Development Goals, behaviour change, and many other opportunities for eco-social transformation.

Despite the recognized need for renovation, a general resistance to change, coupled with the emergence of regressive governance approaches to environmental sustainability, and populist and disinformation-driven narratives against the SD agenda are increasingly evident in global discussions. UN agencies responsible for the SDGs have been reluctant to modify the indicators or expand the Agenda due to the required effort. Yet, many experts argued that to sustain progress, the 2030 Agenda must be reformed and strengthened the sooner the better. Looking ahead to 2040 and 2050 now is the time for the global community to start the dialogue for shaping future sustainability goals to meet emerging challenges.

This dissertation contends that there is no room for ambiguous or lukewarm approaches since the triple transition is unavoidable and urgent, thus it is necessary to raise ambition by pursuing viable and gradual strategies in consensus with global stakeholders.

Ultimately, the cohesive integration of sustainable digital transformation, innovation, and regenerative perspectives into the 2030 Agenda represents not just a needed evolution but also a crucial opportunity. By taking proactive steps today to align these three agendas, the global community can create a solid foundation for addressing the sustainability challenges of the present and the future, paving the way for a more inclusive, resilient, and regenerative world.

Proposal of Roadmap for Aligning Digital and Sustainability Agendas towards the Triple Transition

The strategies previously discussed represent diverse pathways towards better embedding and aligning digital transformation, innovation, and regenerative sustainability trajectories, each with its opportunities and challenges. As argued by many experts, there is no clear preference, and the balanced combination of several approaches is possible to deal with different context specificities. Yet, further research and dialogue with global stakeholders are required to identify the optimal choice to navigate the complexities and effectively advance the integration of digital, integration, and sustainability agendas, keeping its relevance and legitimacy.

Following an in-depth exploration of the advantages and disadvantages of the discussed strategies, along with insights from expert consultations and dialogue, this dissertation proposes a roadmap for enhancing the 2030 Agenda in the near future.

Recognizing the complexity of reaching a global consensus, developing pertinent targets and metrics, along with their dependence on contextual relevance and statistical capacity, this dissertation proposes a preliminary approach, which aims to spark dialogue and mobilize efforts in this critical area.

The overall strategy must remain flexible to address both immediate and future needs, set realistic goals, and stay aligned with the ever-evolving dynamics of sustainable digital transformation, regeneration, and the triple transition.

Therefore, a progressive roadmap is proposed as follows, which combines short-term pragmatic and transitional steps, with a more ambitious strategic vision, for aligning digital and sustainability goals in the evolving dynamics of the triple transition.

In the short term, a feasible and transitional solution for most nations and stakeholders could involve enhancing existing frameworks by refining current ICT targets and indicators, while adding a limited number of additional indicators whenever they are deemed critical. This transitional approach would address the diverse needs of highly digitally developed, emerging, and developing contexts.

Furthermore, this approach should be accompanied by sustaining seed funding for reinforcing statistical capacities and promoting mission-based SRDT programmes. Overall, these efforts would gradually build the necessary capacities and resources, thereby paving the way towards more ambitious and comprehensive strategies in the future.

Moreover, in the medium term, promoting a Sextuple Helix Innovation Model for ecosystem and policy development with plural perspectives would enhance collaboration, dialogue, and capacity building for embedding SRDT gradually while aligning digital, innovation, and sustainability realms. This model would facilitate the reorientation of existing ecosystems, communities, and supportive environments to incubate and accelerate SRDT and the triple transition in a structured and controlled environment. As with the previous approach, this medium-term strategy relies on specific programmes for sustaining the ecosystems.

Considering the long-term scenario, as the 2030 horizon approaches, it becomes crucial to raise the level of ambition and establish a new sustainable development agenda. This approach relies on initiating a stakeholder dialogue towards the development and integration of an ambitious and specifically dedicated goal (e.g., SDG18) for SRDT in the post-2030 agenda.

Additionally, social, and ecological goals should be reinforced with regenerative and resilience perspectives, and prosperity-based goals should align with a purposeful triple transition vision. This step would ensure a more comprehensive and focused approach to the interconnected challenges of sustainability, digital transformation, and regenerative development.

While this option has not been received enthusiastically by some experts, particularly those specialized in digital and social domains, it is the preferred choice in global conversations among other sustainability stakeholders, and indeed, a global consultation is underway to capture experts' ideas to design this goal.

This dissertation argues that the novel SDG18 could be based on the proposed Strategic Objectives for SRDT, further enhanced and with concrete metrics design in co-creation with global stakeholders.

Regarding the key challenge of varying levels of development and differing capacities to address the triple transition among countries, tailored strategies are essential. These strategies must consider contextual specificities and engage in dialogue with local stakeholders and communities to accurately reflect their needs. To bridge these disparities, a combination of approaches is recommended, including targeted programs, capacity-building efforts, and the establishment of pioneering coalitions to support countries on their path toward the triple transition.

Finally, a global institution specifically dedicated to SRDT, and the triple transition should oversee this process at all stages, ensuring holistic management of risks and opportunities, as well as providing oversight and long-term guidance for a sustainable and regenerative digital transformation.

Strengthening multilateral governance structures and periodically reviewing proposed goals and scenarios to keep them updated and forward-looking is also advisable. This approach aligns with the proposed action plan of the CODES coalition (CODES, 2022) and the novel aspirations outlined in the Global Digital Compact (UN, 2024b).

In essence, this roadmap accommodates and balances immediate and future needs with realistic goals and a flexible combination of approaches, effectively positioning society towards a robust sustainable development agenda, which embeds SRDT and the vision of a regenerative triple transition.

Recommendations for Reshaping the Innovation Landscape

Concerted efforts are needed to foster innovation ecosystems capable of driving the regenerative triple transition and holistically addressing the critical environmental, social, and economic contemporary challenges. Achieving the triple transition with a regenerative perspective relies on a deeper exploration of Theories of Change, particularly transformational approaches, and regenerative design principles. These areas emerge as critical research avenues, as they could bridge the gap between vision and implementation to drive long-lasting and meaningful change.

Building on the findings, strategic recommendations are proposed to overcome the current implementation gaps in n-helix models and guide the reorientation of existing policies, programmes, and ecosystems toward the principles of the regenerative transition by embracing the 6HIM model.

Essentially, the mission entails reshaping the innovation agenda and landscape to prioritize and promote regenerative innovation aligned with the triple transition.

This will facilitate the alignment with the regenerative triple transition principles, with a robust strategy for addressing the contemporary deficits at this critical crossroad, since the 6HIM model emphasizes a holistic, pluriversal, and multistakeholder approach beyond technologies and is fully aligned with the vision of the triple transition and regenerative innovation. Furthermore, the Sextuple Helix Innovation Model (6HIM) aligns synergistically with the Taxonomy for SRDT, as its six main helices or societal subsystems correspond to the six taxonomical pillars, and they also share the same mission and vision.

The proposed model seeks to unite diverse stakeholders and accelerate transformative and regenerative progress by encouraging systemic shifts through active engagement with innovation intermediaries termed transition brokers. Thus, this model fosters cross-disciplinary collaboration, co-creation, and the creation of knowledge and multi-capitals, aiming to promote regenerative sustainability in the digital age.

Beyond offering a conceptual blueprint, the 6HIM framework aims to equip innovators, digital transformation agents, and sustainable development practitioners with the tools and capacities to propel the regenerative triple transition forward effectively. Also, founded as a collaborative and intertwined system of systems, it aims to rebalance the relationship between society and nature, and enhance technological sovereignty by plural approaches, preventing the dominance of any single voice in discussions.

The strategic reorientation of relevant R&I initiatives (e.g. partnerships, missions, accelerators) is also needed to closely align with the principles of the regenerative triple transition.

These initiatives should evolve into potential “seed ecosystems” and “sandboxes,” serving as fertile ground for testing, refining, and scaling the 6HIM for the practical applicability of SRDT toward the triple transition vision. Thus, transforming these seed initiatives into transition brokers, may ignite momentum and build the capacities needed for transformative change towards a regenerative triple transition.

It is also recommended to establish a mission-oriented programme specifically designed for accelerating SRDT and the triple transition across the digital, social, and environmental sectors, and fostering an integrated approach that drives holistic, systemic change toward sustainability.

Moreover, case studies are essential to fully understand the barriers to implementation and to design targeted incentives and capacity-building programs to address them effectively. These studies would also provide valuable insights into the interrelationships between helices, the dynamics of collaboration that generate novel knowledge, and strategies to enhance and smooth these interactions to overcome current resistance to change. Additionally, they would shed light on the critical role of transition brokers in driving transformation within this framework.

Furthermore, digital innovation hubs and smart communities represent a promising environment for testing and scaling up the 6HIM, to spark transformative changes and refine the application in the real world. This approach will ensure that R&I efforts not only align with but actively contribute to the overarching goals of regenerative sustainability and holistic societal transformation.

Considering the recommendation for evolving digital innovation ecosystems, drawing from the insights gained, it is advocated to evolve existing suitable initiatives and communities, such as the EDIHs, into “Sustainable and Regenerative DIHs” (RegenDIH). These hubs would act as transition brokers for promoting eco-social transformations, by bridging gaps between stakeholders, facilitating active participation, and fostering knowledge co-creation and sharing. Their primary role would be to ensure the successful implementation of the 6HIM model and testing SRDT initiatives, helping to overcome current barriers, thereby positioning them as key catalysers of the regenerative triple transition and the “knowledge humanity” across Europe and beyond.

For that purpose, the EDIHs need to wholly integrate the six key subsystems of innovation, ensuring their seamless collaboration. This will allow a better understanding of the dynamics of DT and SD, enhancing regenerative solutions with positive societal impact in the digital and sustainable transformation journey.

Moreover, the RegenDIHs hold great potential to drive forward a responsible and regenerative Society 6.0, where the convergence of the digital and physical worlds is harnessed to address societal challenges holistically and sustainably. Through their leadership, EDIHs can guide society towards a balanced, regenerative, and resilient digital transformation.

Learning from successful global alliances like the CODES coalition, and Smart and Sustainable Communities, holds significant potential to promote the regenerative triple transition, aligning with the policy objectives embedded in the 6HIM. However, these alliances often fall short of adopting a pluriversal perspective, which would include a more diverse and inclusive engagement with civil society.

For these global coalitions to maximize their impact, they must strengthen their alignment with policy objectives, foster deeper civil society participation, and focus on more robust, practical implementation strategies. These recommendations would not only enhance their effectiveness but also contribute to fully leveraging the transformative potential of the 6HIM model.

Another recommendation is focused on providing accountability mechanisms, specifically designed for regenerative innovation. Indeed, monitoring and accountability are critical for driving a sustainable digital transformation and innovation.

However, existing frameworks are not designed to align with the transformational culture required to address the triple transition. Stakeholders must develop new capacities and enhance their awareness to track progress accurately while avoiding misleading claims. Therefore, a gradual framework is recommended, enabling stakeholders to monitor their advancements toward achieving regeneration readiness.

Thus, this dissertation recommends the creation of a Seal of Excellence (SoE) grounded in the progressive “Regenerative Readiness Levels” proposed in Chapter 4. This SoE would serve to rigorously assess, monitor, and transparently communicate the progress of innovation programs, policies, and ecosystems in advancing regenerative innovation and driving the triple transition.

Beyond enhancing accountability, this initiative would raise awareness and play a critical role in addressing greenwashing and misleading environmental claims prevalent in the digital and innovation sectors.

The SoE would also be an instrument for aligning initiatives with the vision of the regenerative triple transition, supporting the evolution of the current policies and programmes, and ensuring that social, environmental, and economic objectives are fully integrated.

Additionally, it is crucial to evaluate the long-term impacts of regenerative innovations to gain a deeper understanding of their scalability, their potential to transform socio-ecological ecosystems, and their role in advancing the triple transition. Such assessments will inform the development of strategies and policies that effectively promote sustainable and regenerative development while facilitating systemic transitions.

As some experts argued, these instruments complement but do not substitute other reporting mechanisms and critical measures such as education, capacity building, and regulation. Yet, they reinforce the accountability and awareness mechanisms for facilitating a transitional pathway to the regenerative triple transition.

These described recommendations, together with education, capacity building, mindful governance and regulation, alongside suitable incentives for the transition would help innovation processes to evolve into a more inclusive, sustainable, and regenerative framework, better suited to meet the needs of both people and the planet.

In conclusion, reshaping current innovation models, policies, programmes, and ecosystems is needed to align with the principles of the regenerative triple transition embodied in the 6HIM framework. Diverse strategic recommendations have been proposed to pave the way for their implementation. However, further research and policy alignment are needed to overcome current reluctance and implementation barriers towards scaling these transformative approaches.

Final Reflections and Recommendations

Despite the abundance of methodologies for monitoring digital and sustainable development interventions and their impacts, many fail to address the unique challenges posed by digital disruptions on the environment and society. Indeed, digital transformation often remains disconnected from other existing societal systems. To bridge this gap, innovative transitional approaches are needed that offer flexibility and adaptability to diverse contexts, emerging technologies, and global trends, fostering holistic and regenerative development where all societal and natural systems can thrive together.

The categorization of the research gaps of the SDGs and the role of digital paradigms to address them, along with the Taxonomy and Strategic Objectives for SRDT, the Sextuple Helix Innovation Model and the Strategic Recommendations for co-evolving the three realms towards advancing the triple transition, provide a first foundational step for this ambitious purpose.

Indeed, these contributions provide the structure framework for better understanding and governing this critical interplay and serve as guidance for informing research, policy, and practice about the hallmarks of the regenerative triple transition.

In this regard, the Taxonomy for SRDT provides a comprehensive framework that facilitates a panoramic overview of the key factors, risks, and opportunities, that digital transformation may pose on sustainability. It serves as a valuable tool for informing decision-making, raising awareness, and prioritizing thematic interventions, with the support of context-aware implementation.

Nevertheless, for effective operationalisation, the Taxonomy must be complemented by more specific objectives (i.e., OKR), and metrics localised to the specific circumstances of its context of the application. For instance, in Europe, the focus will be on the responsible use and governance of digital technologies (e.g., AI Act), meanwhile, in less developed countries, basic ICT skills and access to basic broadband connectivity will take precedence.

Therefore, developing compelling and dynamic OKRs for SRDT is critical for mobilizing action, thereby translating the taxonomy and Strategic Objectives proposed into more actionable outcomes.

These OKRs should be articulated with robust metrics capable of capturing the multiple facets of the interplay between the digital and sustainability realms. In addition, they should be accompanied by a Theory of Change for inspiring the transformation, and complementary monitoring frameworks to track progress.

Concerning progress monitoring, this dissertation suggests developing a Report Card Framework (RCF) aligned with the proposed Strategic Objectives and Taxonomy for SRDT, as it serves as an agile monitoring and communication tool to track and display progress in an accessible and easy-to-understand format for all stakeholders. By using this RCF the stakeholders can assess their alignment with long-term objectives while identifying areas for improvement. Also, it raises awareness about the critical aspects of SRDT and triple transition among stakeholders, including civil society.

Hence, the proposed Strategic Objectives for SRDT can be interpreted as a preliminary approach towards the development of a novel SDG18 specifically focused on sustainable and regenerative digital transformation for the triple transition. Indeed, they encompass all the relevant dimensions for that purpose, from mindful governance, conscious prosperity, preparedness covering readiness and resilience, cooperation through partnerships, a regenerated planet, and an empowered and inclusive whole of society.

Additionally, this research advocates for the establishment of mission-based programmes that foster mutual learning between digital, innovation, and sustainability stakeholders, and targeted funding to support the regenerative triple transition. These initiatives would be useful in building communities of practice, scaling successful experiences, and developing the capacities needed across diverse contexts.

Existing programmes in this field should be reevaluated through the lens of the triple transition and regenerative principles, ensuring that both footprints (negative impacts) and handprints (positive contributions) are assessed and incorporated into monitoring and impact assessment frameworks.

Considering the prevalence of naïve narratives and the persistence of greenwashing and ethical washing practices in the digital sector, it is essential to promote accountable mechanisms for identifying, verifying, and incentivizing genuine progress. In this regard, this dissertation recommends integrating, at least, a simplified ESG risk evaluation, based on existing standards into all digital-based projects and research publications. This approach aims to capture the true impacts of DT, enhance accountability, and combat misleading narratives, thereby fostering more responsible and sustainable outcomes in digital transformation, innovation, and sustainability efforts.

Concerning the role of stakeholders in realizing the triple transition, this dissertation emphasizes the critical importance of fostering collaboration and cooperation through continuous dialogue among diverse actors representing societal ecosystems, particularly those from the digital and sustainability domains. A pluriversal, multi-stakeholder, and interdisciplinary perspective is essential for advancing such a transformation. This perspective, embedded throughout the contributions of this Doctoral Thesis, ensures inclusiveness and diversity while promoting effective knowledge creation and sharing.

It also facilitates concerted efforts to collectively understand and articulate the interplay between these domains. While stakeholder collaboration is emphasized across all chapters, it is particularly central to the Sextuple Helix Innovation Model detailed in Chapter 4.

As underscored in the literature and supported by expert feedback, one major barrier to effective collaboration among actors or systems with differing interests is the reluctance of stakeholders to adopt methodologies from other domains.

For example, academics may disregard non-academic literature, practitioners often perceive academics as out of touch, and both groups frequently overlook the insights of citizens. Furthermore, widespread scepticism and mistrust of political processes exacerbate these challenges. Overcoming such resistance and prejudices requires embracing regenerative methodologies that value and integrate diverse perspectives. This shift is essential for addressing complex challenges and ensuring progress in the triple transition.

Hence, promoting a Sextuple Helix Innovation Model for ecosystem development and stakeholder cooperation, aligned with the Taxonomy for SRDT, guided by ambitious strategic goals and a robust monitoring framework (e.g., RCF), and supported and overseen by a global institution with a dedicated mission-based programme for the triple transition, would be highly compelling.

The combination of the contributions provides a well-rounded approach for enabling the convergence and co-evolution of the digital, innovation, and sustainability agendas, sharing significant synergies and mutually reinforcing each other, towards the common vision of achieving the regenerative triple transition.

9. Conclusion

This chapter presents the concluding reflections on the achievements and contributions of the dissertation, emphasizing their significance and broader implications for research, policy, and practice.

Achievements and Contributions

In this section, the research achievements concerning the planned research objectives are outlined, with an emphasis on their contributions to bridging the identified gaps and advancing toward a sustainable and regenerative digital transformation, as well as fostering regenerative innovation for the triple transition.

This dissertation has thoroughly explored the intricate interplay between digital transformation, innovation, and sustainability, with a focus on fostering their cohesive integration and alignment to bridge the current disconnect while advancing the regenerative triple transition. By identifying existing gaps and offering novel insights, holistic frameworks, and strategic directions to address these challenges, this research represents a foundational contribution to navigating this complex and crucial intersection.

To achieve this, this research employed a robust combination of methods to enhance the rigour and soundness of its findings, including a comprehensive systematic literature review, desktop research, qualitative analysis - supported by text mining and visualization techniques - as well as an expert elicitation process complemented with expert dialogue.

The first step of the research consisted of a critical review of the sustainability notion and the identification and categorization of the overarching gaps within the SDG framework, with emphasis on the role of digital paradigms in addressing these challenges responsibly and sustainably. Therefore, in response to the first research question (RQ1) and related objectives, the gaps in this field were systematically uncovered and categorised, along with the potential opportunities to address them. In this regard, an in-depth examination of the role of digital paradigms in responsibly addressing these challenges was conducted, yielding valuable insights for accelerating progress towards achieving the UN's 2030 Agenda.

The resulting contribution of this research line is the comprehensive categorization of the research gaps and opportunities within the SDG framework, and the role of digital paradigms in addressing them. It is concluded that digital advancements provide outstanding opportunities for tackling sustainability challenges, due to their extraordinary potential to provide novel sources of data, and augmented analytical capacities, alongside novel collaboration ecosystems.

Nevertheless, they must be developed and utilized responsibly and sustainably, which remains a challenge. These results provide valuable insights and direction for more effective implementation of the 2030 Agenda, along with the opportunities and challenges that digital transformation presents for advancing sustainability while mitigating its potential effects on society and the environment.

Building on the insights gained from the previous research line, the dissertation expanded its focus to examine the interplay between digital transformation and regenerative sustainability. This analysis was thorough and culminated in the development of a Taxonomy for advancing a Sustainable and Regenerative Digital Transformation (SRDT), providing a comprehensive framework that offers a panoramic view of its opportunities and risks on all the dimensions of sustainability.

The Taxonomy was designed to facilitate awareness about the opportunities and challenges of this interplay and to inform decision-making and governance, for advancing the vision of a sustainable and regenerative digital future.

Furthermore, to fully operationalise the Taxonomy, a set of Strategic Objectives aligned with its main six pillars and thirty-six domains was proposed. These objectives aim to mobilize action toward the vision of the regenerative triple transition, by fostering alignment between digital transformation and regenerative sustainability. In addition, the objectives were complemented with a Theory of Change to facilitate systemic transformation over time towards the long-term vision of the regenerative triple transition.

Thus, in addressing the second research question (RQ2) and its associated objective, this dissertation uncovered critical challenges, including the misalignment between digital transformation and sustainability, as well as the limitations of existing frameworks for evaluating and monitoring their interaction. To overcome these barriers, the research identified and categorised the key determinant factors driving sustainable and regenerative digital transformation. These factors were organized into a comprehensive taxonomy that incorporates regenerative and resilience perspectives, structuring existing and fragmented knowledge into a cohesive and panoramic framework for enhanced governance and awareness about the tenets of this dynamic interplay.

This categorised structure integrates all relevant dimensions of the triple transition (i.e., digital, environmental, social, socio-economic, governance, and cooperation). Moreover, it included a specific pillar for “preparedness,” which leverages the legacy knowledge about digital readiness, while embedding the principles of resilience, regeneration, response to crises, and inclusivity.

The preparedness pillar covers universal and meaningful connectivity, resilient and sustainable infrastructures and systems, including data infrastructures, the capacities and awareness (digital, sustainability, and resilience-oriented), the transformational leadership and culture of responsibility, the conducive enabling environment (regulatory, political, institutional, social, environmental, financial), and lastly the crisis preparedness and emergency response.

It also reflects both the risks and opportunities that digital transformation may pose for regenerative sustainability on the road to the triple transition.

Therefore, this holistic Taxonomy, and especially the preparedness pillar, equips stakeholders with the insights, capacities, and means to navigate the complexities of the triple transition, while fostering alignment between digital transformation and regenerative sustainability.

In addition, this dissertation addressed the interplay between digital transformation, innovation, and sustainability to advance the innovation field as a fundamental driver of systemic change. This dissertation concluded that a paradigm shift is needed in the innovation landscape to adapt to the contemporary challenges and can be articulated through a novel Sextuple Helix Innovation Model (6HIM), aligned with the previously described Taxonomy for SRDT. The proposed 6HIM model promotes regenerative innovation as a critical lever for the triple transition. It enables the reorientation of the R&I landscape and ecosystems towards regenerative innovation hubs, by embedding the principles of regeneration, inclusiveness, and resilience, as well as multistakeholder cooperation, to advance the triple transition. Additionally, this research contribution supports the articulation of regenerative innovation.

Therefore, in response to the third research question (RQ3) and its corresponding objective, this dissertation concludes that the global innovation landscape in the digital and sustainability era must evolve beyond traditional n-helix models and enable ecosystems to address contemporary complexities and emerging trends. Innovation models require reorientation toward a more systemic perspective, catalysed by multistakeholder and plural alliances, as well as transition brokers. The proposed Sextuple Helix Innovation Model (6HIM) integrates all relevant societal and natural actors and subsystems, including whole-of-society, the ecosphere, the digital sphere, open academia, a purpose-driven economy, and whole-of-governance. This model also incorporates a multi-capital approach to align innovation with the principles of the regenerative triple transition while fostering long-term systemic resilience.

The dissertation concluded that innovation ecosystems, policies, and programmes must evolve to embrace the 6HIM model to contribute to the realization of the triple transition and foster systemic regeneration and resilience. The alignment analysis conducted demonstrates that reorienting existing digital ecosystems, programmes, and alliances, such as the European Digital Innovation Hubs (EDIHs), into transition brokers aligned with the principles embedded within the 6HIM model has the potential to catalyse systemic transformations toward this vision. It can also serve as a sandbox for experimenting and scaling sustainable and regenerative digital solutions and multistakeholder networks. Furthermore, this research establishes that the proposed 6HIM model is not merely a conceptual framework but is already being implemented in advanced initiatives such as the CODES coalition.

Nevertheless, the implementation of the model in real-world contexts, through empirical case studies is needed to fully understand the dynamics among helices and actors, as well as to validate its potential scalability, as explained in Chapter 10.

Lastly, several strategic recommendations were presented to advance the evolution and alignment of the three realms of digital transformation, innovation, and sustainability, and their respective strategic agendas, in pursuit of the regenerative triple transition. These recommendations aim to reconcile their priorities and foster a more cohesive and mutually reinforcing approach.

Particularly, considering the exposed caveats of the SDG framework, and the pressing need to renovate it to tackle the digital era and the novel dynamics of innovation, a roadmap was proposed for evolving the 2030 Agenda to fully integrate sustainable and regenerative digital transformation and innovation. This roadmap outlines a feasible and gradual, yet ambitious, transitional trajectory, accommodating the diverse priorities and capabilities of the global contexts.

Therefore, in response to the fourth research question (RQ4) and its related objective, this dissertation concluded that strategic recommendations are essential for evolving digital, innovation, and sustainability agendas toward the regenerative triple transition. These recommendations also provide clear guidance for stakeholders, particularly policymakers, to achieve optimal alignment and systemic integration of these three realms, contributing to long-term regenerative sustainability and resilience.

Overall, this dissertation presents both conceptual insights, actionable frameworks, and strategic directions to advance the following aspects: the responsible reorientation of digital paradigms toward regenerative sustainability; the recalibration of sustainable development frameworks, particularly the UN's 2030 Agenda, to cohesively integrate the potential of digital transformation and innovation alongside regenerative and resilience perspectives; the redirection of the innovation agenda and landscape towards more inclusive, plural and regenerative perspectives; as well as the mutual evolution and synchronization of the agendas for digital transformation, innovation, and sustainability to support the long-term goals of the triple transition: sustainability, resilience, and regeneration across the digital, environmental, and social dimensions.

Hence, the contributions of this research are both novel and significant. They advocate for integrating regenerative sustainability and inclusive perspectives into digital, innovation, and sustainable development agendas, emphasizing that preparedness, regeneration, and resilience as essential levers for navigating unfolding disruptions and global challenges.

Ultimately, the research contributions guide researchers to deepen the understanding, articulation, and operationalisation of sustainable and regenerative digital transformation and regenerative innovation, in the pursuit of the regenerative triple transition.

These frameworks and insights also enhance decision-making, motivate change, mobilize actors and resources, and enable the assessment of progress.

In addition, these contributions support the renewal and systemic integration of the intertwined digital, innovation, and sustainability agendas to meet contemporary demands and envision a more sustainable, inclusive, revitalizing, and resilient future.

While this research provides an innovative and robust foundation, it acknowledges the inherent challenges in implementation. The next Chapter addresses the future research avenues that could contribute to addressing such challenges so as to further advance this promising field.

Implications for Research, Policy, and Practice

The research findings and contributions have relevant implications across research, practical, and policy dimensions since they foster a paradigm shift in how digital transformation, innovation, and sustainability are approached.

Notably, the Taxonomy and Strategic Objectives for SRDT, the Sextuple Helix Innovation Model (6HIM), the categorization of the digital opportunities for the SDG research gaps, along with the strategic recommendations for aligning and co-evolving the agendas of these critical domains, provide novel insights, perspectives and practice pathways to bridge current gaps and advance the triple transition.

Nevertheless, these contributions must be critically assessed in terms of their significance, novelty, added value, and implications for research, policy, and practice. This section addresses these aspects, by providing critical reflections on the proposed contributions, beginning with the conceptual value of the proposed frameworks, and following by the broader implications.

First, from a research perspective, this dissertation advances knowledge through the Taxonomy for SRDT, which illustrates and categorises the key tenets of sustainable and regenerative digital transformation for the triple transition. Thus, it serves as a conceptual bridge that comprehensively integrates the digital and sustainability domains, ensuring that critical perspectives such as regenerative sustainability, inclusiveness, and resilience, are deeply embedded within the fabric of the digital transformation.

Second, considering the practical implications, this dissertation proposes initial pathways for the articulation and operationalisation of the SRDT strategies, such as the Strategic Objectives and Theory of Change for the triple transition, the Regenerative Digital Innovation Hubs, and the proposal of Regenerative Readiness Levels, for driving and scaling regenerative innovation. The strategic objectives proposed lay the preliminary groundwork for advancing the dialogue with stakeholders towards a potential future Sustainable Development Goal (SDG 18), focused on sustainable and regenerative digital transformation.

These contributions offer guidance for all organizations and stakeholders, consolidating the diverse dimensions of sustainable and regenerative digital transformation, and the triple transition, into actionable insights.

Third, in terms of policy and governance implications, this research contributes to science-informed, inclusive, whole-of-government and whole-of-society approaches. The proposed frameworks inform the prioritization of policy interventions in the digital and innovation domains, ensuring their alignment with social and environmental goals. It also provides strategic recommendations to support the alignment and evolution of digital, innovation, and sustainability agendas towards their synchronization with the regenerative triple transition, addressing contemporary societal demands.

Each of these implications is further analysed as follows.

Research Significance and Added Value of the Contributions

The proposed contributions provide substantial value to the related research fields. The intersection of digital transformation, sustainability, and innovation, along with the triple transition, remain emerging and little-explored fields, rendering the proposed approaches original and novel.

Considering the Taxonomy for SRDT framework, it adds value by capturing, organizing, and categorizing the complex intersection between digital transformation and regenerative sustainability, bridging current knowledge gaps and providing comprehensive insights into both the risks and opportunities inherent in this interplay. It not only organised existing knowledge but also introduced an adaptable, holistic, and forward-looking framework, able to evolve with emerging trends.

Its systemic and integrative structure organised into six pillars aligned with the 2030 Agenda, the Digital Development Compass, and Digital Global Compact, provides a comprehensive panorama of the triple transition dimensions alongside cross-cutting governance and cooperation. Furthermore, the integration of a reinforced vision of preparedness for the triple transition, founded in readiness, resilience, and response to crises, provides valuable guidance for decision-making in governing these intertwined fields.

In addition, its alignment with recognized frameworks, combined with the adoption of common terminology and an ambitious narrative centred on regeneration and resilience, enhances its legitimacy and significance. Thus, this framework facilitates broader adoption and reinforces its potential to connect digital and sustainability transformations.

Despite its conceptual value, this contribution may face implementation barriers when translating into practical applications. In particular, the Taxonomy and related Strategic Objectives need to be complemented with elaborated metrics tailored to the context of implementation and supported by accessible and agile monitoring mechanisms.

Regarding the 6HIM model and the respective enabling ecosystems “RegenDIH”, they represent a significant evolution from conventional triple helix innovation approaches.

Notably, this model addresses one of the main criticisms of innovation systems: their tendency to exclude key actors and operate in silos disconnected from social realities. Therefore, they allow a more holistic and collaborative approach for leveraging knowledge and multi-capital creation from all societal actors, including those representing nature, civil society, and the digital sector.

This inclusive, pluriversal, and systemic approach accounts for all voices and social and environmental transformations, which is particularly relevant in the context of the SDGs. It also aims to expand the capacity of innovation subsystems, or helices, to address the interconnected global challenges by leveraging the knowledge, the relationships, the generation of capital, and the collaborative culture to succeed when facing eco-social transformations.

The emphasis on interdisciplinary, multilevel, and multistakeholder collaboration, co-creation, and co-opetition is particularly relevant for promoting resilience and regenerative innovation in complex contexts. Moreover, it is soundly aligned with the Taxonomy dimensions, contributing to providing an ecosystem for its implementation and scaling.

Furthermore, both contributions respond to a critical need for overcoming technocentric and growth-oriented narratives that dominate traditional approaches. The Taxonomy and Strategic Objectives for SRDT, alongside the 6HIM and related enabling ecosystems, offer a more systemic vision aligned with the principles of regenerative sustainability and resilience.

Nevertheless, the 6HIM model requires strong coordination and collaboration among diverse actors and societal subsystems, as well as the evolution of current ecosystems, which may be difficult to achieve in fragmented contexts, especially when considering the inherent barriers of collaboration and the lack of effective mechanisms for its implementation. In addition, further understanding of the interrelationships between the six helices is needed to translate this concept into practice, along with capacity building. These barriers can be tackled by empirical research in real-world case studies, with the support of specific mission-oriented incentive programmes, such as the EU's Horizon Europe Framework Programme.

Furthermore, the practical implementation of these frameworks faces the dilemma of balancing simplicity and ease of application, with the robust and holistic approaches demanded by this complex interplay between digital transformation, sustainability, and innovation. Another dilemma exists when balancing universally applicable commitments and global thinking with local action, considering the need for localization to specific implementation contexts. Adopting a "glocal" approach is inherently complex, but achievable with suitable and tailored mechanisms and effective multilevel governance, akin to the 2030 Agenda framework.

Having described the significance of the scientific research domain, the next part approaches the implications for policy and governance in general.

Implications for Governance and Policy

Considering the potential policy implications, the research contributions offer in-depth insights, structured frameworks, and strategic directions to raise awareness of the risks and opportunities of digital transformation and innovation regarding sustainability, thereby guiding more effective interventions. They aim to address current fragmentation and promote more integrated, science-informed guidelines for governance mechanisms adapted to the novel realities of the triple transition.

The Taxonomy for SRDT and its subsequent Strategic Objectives provide a comprehensive and organized structure, offering a panoramic view of the key factors of SRDT. This framework is particularly valuable for raising awareness about the importance of these aspects and informing decision-making by all the stakeholders working in this field, but particularly for policymakers, considering the relevance of suitable regulation and oversight in the digital, and innovation fields. This is especially critical in contexts where sustainability aspects are often ignored, and policies lack coordination and coherence.

The 6HIM model also holds significant implications for policy and governance, emphasizing the importance of multi-stakeholder and pluralistic innovation ecosystems. These ecosystems prioritize collaborative environments and governance aimed at generating greater eco-social value. In contexts where research and innovation (R&I) policies and programs are heavily influenced by governments, such as in the European Union, this paradigm shift is particularly relevant. However, it poses challenges for conventional governance systems that are often designed to prioritize economic interests over eco-social objectives.

Implementing the 6HIM model requires structural and cultural changes to operationalize this holistic and pluralistic approach. This includes the development of specific mission-oriented programmes, incentives, and capacity-building initiatives. One promising avenue is the reorientation of existing digital ecosystems, such as Digital Innovation Hubs, to serve as transition brokers for the triple transition, gradually catalysing and scaling this transformation.

A critical implication of the taxonomy-based objectives is the need for binding commitments to translate knowledge into action. Lessons from the 2030 Agenda have demonstrated that voluntary frameworks with unclear responsibilities are insufficient to drive systemic change. Yet, a dilemma arises when implementing stricter regulations and public oversight, as many experts suggest.

While such measures could enhance accountability, they might also risk stifling innovation and reducing the competitiveness of national actors compared to less-regulated contexts. Addressing asymmetries in the digital and innovation sectors requires balancing regulation and competition at both global and domestic levels.

Moreover, governance alone is insufficient to achieve the societal change and commitment required for this transformation. Broad societal involvement is essential and must be supported by accessible mechanisms and appropriate incentives, including behaviour change, awareness-raising, inner development capacities, and transformational approaches, as emphasized by experts. Nevertheless, regulation and mandatory reporting standards are necessary to strengthen the currently weak accountability and oversight of digital transformation and innovation risks.

Hence, education and awareness-raising for promoting a culture of responsibility, ownership, and stewardship toward sustainable innovation and digitalisation are equally crucial transformational drivers of change. Building these aspects related to educational and personal development is a fundamental function of the preparedness pillar. Only through mindful and shared governance, coupled with widespread education, can society develop the transformative culture, preparedness, and shared responsibility needed to align digitalization and innovation with regenerative sustainability.

Lastly, the next section describes the implication of the research contributions to the practical advancement of the fields of sustainability, digital transformation, and innovation.

Practical Implications

Considering the practical implications of the research contributions, while they hold significant potential, they also face implementation barriers that must be acknowledged and addressed.

First, it is important to note that the proposed contributions, particularly the Taxonomy and Strategic Objectives for SRDT, represent a foundational first step. To ensure efficient implementation, these contributions must be further developed with concrete metrics, robust monitoring mechanisms, and empirical case studies.

The inherent complexity of the proposed approaches, while necessary to address the intricacies of the interplay between digital transformation, sustainability, and innovation, may hinder their adoption if suitable mechanisms are not provided.

For example, implementing the 6HIM requires coordination among multiple actors and significant policy commitment, which may lack the necessary resources or support if specific incentive programmes are not provided. Similarly, the SRDT Taxonomy must be complemented with accountability mechanisms, regulations, standards, and global cooperation to ensure its practical applicability, which requires specific programmes, such as the CODES coalition (CODES, 2022).

This dissertation concludes that, with suitable incentive programmes and policy support, the implementation is feasible, considering that existing initiatives such as CODES and the European DIHs have already demonstrated their alignment with both SRDT and the 6HIM, as described in Chapter 4.

Concerning the implementation barriers, they are common to any novel approach aiming to challenge the status quo. The most relevant is overcoming resistance to change and mistrust in collaboration, particularly within established, dominant systems with a preference for hierarchical structures, technocentric approaches, and growth-first mindsets. This resistance is not limited to economic or academic actors but is also evident in contexts where conventional narratives of progress are deeply entrenched, often dismissing civil society participation and undervaluing inclusion, diversity, and ecological considerations.

Another significant challenge is the lack of supporting structures, policies, and funding for regenerative-focused initiatives and ecosystems. Mechanisms such as incubators with seed funding and sandboxes for experimentation and scaling are essential. While programmes like the European Commission's Horizon Europe Programme have promoted collaborative environments for sustainable digital innovations, their scope remains limited and constrained, hindering scalability. Programs like the European Commission's Digital Europe Programme, which are more focused on deployment, largely neglect social and environmental dimensions. Scaling novel approaches like the 6HIM will depend on policy commitment, societal involvement, resource mobilization, and the creation of a supportive environment for regenerative innovations. Success in this area hinges on preparedness for the triple transition.

As previously emphasized, the actionability of the proposed frameworks and insights also depends on education and capacity building across all stakeholders. Policymakers, who are responsible for creating the enabling environment, and practitioners, tasked with deploying technologies, infrastructures, and services, require targeted training. There is no room for weak ambition since decisive and binding action toward balanced development and prosperity that integrates sustainability for all stakeholders is imperative for addressing unfolding global challenges with dire consequences for society such as the climate crisis.

Despite these barriers, the proposed contributions provide a valuable foundation and open a promising debate and research directions for better articulating and leveraging this interplay to advance the triple transition, as addressed in the next chapter on future research avenues.

The research contributions provide both novel insights and guidance frameworks for advancing research, as well as for practical and policy application. They represent an original, holistic, and regenerative-centred response to the current gaps and misalignment between digital transformation, sustainability, and innovation.

These contributions not only help bridge existing challenges but also lay the groundwork for promising future developments. However, the successful implementation of the proposed frameworks and the actionable potential of the insights gained will depend on achieving collective commitment, widespread societal education, and transformative governance to unlock and scale their full potential.

The triple transition (digital, environmental, and social) represents both a challenge and a historic opportunity to transform the systems that define human society. In this context, the contributions proposed in this dissertation stand out for their conceptual relevance in advancing the field and also for their ability to provide actionable frameworks to guide this transformation toward a regenerative and resilient future.

The next Chapter addresses the limitations of the research and proposes future avenues to keep advancing this promising field.

10. Limitations and Future Research Avenues

In this concluding section of the dissertation, the research limitations are outlined followed by potential future research avenues to deepen the understanding of the dynamics of the triple transition and advance the alignment and integration of digital transformation, innovation, and regenerative sustainability goals.

Certainly, the value of the research contributions lies not only in their current advancement of the field but also in their capacity to open novel research directions and inspire further exploration of these promising interplay and transformations.

Research Limitations

This dissertation acknowledged several limitations, mainly stemming from the complexity and rapid evolution of the phenomena under study, as well as the insufficient development of scientific literature and policy regarding the interplay between digital transformation, innovation, sustainability, and the triple transition. Certainly, the lack of robust theoretical and practical foundations in this research area is particularly evident.

This critical limitation has also presented a unique opportunity, since this dissertation has evolved in parallel with the dynamic progression of digital transformation, innovation, and sustainability, along with their complex interplay. This parallel evolution required continuous adaptation to three multifaceted and rapidly changing fields and their intersection, demanding significant effort to capture emerging insights and maintain an ongoing dialogue with experts. This approach has ensured that the dissertation remains relevant and responsive to the fast-paced developments within this research area.

Another key limitation arose from the novelty of the research field, and the subsequent gap between research and practical implementation. The interplay between digital transformation, innovation, and sustainability is an emerging and rapidly changing field lacking established definitions, clear boundaries, and a solid theoretical foundation. This was reflected in the scarcity of scholarly contributions, fragmentation of grey literature, strong contradictions between studies, and a general lack of awareness about regenerative sustainability across research, practice, and policy.

Indeed, the rapid pace of digital transformation has occurred disruptively and disorderly, without the necessary reflection on its ethos, combined with inattention to its impact on sustainability. Furthermore, dominant narratives from both practitioners and governments often depict digital solutions as inherently beneficial, which can obscure critical risks and aggravate divides and inequalities. Digital transformation, therefore, not only amplifies existing risks, but also introduces new, yet unknown threats.

Thus far, efforts to foster multidisciplinary, multi-stakeholder, and cross-sectoral research have revealed persistent gaps between domains and actors. In this sense, silo-based resistance hampers the holistic approach required to tackle the triple transition, particularly in bridging divides between ecological and social sciences, as well as between the digital and ecological realms.

Moreover, another limitation pertains to the expert elicitation process and dialogue, and the insufficient awareness and literacy about sustainability and digitalisation among many researchers.

Therefore, identifying experts with robust knowledge and awareness of both digital transformation and regenerative sustainability is a complex task. This challenge is particularly pronounced when attempting to engage stakeholders from the enterprise and public sectors, where naïve narratives framing digitalisation as a universal solution are more prevalent.

Additionally, it is widely recognized that expert judgment can introduce biases that may influence the results, and, therefore, this methodology needs supporting strategies to mitigate such effects.

Considering the scarcity of empirical case studies in many areas of this field, the existing body of literature often relies on expert opinions, further underscoring the need for rigorous methodologies to balance potential biases and enhance the reliability of findings.

Regarding the qualitative analysis methods, the employed techniques, such as content analysis, text mining, and topic modelling, also present certain limitations. While advanced text mining and machine learning tools facilitate data exploration and visualization, particularly when managing a large volume of documents, they may not always produce contextually relevant outcomes. As a result, expert judgment is essential to interpret and validate the findings, ensuring their relevance and alignment with the research objectives.

The extensive volume of documents reviewed during the systematic literature review and desktop research process complicated traditional content analysis, which led to the use of data-driven tools such as machine learning techniques. These tools posed challenges regarding accuracy and contextual understanding, with the potential to overlook key insights. Nevertheless, the dissertation combined traditional analysis, data-driven methods, and expert elicitation so as to mitigate these limitations and ensure the comprehensiveness and robustness of the results.

In addition, another significant limitation, particularly evident when assessing the interlinkages between the SDGs but also applicable to the broader research objectives, was the lack of high-quality data required for conducting robust quantitative analysis. This challenge poses a critical barrier to the advancement of this field, hindering efforts to provide reliable assessments of the synergies and trade-offs between goals, which are essential for informing effective policy and practical interventions.

Moreover, as previously discussed, the lack of empirical cases and the need to further test the proposed frameworks represented a limitation in fully understanding their real-world applications and addressing the implementation challenges inherent in multistakeholder collaboration and systemic transformations. To address this limitation, the future research directions presented in the next chapter, emphasize the need to develop empirical case studies for validating these contributions within real-world contexts.

Despite these challenges, different mitigation strategies and a robust combination of research techniques were applied to address the limitations inherent to individual approaches. Also, a broad range of literature, including scientific, grey, and comitology documents, was employed to overcome the numerous contradictions among studies and the naïve narratives in the field. Additionally, expert dialogue was conducted with diverse stakeholders through relevant international forums, working groups, and conferences to incorporate perspectives from various sectors and disciplines over time, and therefore, mitigate potential biases.

Furthermore, considering the fast-evolving nature of the three realms under study, an iterative process was adopted, enabling continuous review and refinement. This agile approach enabled the integration of emerging trends within the digital, innovation, and sustainability fields, ensuring that the research remained aligned with the most relevant themes.

Hence, this blended methodology, together with the mitigation measures applied, facilitated that the results obtained were robust and contextually relevant.

In conclusion, this dissertation has acknowledged the research limitations inherent in the interplay of digital transformation, innovation, and sustainability, and adopted an iterative and agile methodological approach to mitigate these challenges. This methodology integrated diverse techniques, information sources, and experts' perspectives to ensure the robustness, relevance, and contextual alignment of the findings.

Future Avenues to further advance the Taxonomy and Strategic Objectives for SRDT

First, considering the Taxonomy and Strategic Objectives for SRDT and the triple transition, these frameworks offer a solid foundation that should be further elaborated by their application to specific technological, geographical, political, and sectoral contexts. They should also be complemented with pertinent metrics and agile monitoring frameworks.

Therefore, a crucial next step involves developing more concrete and contextually relevant Objectives and Key Results (OKRs), followed by identifying robust and pertinent metrics to support their implementation and monitoring.

This future research direction should assess and articulate the interlinkages among the different taxonomical pillars and domains, reinforcing their coordination, to ensure a truly systemic and integrative implementation. This assessment should also examine the interlinkages of this framework with the SDGs, as well as its alignment with other relevant frameworks.

One relevant future research direction will be the development of a Report Card Framework (RCF) aligned with the six pillars and thirty-six domains within the Taxonomy and Strategic Objectives. Such a framework could serve as an accessible tool for enhancing reporting, accountability, and awareness-raising. Indeed, RCFs are widely used in the environmental domain to transform complex knowledge into accessible insights for a broad audience, thereby facilitating informed decision-making through a clear and concise overview of progress toward set goals.

Furthermore, RCFs are flexible and adaptable to local context while maintaining their alignment with global frameworks, thus enabling “glocal” governance approaches. A key aspect of the potential RCF is agile governance, therefore, this framework should be based on OKRs and be reviewed and updated periodically to ensure relevance and allow for the redirection of actions as needed. In this way, the RCF can bridge the gap between the conceptual insights of the Taxonomy and the high-level aspirations of the Strategic Objectives and the practical and context-relevant implementation pathway. An outline of this perspective is provided in Figure 10.1.

Additionally, further elaboration of the proposed Strategic Objectives into OKRs will establish the foundation for advancing the dialogue towards a future SDG18 on Sustainable and Regenerative Digital Transformation (SRDT) as part of the post-2030 agenda. This novel goal should be mainly rooted in the Preparedness pillar of the taxonomy.

Another important future research direction involves the implementation of the Taxonomy, Strategic Objectives, and RCF in real-world settings, such as through case studies applied to specific technologies, regional contexts, different political and regulatory environments, as well as different sectors. This would not only complete the final validation process but also enable a more nuanced and context-sensitive approach to the proposed key determinant factors. Such an approach would facilitate a deeper understanding of potential implementation barriers, support the development of specific metrics, and enhance the representativeness and legitimacy of the proposed frameworks.

In particular, it would be beneficial to apply these frameworks in both developed, emerging and developing contexts, while integrating underrepresented perspectives, particularly from the Global South. In this regard, expanding the expert elicitation process to include a broader cohort of stakeholders could yield valuable insights for tailoring these frameworks to “Base of the Pyramid” contexts and less digitalized nations. Tackling the classical dilemmas of balancing global thinking with local action and addressing the needs of both highly developed and less developed contexts, future research should explore strategies to harmonize a universal guiding framework with local needs. This involves ensuring that global frameworks, such as the SDGs, are adaptable to regional contexts while accommodating varying levels of development, resources, and digital and sustainability literacy.

Concerning specific examples of case studies for technological contexts, emerging technologies with significant sustainability risks, such as artificial intelligence (including regenerative and general AI), quantum computing and communications, and virtual worlds, could be highly relevant areas for study. These technologies provide opportunities to assess impacts and explore resilience and regeneration before full commercialisation. Nevertheless, most digital paradigms hold interest, particularly as sustainability research, especially from a regenerative perspective, remains limited in both literature and practice. Moreover, exploring synergistic applications with positive social and environmental impacts is also essential, and could complement the limited state of development, as described in sections 5.2.8 and 5.3.5 on environmental and social regeneration solutions.

In relation to geographical and political contexts, as already mentioned, it is important to compare developed, emerging, and digitally mature regions, recognising their differing challenges and governance structures. Key comparisons include highly regulated, ethics-driven regions like the EU and Singapore versus more flexible, innovation-oriented but less sustainability-focused regions like the US. Besides, emerging economies, such as China with high state intervention, and nations leading in inclusive digitalisation, like Colombia and Kenya, also merit attention.

In terms of sectoral contexts, most industries and sectors are susceptible to benefit from further exploration of the challenges and opportunities of SRDT and regenerative innovation. Nevertheless, potential priority areas include urban environments, energy and climate, bioeconomy, biomedical technologies, industrial circularity, biodiversity protection, and behavioural change. These sectors are ideal for testing regenerative technologies, resilience, and digital readiness.

Ultimately, another research direction would be to further advance the Theory of Change proposed towards a more transformational approach, based on regenerative design, so as to reinforce this crucial aspect.

Figure 10.1. Scheme of the Future Research Directions
(Own elaboration)



Future Avenues to further advance the Sextuple Helix Innovation Model Implementation

Regarding future avenues stemming from the Sextuple Helix Innovation Model (6HIM), while it offers a transformative framework for advancing regenerative innovation aligned with the principles of the triple transition, its implementation faces challenges that need to be addressed with further empirical research.

First, future research should explore the application of the model in specific regional contexts and ecosystems, such as the European Digital Innovation Hubs (DIHs), UN digital innovation labs and initiatives like as UN Global Pulse, CODES and AI for Good, as well as Smart and Sustainable Communities in diverse sectors, including urban environment and Smart Cities, Smart Energy Communities, Smart Agriculture Communities, among others. Also, another relevant case study could be the integration of a specific mission within the EU's Horizon Europe programme or its successor Framework Programme 10th.

These case studies could provide valuable empirical insights into the complexities arising from the implementation, in particular, the interrelations and dynamics among helices and actors, as well as the role of these ecosystems as transition brokers of the triple transition. Such insights could inform the design of effective measures to coordinate efforts and foster systemic transformations.

Case studies would also allow researchers to test the adaptability of the proposed model to diverse cultural, socioeconomic, and technological settings, thereby refining its significance and scalability. Additionally, it could also offer strategies for enhancing collaboration, addressing power imbalances among helices, and supporting transition brokers in their facilitation roles. Furthermore, implementing the 6HIM framework in diverse settings can unlock its full potential and facilitate comparative studies across regions, sectors, and cultural contexts. These comparative insights would support the refinement of the model's adaptability and guide the development of policies tailored to specific local contexts.

In this regard, experimenting with the 6HIM in real-world contexts can also enhance understanding of innovative and sustainable approaches, such as frugal eco-innovation, catalytic innovation, and grassroots innovation, among others. Also, the implementation of the model to inspire the reorientation of current policies, programmes and ecosystems could benefit from specific mission-oriented programmes specific to this purpose. Future directions in the field of policy could focus on creating mechanisms that support the evolution of innovation ecosystems into regenerative transition brokers. Additionally, it could explore regenerative design strategies for reorienting these initiatives in alignment with these principles and the triple transition goals.

Another relevant aspect for future research is tackling the current lack of robust metrics, evaluation frameworks, and accountability mechanisms in this realm. Thus, future studies could advance the development of evaluation frameworks that align with the 6HIM principles and the vision of the triple transition. These frameworks should also be accompanied by accountability measures to ensure genuine progress while avoiding misleading sustainability claims.

Governance structures should also evolve to address the emerging demands of the triple transition and regenerative perspectives. Therefore, future research could explore innovative mechanisms to balance innovation with regulatory oversight, develop strategies for early and equitable engagement, and promote capacity building for transformation, ownership, and stewardship among all relevant stakeholders.

These research directions are multifaceted and underline the relevance of combining practical applications in real-world contexts, empirical validation, and tailored interventions. Such concerted efforts aim to advance the principles of regenerative innovation within the 6HIM framework while inspiring stewardship and transformation toward the vision of the triple transition. All these potential avenues could enhance the relevance, scalability and impact of the model and its contribution to the vision of the regenerative triple transition and systemic resilience.

Future Avenues concerning the SDG challenges.

The examination of SDG research gaps concluded that the most critical challenge lies in understanding and articulating the interlinkages among SDG goals and targets to ensure suitable and systemic implementation and more effective policy interventions. The study of SDG interlinkages is still in its early stages, requiring further research to develop more effective and robust methodologies, foster multidisciplinary knowledge and collaboration across

In this regard, Chapter 1 provided insights into the difficulties faced by the research community in assessing SDG interlinkages due to methodological limitations, complexities, and data gaps or lags.

A critical future research avenue involves developing robust hybrid methodologies that combine quantitative approaches with causal analysis supported by digital advancements, as well as qualitative insights from expert judgment.

This integrated approach would better assess and understand these interconnections, enabling more accurate and holistic assessments that support targeted interventions addressing multiple sustainability challenges simultaneously and synergistically.

Causal Machine Learning (CML) approaches emerge as a particularly promising research direction in this domain. These methods offer significant potential for advancing the understanding of SDG interlinkages, including their causal mechanisms, and for informing more effective policy decisions. Integrating CML approaches can enhance the robustness of existing methods while providing deeper insights into the complex dynamics among the SDGs. However, the exploration of these approaches must be accompanied by ethics research to ensure fairness, transparency, and accountability.

Moreover, future research should address the interrelationships between the SDGs and digital development goals, as well as other frameworks, such as the Inner Development Goals. A particularly relevant research direction involves integrating regenerative and resilience perspectives and exploring the evolution of the SDGs toward Regenerative Development Goals. While proposals in this area have emerged in the literature, regenerative sustainability remains in its infancy, necessitating further research to unlock its full potential.

Advancing assessment and accountability depends on improving the availability of high-quality data. A critical future avenue involves exploring the potential of novel data sources alongside unified, interoperable, and accessible databases to provide high-quality, context-specific data with sufficient granularity for SDG advancement, monitoring, and impact assessment. Furthermore, many existing studies on the SDGs are limited by their focus on national-level interactions. Future research should examine interlinkages at multiple scales, including sub-national, regional, and global levels. It should also adopt a context-specific approach to tailor policy recommendations more effectively. While recent advancements have begun incorporating spillover effects into SDG assessments, further research is needed to understand the cross-border implications of domestic policies on global SDG progress. This is crucial for fostering enhanced international collaboration and policy coherence.

Future research should also prioritise the development and validation of new metrics and indicators that better capture the complex dynamics of the 2030 Agenda and ensure their applicability across various contexts. Empirical case studies are especially needed to analyse how specific countries or regions address SDG interlinkages.

In conclusion, future research on the SDGs should leverage digital advancements in analytics, causal-oriented algorithms, and data-driven methodologies, combined with expert judgment, to provide a more integrated, context-relevant, and comprehensive understanding of SDG interlinkages. Such efforts will be critical for translating research insights into effective policies that promote the achievement of the 2030 Agenda, balancing social, economic, and environmental priorities while aligning with the imperative of the regenerative triple transition.

Future Avenues Concerning the Interplay between Sustainability and Digital Transformation

The exploration of digital solutions to address SDG challenges responsibly and sustainably opens multiple promising avenues for future research. Further research is essential to fully unlock the potential of digital solutions in providing novel data sources, augmented capacities, and innovative networks to benefit sustainability. In this context, a key research avenue is leveraging new data sources, such as Earth Observation data and IoT-generated data, to complement traditional datasets and enrich the understanding of SDG dynamics. Combining traditional datasets with non-traditional sources can refine predictive models and support evidence-based policy interventions.

Additionally, digital transformation must align with sustainability principles to address SDG challenges effectively. This includes exploring ways to integrate environmental and social considerations into the technological, ethical, and governance development of digital technologies, particularly Artificial Intelligence (AI). While digital solutions have demonstrated their potential at a small scale, scaling their application for widespread sustainability impacts remains an untapped area requiring further research.

Future research should also focus on developing accountability mechanisms for more accurate and comprehensive assessments of the environmental impacts of digital technologies, particularly concerning rebound and systemic effects. Quantifying and mitigating the rebound effects of digital solutions is a pressing research priority.

Developing robust metrics and standards is critical for ensuring the sustainability of digital development, including achieving regenerative and net-positive impacts. Research should explore how digital solutions influence broader societal and environmental systems, ensuring interventions are net-positive over the long term.

Furthermore, methodologies for embedding regenerative design principles into digital development stages should be advanced to ensure alignment with environmental and social sustainability goals.

In this regard, specific standards for assessing Scope 3 emissions and other systemic impacts of digital technologies require further exploration. Tailored methodologies should be developed to address the unique environmental and social impacts of individual technologies. Life cycle assessment methodologies must be adapted to specific digital technologies to evaluate their effects across diverse contexts. It is particularly important to integrate environmental and social aspects from the outset to prevent technological advancements, such as in AI, from undermining sustainability objectives.

Future Avenues Concerning Transversal Aspects for The Regenerative Triple Transition

Apart from the specific research avenues stemming from the main objectives of this dissertation, another transversal future direction involves deepening the understanding of governance, education, and regenerative approaches as enablers of the triple transition.

As one expert suggests, a promising approach focuses on the inner motivations needed to engage all stakeholders, including civil society actors, and the role of digitalisation in supporting human development and inner growth. This is closely related to integrating the Inner Development Goals (IDGs) into global agendas.

Future research should investigate governance mechanisms and educational strategies that foster ownership and stewardship of regenerative triple transition goals. This includes practices for facilitating meaningful engagement across diverse sectors and communities.

Additionally, as emphasized in the discussion, education, capacity building, awareness-raising, and behaviour change are critical elements for mobilizing society toward transformative sustainability and systemic change. Raising awareness about the risks and opportunities of digital transformation and innovation, while building a culture of responsibility and stewardship, is essential and warrants further attention.

In this context, transformational approaches, such as regenerative design, emerge as promising future research directions. Future work should focus on reinforcing Theories of Change (ToCs) with a stronger emphasis on transformational approaches that incorporate regenerative design qualities.

While the potential of digital technologies and innovations is widely recognized in the literature and among experts, significant challenges persist at all levels and across both technological and non-technological domains. Human interpretation and agency, along with education and capacity building, are critical to ensuring context relevance and accuracy in this field.

Although the advent of “General AI” and other promising paradigms holds the potential for more reliable knowledge discovery in the future, expert elicitation and conventional qualitative analysis will remain essential for generating meaningful insights.

As previously noted, the reorientation of sustainability, innovation, and digital agendas toward a vision of a regenerative triple transition demands close collaboration and dialogue with stakeholders, as well as robust and multilevel governance tasks that are inherently complex. However, the scientific community must take the lead in formulating, prioritizing, and improving robust and relevant metrics, along with methodologies to ensure their appropriateness and rigour. Furthermore, governance and transformational approaches are needed to inspire stewardship and meaningful change.

The triple transition and the concept of regeneration are still underdeveloped, requiring further research, empirical studies, and policy development to fully understand and unlock their potential. Consequently, advancing regenerative design and transformation approaches in collaboration with stakeholders emerges as a promising avenue for future exploration. Additionally, further research on behavioural change will be valuable for engaging stakeholders to advance the triple transition and address the complex digital and eco-social transformations underpinning it.

In conclusion, pursuing the triple transition with regenerative and resilience perspectives will be crucial for building a sustainable, inclusive, and peaceful future, where digital paradigms and innovations serve as forces for positive and lasting change, promoting harmony between society and the planet. This research provides a foundational scientific perspective that must be complemented by further theoretical and practical studies, as well as policy development in dialogue with global stakeholders, to realize its full potential.

The future research avenues proposed form a roadmap for advancing the understanding and application of SDG interlinkages, digital transformation for sustainability, and regenerative innovation. These efforts have the potential to bridge gaps between science, policy, and practice, ensuring that digital, innovation, and sustainability goals are aligned and reconciled with regeneration to address complex global challenges.

With the future of digital transformation and innovation being shaped now, this dissertation encourages the scientific community to pursue these future avenues with urgency and ambition, driving the regenerative triple transition forward.

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Annexes

ANNEX I. Research Production and Dissemination Contributions

Table Annex I. Research Production and Dissemination Contributions
(Own elaboration)

CATEGORY	RESEARCH PUBLICATION	THESIS CHAPTER
Published Research Article Q1 journal	Del Río Castro, G., González Fernández, M. C., Uruburu Colsa, Á. (2021). <i>Unleashing the convergence amid digitalization and sustainability towards pursuing the Sustainable Development Goals (SDGs): A holistic review</i> . <i>Journal of Cleaner Production</i> , 280(Part 1), 122204. https://doi.org/10.1016/j.jclepro.2020.122204	Chapters 2 and 3
Published Research Article Q2 journal	Gupta, S., Campos Zeballos, J., del Río Castro, G. et al. (2023). <i>Operationalizing Digitainability: Encouraging Mindfulness to Harness the Power of Digitalization for Sustainable Development</i> . <i>Sustainability</i> , 15(6844). https://doi.org/10.3390/su15086844	Chapter 3
Research Article Under Review (preprint) Q1 journal	Del Río Castro, G., Uruburu Colsa, Á., González Fernández, M. C. (n.d.). <i>Towards a regenerative innovation: A holistic sextuple helix innovation model for pursuing the digital, ecological, and just transitions</i> . http://dx.doi.org/10.2139/ssrn.5003901	Chapter 4
Research Article Presented at International Conference (pending publication of proceedings at IEEE Computer Society Digital Library)	Del Río Castro, G., Uruburu Colsa, Á., González Fernández, M.C. (2024). <i>Navigating the Triple Transition: A Holistic Taxonomy towards a Sustainable and Regenerative Digital Transformation</i> . <i>International Conference on ICT for Sustainability</i> . This article was presented at the 9 th International Conference on ICT for Sustainability (ICT4S 2024), 24 th -28 th June 2024, Stockholm, Sweden. https://conf.researchr.org/track/ict4s-2024/ict4s-2024-research-papers?#event-overview	Chapters 5, 6, 7, and 8
Research Article Presented at International Conference (abstract published)	Del Río Castro, G., Uruburu Colsa, Á., González Fernández, M. C. (2023). <i>A digital, green, and socially fair future: Unravelling the triple transition with a pluriversal sextuple helix model of innovation for sustainable development in the age of digitalization</i> . The article was presented at the 11 th International Conference on Sustainable Development (ICSD) 2023, 19 th – 20 th September 2024, New York, United States. https://virtual.oxfordabstracts.com/event/4228/submission/313	Chapters 4, 5, 8

ANNEX II. Complete Version of the Proposed Taxonomy for SRDT

Table Annex II. Complete Version of the Proposed Taxonomy for SRDT
(Own elaboration)

PILLAR	DOMAIN	THEMATIC FACTOR
PEACE	Oversight and Regulation	Whole-of-Government Approach
PEACE	Oversight and Regulation	Multilevel Governance and Oversight
PEACE	Oversight and Regulation	Whole-of-Society Approach
PEACE	Oversight and Regulation	Communalism and Bottom-up Governance
PEACE	Oversight and Regulation	Trustworthiness Digital Development Policies & Strategies
PEACE	Oversight and Regulation	Open Internet Governance
PEACE	Oversight and Regulation	Internet Governance - Misinformation & Disinformation
PEACE	Oversight and Regulation	Internet Governance - Harassment
PEACE	Oversight and Regulation	Internet Governance - Censorship & Shutdown
PEACE	Oversight and Regulation	Digital Democracy, Digital Agency, and Sovereignty
PEACE	Oversight and Regulation	Agile Data-Driven Oversight
PEACE	Oversight and Regulation	Domestic & Global Data Protection Regulation
PEACE	Oversight and Regulation	Domestic & Global AI Regulation
PEACE	Oversight and Regulation	Regulation of Mass Surveillance
PEACE	Oversight and Regulation	Regulation of Digital Technologies
PEACE	Oversight and Regulation	Regulation for Cybersecurity, Resilience, and Cybercrime
PEACE	Oversight and Regulation	Regulation & Policies for Safeguarding Digital Human Rights
PEACE	Oversight and Regulation	Innovative Legal Sandboxes
PEACE	Oversight and Regulation	Soft Regulation - Principles and Standards
PEACE	Oversight and Regulation	Soft Regulation - Incentives
PEACE	Oversight and Regulation	Anti-Fraud & Anti-Competitive Regulation
PEACE	Trust, Transparency, and Accountability	Accountability, Trust, and Transparency Mechanisms
PEACE	Trust, Transparency, and Accountability	Client Protection and Repair Mechanisms
PEACE	Trust, Transparency, and Accountability	Due Diligence & Risk Assessment Schemes
PEACE	Digital Ethics, Human Rights and Peace	AI Ethics
PEACE	Digital Ethics, Human Rights and Peace	Digital Democracy
PEACE	Digital Ethics, Human Rights and Peace	Peaceful Digital Society
PEACE	Digital Ethics, Human Rights and Peace	Digital Agency and Sovereignty
PEACE	Digital Ethics, Human Rights and Peace	Human Agency
PEACE	Digital Ethics, Human Rights and Peace	Robustness
PEACE	Digital Ethics, Human Rights and Peace	Security and Safety
PEACE	Digital Ethics, Human Rights and Peace	Explainability
PEACE	Digital Ethics, Human Rights and Peace	Non-Discrimination & Fairness
PEACE	Digital Ethics, Human Rights and Peace	Privacy / Data Management
PEACE	Digital Ethics, Human Rights and Peace	Prevention of Misuse
PEACE	Digital Ethics, Human Rights and Peace	Protection of Human Rights in Supply Chains
PEACE	Digital Responsibility and Ownership	Shared Responsibility and Ownership Incentives
PEACE	Digital Responsibility and Ownership	Stakeholders' Engagement and Management
PEACE	Digital Responsibility and Ownership	Digital Responsibility Policies and Mechanisms (CDR)
PEACE	Digital Responsibility and Ownership	Fairness-By-Design Policies
PEACE	Digital Responsibility and Ownership	Open-by-Design Policies
PEACE	Digital Responsibility and Ownership	Codes of Conduct & Certifications
PEACE	Digital Goods and Commons	Data Markets & Data Sharing Principles
PEACE	Digital Goods and Commons	Data Stewardship
PEACE	Digital Goods and Commons	Data Partnerships & Collaboratives
PEACE	Digital Goods and Commons	Openness - Open Data
PEACE	Digital Goods and Commons	Openness - Open-Source Software
PEACE	Digital Goods and Commons	Openness - Open Platforms & Apis
PEACE	Digital Goods and Commons	Openness - Open Models
PEACE	Digital Goods and Commons	Openness - Open Content & Licences
PEACE	Digital Goods and Commons	Openness - Open Standards
PEACE	Inclusive Digital Government	Online Services for Citizens (G2C)
PEACE	Inclusive Digital Government	Online Services for Employees (G2E)
PEACE	Inclusive Digital Government	Online Services for Business (G2B)
PEACE	Inclusive Digital Government	Online Services Interagency (G2G)
PEACE	Inclusive Digital Government	e-administration / e-government Processes
PEACE	Inclusive Digital Government	Digital Public Infrastructure Oversight
PLANET	Regenerative Sustainability Principles and Policies	Regeneration
PLANET	Regenerative Sustainability Principles and Policies	Ecological Protection & Resilience

PLANET	Regenerative Sustainability Principles and Policies	Climate Neutrality and Climate Adaptation
PLANET	Regenerative Sustainability Principles and Policies	Circularity
PLANET	Regenerative Sustainability Principles and Policies	Resource Efficiency
PLANET	Regenerative Sustainability Principles and Policies	Sufficiency (Sobriety)
PLANET	Regenerative Sustainability Principles and Policies	Eco-Social Connection and Transition
PLANET	Regenerative Sustainability Principles and Policies	One Health (Ecological and Human Health and Well-Being)
PLANET	Regenerative Sustainability Principles and Policies	Eco-design & Regenerative Design
PLANET	Environmental Direct Impacts	GHG Emissions / Carbon Footprint
PLANET	Environmental Direct Impacts	Water Consumption / Footprint
PLANET	Environmental Direct Impacts	Raw Materials Footprint
PLANET	Environmental Direct Impacts	Electronic Waste (e-waste)
PLANET	Environmental Direct Impacts	Ecological Footprint and Well-being
PLANET	Environmental Direct Impacts	Land Use and Change
PLANET	Environmental Direct Impacts	Biodiversity Loss
PLANET	Environmental Direct Impacts	Ecosystems and Habitat Alteration
PLANET	Environmental Direct Impacts	Air Quality
PLANET	Environmental Direct Impacts	Health Impacts
PLANET	Environmental Direct Impacts	Pollution (Air, Soil, Water, Noise)
PLANET	Environmental Direct Impacts	Pressure/Depletion of Natural Resources
PLANET	Environmental Direct Impacts	Electromagnetic Field (EMF) Emissions
PLANET	Environmental Direct Impacts	Space Debris and Pollution
PLANET	Environmental Indirect Impacts	Enabling Effect - Optimisation
PLANET	Environmental Indirect Impacts	Enabling Effect - Substitution
PLANET	Environmental Indirect Impacts	Undesirable Effects - Induction
PLANET	Environmental Indirect Impacts	Undesirable Effects - Obsolescence
PLANET	Environmental Indirect Impacts	Transboundary Spillovers
PLANET	Rebound Effects	Increase of Consumption
PLANET	Rebound Effects	Increase of Energy Use/GHG Emissions
PLANET	Systemic & Transformational Effects	Society-Wide Systemic Transformations
PLANET	Systemic & Transformational Effects	Environmental Behavioural Change (Lifestyles)
PLANET	Environmental Handprints Effects	Net-Positive Impacts (Direct or Indirect)
PLANET	Green ICT Mitigation Strategies	Eco-design/Sufficiency/Regenerative Design Strategies
PLANET	Green ICT Mitigation Strategies	Ecological Frugal Innovation /Eco-Innovation
PLANET	Green ICT Mitigation Strategies	Greentech/Renewables
PLANET	Green ICT Mitigation Strategies	Nature-Based Solutions & Biomimicry
PLANET	Green ICT Mitigation Strategies	Green Virtualisation/Green Cloud
PLANET	Green ICT Mitigation Strategies	Digital Product Passports
PLANET	Green ICT Mitigation Strategies	Green Labels/Certificates
PLANET	Green ICT Mitigation Strategies	Longevity and Upgradeability/Right-To-Repair
PLANET	Green ICT Mitigation Strategies	Longevity and Upgradeability/Reuse
PLANET	Green ICT Mitigation Strategies	Sustainable Materials & Electronics
PLANET	Green ICT Mitigation Strategies	Recyclability / Urban Mining
PLANET	Green ICT Mitigation Strategies	Green Procurement & Green Pledges
PLANET	Green ICT Mitigation Strategies	Responsible Sourcing for Supply Chains
PLANET	Green ICT Mitigation Strategies	Green Data Centres
PLANET	Green ICT Mitigation Strategies	Commonality/Resource Sharing
PLANET	Green ICT Mitigation Strategies	Sustainability Standards and Guidelines for ICTs
PLANET	Green ICT Mitigation Strategies	Energy-efficient Software, Hardware, Sustainable Computing
PLANET	Green ICT Mitigation Strategies	Energy-aware Algorithms
PLANET	Green ICT Mitigation Strategies	Sustainability Incentives for All Stakeholders
PLANET	Green ICT Mitigation Strategies	Environmental Awareness-Raising and Education for All
PLANET	Green ICT Mitigation Strategies	Behavioural Change Mechanisms and Incentives
PLANET	Digital for Sustainability Opportunities	Digital for Sustainability Incentive Programmes
PLANET	Digital for Sustainability Opportunities	Digital for Sustainability Communities of Practice
PLANET	Digital for Sustainability Opportunities	AI for Sustainability Initiatives
PLANET	Digital for Sustainability Opportunities	Biodiversity Tracking & Regeneration
PLANET	Digital for Sustainability Opportunities	ICTs for GHG Emissions Abatement
PLANET	Digital for Sustainability Opportunities	Environmental Flows Modelling
PLANET	Digital for Sustainability Opportunities	Ecological Modelling/Simulation
PLANET	Digital for Sustainability Opportunities	Environmental Remote Sensing & Tacking
PLANET	Digital for Sustainability Opportunities	Climate and Natural Disaster Response
PLANET	Digital for Sustainability Opportunities	Environmental Open Data Inventories/Analytics
PLANET	Digital for Sustainability Opportunities	Earth Observation Data/Tele-detection
PLANET	Digital for Sustainability Opportunities	Smart and Sustainable Communities (e.g., water, energy)
PLANET	Digital for Sustainability Opportunities	Bioinformatics/Bio-Robotics for Sustainability
PLANET	Digital for Sustainability Opportunities	Data-Driven ESG Reporting
PLANET	Digital for Sustainability Opportunities	Responsible Second Life/Second-Hand Platforms

PLANET	Digital for Sustainability Opportunities	Environmental Awareness Applications
PLANET	Digital for Sustainability Opportunities	Green & Ethical Nudging
PLANET	Digital for Sustainability Opportunities	Earth Digital Twin
PLANET	Digital for Sustainability Opportunities	Green Digital Innovation Hubs
PLANET	Digital for Sustainability Opportunities	Virtual Platforms and Augmented Research
PLANET	Digital for Sustainability Opportunities	Augmented Reality for Ecological Education
PLANET	Digital for Sustainability Opportunities	Green Blockchain for Traceability and Reporting
PLANET	Digital for Sustainability Opportunities	Environmental Citizen Science Platforms
PREPAREDNESS	Universal and Meaningful Connectivity	Universal Access to Reliable Internet (All Individuals)
PREPAREDNESS	Universal and Meaningful Connectivity	Universal Access to Reliable Internet (Women)
PREPAREDNESS	Universal and Meaningful Connectivity	Universal Access to Reliable Internet (Businesses)
PREPAREDNESS	Universal and Meaningful Connectivity	Universal Access to Reliable Internet (Rural/Remote)
PREPAREDNESS	Universal and Meaningful Connectivity	Affordability of Fixed Broadband
PREPAREDNESS	Universal and Meaningful Connectivity	Affordability of Mobile Broadband
PREPAREDNESS	Universal and Meaningful Connectivity	Ownership of Digital Devices
PREPAREDNESS	Universal and Meaningful Connectivity	Significant and Reliable Content Free of Disinformation
PREPAREDNESS	Universal and Meaningful Connectivity	Universal Accessibility and Usability
PREPAREDNESS	Universal and Meaningful Connectivity	Conviviality
PREPAREDNESS	Universal and Meaningful Connectivity	Free Access to Information & Basic Services
PREPAREDNESS	Sustainable and Resilient Infrastructures	Resilient, Secure, Sustainable Infrastructures
PREPAREDNESS	Sustainable and Resilient Infrastructures	Resilient, Secure, Sustainable DPIs
PREPAREDNESS	Sustainable and Resilient Infrastructures	Resilient, Secure, Sustainable Digital Systems / ICTs
PREPAREDNESS	Sustainable and Resilient Infrastructures	Cybersecurity and Resilience in Digital Assets
PREPAREDNESS	Sustainable and Resilient Infrastructures	Technical Robustness, Reliability, Explainability
PREPAREDNESS	Resilient Data Infrastructures	System Modularity and Flexibility
PREPAREDNESS	Resilient Data Infrastructures	Robust Data & Network Architectures
PREPAREDNESS	Resilient Data Infrastructures	Data Interoperability
PREPAREDNESS	Resilient Data Infrastructures	Data Availability, Quality & Integrity, Openness
PREPAREDNESS	Digital and Sustainability Capacities	Capacity Building & Lifelong Learning Mechanisms
PREPAREDNESS	Digital and Sustainability Capacities	Digital and Sustainability Awareness and Literacy
PREPAREDNESS	Digital and Sustainability Capacities	Digital and Sustainability Advanced Capacities
PREPAREDNESS	Digital and Sustainability Capacities	Resilience-oriented Skills
PREPAREDNESS	Leadership and Culture	Transformational Leadership
PREPAREDNESS	Leadership and Culture	Culture of Responsibility and Care for the Common Good
PREPAREDNESS	Leadership and Culture	Agility and Ambidexterity
PREPAREDNESS	Conducive Enabling Environment	Favourable Regulatory and Political Setting
PREPAREDNESS	Conducive Enabling Environment	Favourable Business and Investment Setting
PREPAREDNESS	Conducive Enabling Environment	Social Welfare, Cohesion, and Quality of Living
PREPAREDNESS	Conducive Enabling Environment	Resilient, Trustworthiness, and Capable Institutions
PREPAREDNESS	Conducive Enabling Environment	Availability of Reliable Renewable Electricity
PREPAREDNESS	Conducive Enabling Environment	Availability of Quality Water
PREPAREDNESS	Conducive Enabling Environment	Access to Enabling Infrastructures and Logistics
PREPAREDNESS	Conducive Enabling Environment	Supportive Digital Ecosystems
PREPAREDNESS	Crisis Preparedness and Response	Robust Early Warning and Prediction Systems
PREPAREDNESS	Crisis Preparedness and Response	Risk Reduction, Response & Recovery Plans
PREPAREDNESS	Crisis Preparedness and Response	Emergency Education for All
PEOPLE	Inclusive/Human-centred Digital Development	Whole-of-Society Approach for Inclusiveness and Equity
PEOPLE	Inclusive/Human-centred Digital Development	Just Transition Approach
PEOPLE	Inclusive/Human-centred Digital Development	Digital Equity for Bridging Digital Divides
PEOPLE	Inclusive/Human-centred Digital Development	Inclusion for Vulnerable Groups, Women, the Elderly, Children, Persons with Disabilities, Minorities
PEOPLE	Inclusive/Human-centred Digital Development	Diversity and Non-Discrimination
PEOPLE	Inclusive/Human-centred Digital Development	Intergenerational Digital Inclusion
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Digital Self-Sovereign Identity (SSI) and Digital Agency
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Safeguarding of Personal Data Privacy and Security
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Right to Be Forgotten
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Right to Digital Safety
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Freedom of Speech
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Right to Disconnect
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Right to Online Impartiality
PEOPLE	Responsible Use, Safe Adoption, Digital Rights	Awareness of Consumer Rights Protection Mechanisms
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Responsible and Safe Use of Digital Services
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Responsible and Safe Use of Social Networks
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Responsible and Safe Use of Generative AI
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Risk Awareness, Ownership, Shared Responsibility
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Ethical Behaviour Online against Disinformation/ Misuse
PEOPLE	Responsible Use, Safe Adoption, Digital Well-being	Social Perception and Acceptance

PEOPLE	Empowerment and Emotional Engagement	Engagement for Responsible Digital Development
PEOPLE	Empowerment and Emotional Engagement	Inner Transformation and Development
PEOPLE	Empowerment and Emotional Engagement	Digital Humanism
PEOPLE	Empowerment and Emotional Engagement	Societal Empowerment by Digital Solutions
PEOPLE	Inclusive Digital Participation	Safe and Accessible Virtual Civic Spaces for Everyone
PEOPLE	Inclusive Digital Participation	Accessible, Usable, Safe Citizen to Government (C2G) Platforms
PEOPLE	Inclusive Digital Participation	Accessible, Usable, Safe Citizen to Citizen (C2C) Platforms
PEOPLE	Inclusive Digital Participation	Accessible, Usable, and Safe e-Participation Platforms
PEOPLE	Digital Culture and Humanities	Accessible and Safe Virtual Content Creation Platforms
PEOPLE	Digital Culture and Humanities	Digital New Bauhaus and Safe Virtual Worlds
PEOPLE	Digital Culture and Humanities	Digital Creation, Culture, Art, Humanities
PEOPLE	Digital Culture and Humanities	Right to Intellectual Property
PEOPLE	Digital Culture and Humanities	Heritage Conservation and Preservation
PEOPLE	Digital Opportunities for Society	Digital Wellness and Inner Growth Applications
PEOPLE	Digital Opportunities for Society	Society 6.0
PEOPLE	Digital Opportunities for Society	e-learning/e-education
PEOPLE	Digital Opportunities for Society	e-inclusion
PEOPLE	Digital Opportunities for Society	e-health and Tele-Assistance
PEOPLE	Digital Opportunities for Society	Responsible Sharing Economy Platforms
PEOPLE	Digital Opportunities for Society	Virtual Volunteering and Activism
PEOPLE	Digital Opportunities for Society	Citizen Science and Knowledge Transfer Open Platforms
PROSPERITY	Equitable Digital Economy and Competitiveness	Equitable Digital Economy Policies
PROSPERITY	Equitable Digital Economy and Competitiveness	Fair Market Competitiveness Policies and Incentives
PROSPERITY	Equitable Digital Economy and Competitiveness	Fair Trade Mechanisms
PROSPERITY	Equitable Digital Economy and Competitiveness	Responsible and Sustainable E-Commerce
PROSPERITY	Equitable Digital Economy and Competitiveness	Level Playing Field Mechanisms
PROSPERITY	Equitable Digital Economy and Competitiveness	Responsible Productivity Enhancement and Automation
PROSPERITY	Equitable Digital Economy and Competitiveness	Reliant, Fair and Sustainable Value Chains
PROSPERITY	Equitable Digital Economy and Competitiveness	Responsible Digital Platform Economy
PROSPERITY	Equitable Digital Economy and Competitiveness	Ethical Digital Business Models (General)
PROSPERITY	Equitable Digital Economy and Competitiveness	Ethical Digital Business Models (Base of Pyramid)
PROSPERITY	Equitable Digital Economy and Competitiveness	Ethical Digital Products and Services
PROSPERITY	Responsible Innovation and Entrepreneurship	Responsible Digital Innovation
PROSPERITY	Responsible Innovation and Entrepreneurship	Ecological Frugal Innovation and Reverse Innovation
PROSPERITY	Responsible Innovation and Entrepreneurship	Public-Private Innovation Hubs and Ecosystems
PROSPERITY	Responsible Innovation and Entrepreneurship	Research and Innovation Incentives
PROSPERITY	Responsible Innovation and Entrepreneurship	Conscious Entrepreneurship Ecosystems
PROSPERITY	Responsible Innovation and Entrepreneurship	Digital and Sustainability Research Community and Workforce
PROSPERITY	Responsible Innovation and Entrepreneurship	Knowledge and Technology Transfer Mechanisms
PROSPERITY	Responsible Innovation and Entrepreneurship	Intellectual Property and Patent Protection
PROSPERITY	Fair Labour, Decent Jobs, Reskilling/Upskilling	Fair Labour Policies and Incentives
PROSPERITY	Fair Labour, Decent Jobs, Reskilling/Upskilling	Decent Formal Work and Living Wage
PROSPERITY	Fair Labour, Decent Jobs, Reskilling/Upskilling	Remote Working Opportunities
PROSPERITY	Fair Labour, Decent Jobs, Reskilling/Upskilling	Upskilling/Reskilling/ Future of Work
PROSPERITY	Fair Labour, Decent Jobs, Reskilling/Upskilling	Self-Employment through Digital Platforms
PROSPERITY	Responsible End-to-End Technology Lifecycle	Responsible Design and Development of Technologies
PROSPERITY	Responsible End-to-End Technology Lifecycle	Responsible Uptake and Adoption of Technologies
PROSPERITY	Responsible End-to-End Technology Lifecycle	Smart Manufacturing / Industry 5.0
PROSPERITY	Responsible End-to-End Technology Lifecycle	Smart Logistics and Mobility
PROSPERITY	Responsible End-to-End Technology Lifecycle	Health-Tech
PROSPERITY	Smart and Sustainable Communities / Services	Smart Sustainable Cities and Communities (Energy, Water, Agri)
PROSPERITY	Smart and Sustainable Communities / Services	Smart Services/ Smart Everything Everywhere
PROSPERITY	Smart and Sustainable Communities / Services	Smart Building/ Smart Home
PROSPERITY	Inclusive Digital Financing and Taxation	Inclusive and Sustainable Digital Finance/Fintech
PROSPERITY	Inclusive Digital Financing and Taxation	Sustainable and Impact Finance for Digital Transformation
PROSPERITY	Inclusive Digital Financing and Taxation	Accessible, Secure, and Inclusive Online Banking
PROSPERITY	Inclusive Digital Financing and Taxation	Accessible, Secure, and Inclusive Digital Payments/e-Wallets
PROSPERITY	Inclusive Digital Financing and Taxation	Secure and Sustainable Smart Contracts
PROSPERITY	Inclusive Digital Financing and Taxation	Secure and Sustainable Virtual Currencies
PROSPERITY	Inclusive Digital Financing and Taxation	Tax Incentives for Sustainability and SRDT
PROSPERITY	Inclusive Digital Financing and Taxation	Anti-Fraud Mechanisms and Traceable Transactions
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Multilevel Digital Cooperation Mechanisms
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Digital Cooperation Agreements / Binding Commitments
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Effective Global Architecture for Digital Development
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Binding Global Digital Agenda for SRDT
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Global Commission on SRDT

PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Cross-Border Trade and Data Flows Binding Agreements
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Digital Diplomacy Mechanisms and Capacities
PARTNERSHIPS	Multilevel Digital Cooperation and Diplomacy	Cross-Border Cooperation for Risk Management, and Crisis Response
PARTNERSHIPS	Multi-stakeholder Communities and Alliances	Public-Private Partnerships for Digital Cooperation
PARTNERSHIPS	Multi-stakeholder Communities and Alliances	Multi-Stakeholder Alliances for SRDT
PARTNERSHIPS	Multi-stakeholder Communities and Alliances	Alliances for Digital Humanitarian Action
PARTNERSHIPS	Multi-stakeholder Communities and Alliances	Empowered Convivial and Collaborative Communities
PARTNERSHIPS	Multilateral Programmes for SRDT	Global Programmes and Funding for SRDT
PARTNERSHIPS	Multilateral Programmes for SRDT	North-South, South-South, Triangular Cooperation
PARTNERSHIPS	Multilateral Programmes for SRDT	Capacity Building, Technical Assistance for Vulnerable Groups
PARTNERSHIPS	Multilateral Programmes for SRDT	Capacity Building, Technical Assistance for Women
PARTNERSHIPS	Multilateral Programmes for SRDT	Cross-Border Scientific and Technological Cooperation
PARTNERSHIPS	Multilateral Programmes for SRDT	Global Repositories for Environmental Open Data
PARTNERSHIPS	Multilateral Programmes for SRDT	Global Open Platforms for Education, Knowledge Sharing, and Co-creation on SRD
PARTNERSHIPS	Multilateral Programmes for SRDT	Global Awareness Campaigns for the Younger Generations

ANNEX III. Questionnaire for the Expert Interviews

CUESTIONARIO I: HERRAMIENTAS PARA UNA TRANSFORMACIÓN DIGITAL SOSTENIBLE Y REGENERATIVA HACIA UNA TRIPLE TRANSICIÓN

A.1. MOTIVACIÓN DEL CUESTIONARIO Y DECLARACIÓN DE PROTECCIÓN DE DATOS

Motivación

Este cuestionario tiene como objetivo recopilar opiniones de expertos en el campo científico de la transformación digital sostenible e innovación, como parte del proceso de obtención de información de expertos dentro de la metodología de una tesis doctoral.

Declaración de tratamiento de datos

Sus respuestas se utilizarán únicamente con fines de investigación académica y los datos personales se tratarán de acuerdo con las regulaciones de protección de datos. Su identidad personal permanecerá confidencial si así lo solicita. Gracias por su colaboración.

NÚMERO DE CUESTIONARIO:

EXPERTO/A:

OBSERVACIONES: ámbito de conocimiento, tipo de actor, afiliación, etc.

A.2. CONTEXTO Y DEFINICIONES

BREVE CONTEXTO DE LA INVESTIGACIÓN

Esta investigación se centra en el estudio y conceptualización de la interrelación entre la transformación digital y la sostenibilidad, para reorientarlas hacia un enfoque más holístico y regenerativo que permita abordar los desafíos actuales. A pesar de las prometedoras oportunidades que este nexo ofrece, ambas transiciones permanecen desconectadas, impidiendo aprovechar plenamente sus ventajas y mitigar los riesgos inherentes a las disrupciones digitales.

Además, existe una narrativa ingenua en torno a la transformación digital, que a menudo se presenta como una herramienta inmaterial, capaz de optimizar y resolver todos los retos científicos y sociales sin generar impactos negativos. Esta narrativa tecno-optimista, alejada de la realidad, ha sido adoptada por los principales marcos gubernamentales y empresariales, agravando la problemática.

Adicionalmente, el rápido desarrollo tecnológico digital ha acontecido sin el adecuado desarrollo teórico y normativo para una óptima gobernanza e integración de aspectos sociales, ambientales. La ausencia de una adecuada conceptualización, unido a la omisión de la perspectiva de la sostenibilidad en la mayoría de los marcos de desarrollo digital, se ve acentuada por la ausencia de metodologías y estándares, así como de datos adecuados para evaluar los impactos. Al mismo tiempo, las agendas de sostenibilidad, en concreto, la Agenda 2030, también presentan retos de diseño y una deficiente integración de aspectos vitales para el desarrollo, como la transformación digital o la innovación. Asimismo, la regeneración es una tendencia aún incipiente incluso en el ámbito de la ecología.

Todo este contexto ha derivado en una alta fragmentación, ausencia de terminología consensuada, falta de alineamiento, así como de múltiples controversias alrededor de los riesgos y oportunidades del nexo entre digitalización y sostenibilidad. Por todo ello, se evidencia la necesidad de mejorar la conceptualización de la transformación digital desde una perspectiva de sostenibilidad regenerativa, proponiendo enfoques que permitan una mejor comprensión de los fenómenos involucrados, así como herramientas prácticas que faciliten la convergencia entre ambas agendas, reorientándolas hacia la regeneración y la triple transición.

En la presente investigación se propone una taxonomía que aporta una mejor definición conceptual de los factores que influyen una transformación digital sostenible y regenerativa para la triple transición, con las siguientes motivaciones: a) informar de los riesgos y oportunidades en la formulación de prioridades políticas o agendas de investigación; b) concienciar acerca de aspectos relevantes que precisan más investigación y que actualmente no se consideran en los marcos de digitales o de sostenibilidad; c) mejorar la clasificación del conocimiento disponible para una mejor toma de decisiones, para impulsar la triple transición digital, ecológica y socialmente justa.

Adicionalmente, con objeto de trasladar estos resultados conceptuales a una implementación práctica que permita catalizar una transformación digital sostenible y regenerativa, se plantea definir unos objetivos estratégicos a partir de la taxonomía. Para cada pilar de la taxonomía se propone una meta general y para cada subdimensión comprendida en dicha meta, se propone un objetivo estratégico. En total 6 metas y 36 objetivos recogen las prioridades para movilizar la acción hacia la materialización de la triple transición.

Asimismo, para favorecer una monitorización eficiente que promueva la concienciación en relación con esta visión de triple transición, se define una “Report Card” (boletín de reporte). Para su formulación, se parte de los objetivos estratégicos para los que se establecen métricas que permiten medir el progreso hacia una transformación digital sostenible y regenerativa que catalice la triple transición. El esquema del proceso de desarrollo de las herramientas propuestas se describe, a continuación, en la Figura 1.

Figura 1: Esquema de las herramientas propuestas para promover una Transformación Digital Sostenible y Regenerativa (SRDT).



A.3. DEFINICIONES RELEVANTES / TERMINOLOGÍA RELEVANTE

TRANSFORMACIÓN DIGITAL

En esta investigación, la transformación digital no abarca únicamente la integración de tecnología, sino los cambios culturales, sociales, organizativos y operativos que resultan de la adopción a gran escala de soluciones digitales. Estos cambios requieren una óptima adaptación a un entorno digital en constante evolución.

SOSTENIBILIDAD REGENERATIVA

El concepto de regeneración en el ámbito de la sostenibilidad, o sostenibilidad regenerativa, se refiere a un enfoque que busca restaurar y revitalizar los sistemas naturales, sociales y económicos, en lugar de simplemente mantenerlos o minimizar el impacto negativo sobre ellos. Este enfoque persigue activamente mejorar y regenerar los sistemas eco-sociales, reequilibrando la relación entre sociedad y naturaleza, para alcanzar un equilibrio mutuamente beneficioso. Está íntimamente relacionada con la convivencia, que implica la creación de entornos y prácticas que fomenten la interacción, la cooperación y el bienestar colectivo, promoviendo un uso equitativo y responsable de los recursos, dentro de los límites ambientales y sociales.

TRANSFORMACIÓN DIGITAL SOSTENIBLE Y REGENERATIVA (SRDT)

Este concepto se refiere a la aplicación de principios de sostenibilidad y regeneración en el proceso de transformación digital de una organización o de la sociedad. Esto implica utilizar las soluciones digitales de manera responsable y consciente para promover beneficios en los sistemas naturales, sociales y económicos y contribuir a su equilibrio y renovación, al tiempo que se mitigan los riesgos inherentes. En este enfoque, la tecnología y demás elementos de transformación digital se utilizan como una herramienta para crear valor de manera sostenible y equitativa, maximizando los beneficios para la renovación eco-social.

TRIPLE TRANSICIÓN

Según la OCDE (2023), la “triple transición” se refiere a un enfoque sistémico que enfatiza la fuerte interconexión existente entre los aspectos ecológicos, sociales y digitales para el desarrollo. Este enfoque aspira a poder afrontar mejor los actuales y complejos retos globales, al tiempo que promueve un desarrollo genuinamente sostenible e inclusivo.

MODELO DE INNOVACIÓN DE HÉLICES

El Modelo de Hélices de Innovación es un marco conceptual que describe la interacción y colaboración entre varios actores o subsistemas de la sociedad para impulsar soluciones innovadoras en un sentido amplio, la creación y difusión del conocimiento, así como el desarrollo socioeconómico. El modelo implica múltiples hélices, representando a diferentes grupos de interés o subsistemas sociales, trabajando juntos de manera sinérgica. El modelo más conocido y aplicado es el de la triple hélice, formado por el sector científico o académico (universidad), el sector empresarial y el sector público.

PACTO DIGITAL GLOBAL (DIGITAL GLOBAL COMPACT - GDC)

El Pacto Digital Global (GDC) de Naciones Unidas, cuya publicación se espera para otoño de 2024, representa un marco destinado a crear un futuro digital más inclusivo, abierto y seguro, mediante la promoción de la cooperación y la gobernanza internacional. El GDC se basa en principios de la Carta de las Naciones Unidas, la Declaración Universal de los Derechos Humanos y la Agenda 2030. Sin embargo, su primer borrador, ha sido ampliamente criticado por expertos ambientales y sociales (CODES, 2023; Unwind, 2024) debido a su débil integración de la sostenibilidad ambiental y su dependencia de una narrativa convencional y tecnocrática de la transformación digital.

B. CONTEXTO Y PERCEPCIONES SOBRE LA INTERRELACIÓN ENTRE TRANSFORMACIÓN DIGITAL Y SOSTENIBILIDAD

Por favor, exprese su opinión sobre los posibles impactos de la transformación digital en la sostenibilidad social y ambiental.

PREGUNTA 1. En su opinión, ¿el panorama actual de la transformación digital probablemente brinde a la sociedad?:

- *Más impactos positivos que negativos, resultando en un efecto general positivo.*
- *Más impactos negativos que positivos, resultando en un efecto general negativo.*
- *Tanto efectos positivos como negativos, con un impacto neto aún desconocido.*
- *Otra respuesta, por favor describa su opinión a continuación: _____*

PREGUNTA 2. ¿Cómo percibe el impacto potencial de la transformación digital en los siguientes aspectos de la sostenibilidad y en los grupos temáticos de los Objetivos de Desarrollo Sostenible (ODS)?

Por favor, califique en una escala del 1 al 5 cada grupo de ODS, donde el 1 indica un impacto muy negativo y el 5 indica un impacto muy positivo:

- **Objetivos sociales** (ODS 1: Fin de la Pobreza; ODS 2: Hambre Cero; ODS 3: Salud y Bienestar; ODS 4: Educación de Calidad; ODS 5: Igualdad de Género; ODS 10: Reducción de las Desigualdades).
Impacto en el grupo de objetivos sociales → (1: impacto muy negativo; 2: impacto negativo; 3: impacto neutral; 4: impacto positivo (aunque será muy desigual entre los 6); 5: impacto muy positivo).
- **Objetivos ambientales** (ODS 6: Agua Limpia y Saneamiento; ODS 7: Energía Asequible y No Contaminante; ODS 12: Producción y Consumo Responsables; ODS 13: Acción por el Clima; ODS 14: Ecosistemas marinos; ODS 15: Ecosistemas Terrestres).
Impacto en el grupo de objetivos ambientales → (1: impacto muy negativo; 2: impacto negativo; 3: impacto neutral; 4: impacto positivo; 5: impacto muy positivo).
- **Objetivos socioeconómicos** (ODS 8: Trabajo Decente y Crecimiento Económico; ODS 9: Industria, Innovación e Infraestructura; ODS 11: Ciudades y Comunidades Sostenibles).
Impacto en el grupo de objetivos socioeconómicos → (1: impacto muy negativo; 2: impacto negativo (especialmente en lo relativo a trabajo de calidad, entornos sostenibles e igualdad en la distribución de la riqueza); 3: impacto neutral; 4: impacto positivo; 5: impacto muy positivo).
- **Objetivos de gobernanza y medios de implementación** (ODS 16: Paz, Justicia e Instituciones Sólidas; ODS 17: Alianzas para Lograr los Objetivos).
Impacto en el grupo de objetivos de gobernanza y medios de implementación → (1: impacto muy negativo; 2: impacto negativo; 3: impacto neutral; 4: impacto positivo; 5: impacto muy positivo).

C. HERRAMIENTAS PARA LA CONCEPTUALIZACIÓN E IMPLEMENTACIÓN DE LA TRANSFORMACIÓN DIGITAL SOSTENIBLE Y REGENERATIVA

C.1. TAXONOMÍA PARA LA TRANSFORMACIÓN DIGITAL SOSTENIBLE Y REGENERATIVA.

C.1.1. INTRODUCCIÓN

Se presenta a continuación, una propuesta de taxonomía, que clasifica las dimensiones, subdimensiones y factores temáticos relevantes, en relación con la conceptualización de la transformación digital en relación con sus posibles impactos y oportunidades en la sostenibilidad. El objetivo es conceptualizar los factores que caracterizan una transformación digital sostenible y regenerativa que contribuya a una visión de triple transición en la sociedad y economía.

*Las taxonomías representan una valiosa herramienta para la clasificación, conceptualización y comprensión de un dominio científico, así como para facilitar una mejor toma de decisiones. Aunque se originaron en el ámbito de la ecología, en la actualidad se han extendido a todas las disciplinas científicas, incluyendo las relativas al sector digital. No obstante, en la esfera digital aún son incipientes y **no existe ninguna clasificación ni ontología para el nexo entre transformación digital y sostenibilidad.***

En esta investigación, se ha desarrollado una taxonomía de los factores que contribuyen a una transformación digital sostenible, inclusiva y regenerativa. Para ello, se ha realizado una revisión sistémica de la literatura, científica y gris, incluyendo más de 350 marcos internacionales en materia de transformación digital y sostenibilidad, así como su intersección.

Se ha priorizado la selección de marcos de transformación digital, dado que el ámbito científico es más incipiente y, en especial, aquellos que integran factores o principios dedicados a la sostenibilidad o el desarrollo sostenible. En la revisión de la literatura, se evidencia, un relevante hueco de conocimiento en la integración de la sostenibilidad en los marcos digitales. Este reto, es especialmente severo y complejo en lo que respecta a la dimensión ambiental, que permanece muy poco representada.

*Mediante análisis cualitativo y herramientas de minería de textos y modelización de temáticas, se han identificado los dominios y factores temáticos más relevantes de los fenómenos investigados, según el estado del arte. Asimismo, con el conocimiento adquirido mediante el exhaustivo análisis cualitativo desarrollado, se han clasificado los fenómenos de estudio en **seis pilares o dimensiones principales, 36 subdimensiones y 255 factores temáticos de interés.***

*De estos seis pilares (ver Figura 2), **cinco de ellos están inspirados en los respectivos de la Agenda 2030** (planeta, personas, prosperidad, paz y partenariados), para asegurar su alineamiento con marcos aceptados en la comunidad internacional.*

*Adicionalmente, como aportación de la investigación, se ha propuesto un sexto pilar dedicado a la **“preparación”** frente a las crisis y retos globales, esencial para afrontar de manera eficiente y responsable la triple transición ecológica, socialmente justa y digital. Este nuevo pilar, se ha concebido considerando su alineación con las prioridades de los marcos reconocidos para la transformación digital y el desarrollo sostenible.*

*En definitiva, “preparación” significa **disponer de la capacidad, los medios, la cultura y compromiso estratégico, así como de un entorno facilitador y favorable**, para hacer frente a los complejos retos globales actuales, como son las transformaciones digitales y de sostenibilidad ecológica y social.*

*De tal modo, la taxonomía propuesta ofrece una **panorámica holística de lo que constituye una transformación digital sostenible y regenerativa**, alineada con los actuales marcos y recogiendo las tendencias más punteras de los ámbitos de estudio de la sostenibilidad y la digitalización.*

Figura 2: Esquema de los seis pilares de la Taxonomía propuesta.



PREGUNTA 3.

En relación con el pilar propuesto para Preparación en respuesta a las crisis y los retos globales que plantea la triple transición:

3.a. ¿Considera que la integración de este pilar es coherente y relevante para el objetivo de lograr una mejor conceptualización e implementación de una transformación digital sostenible y regenerativa?

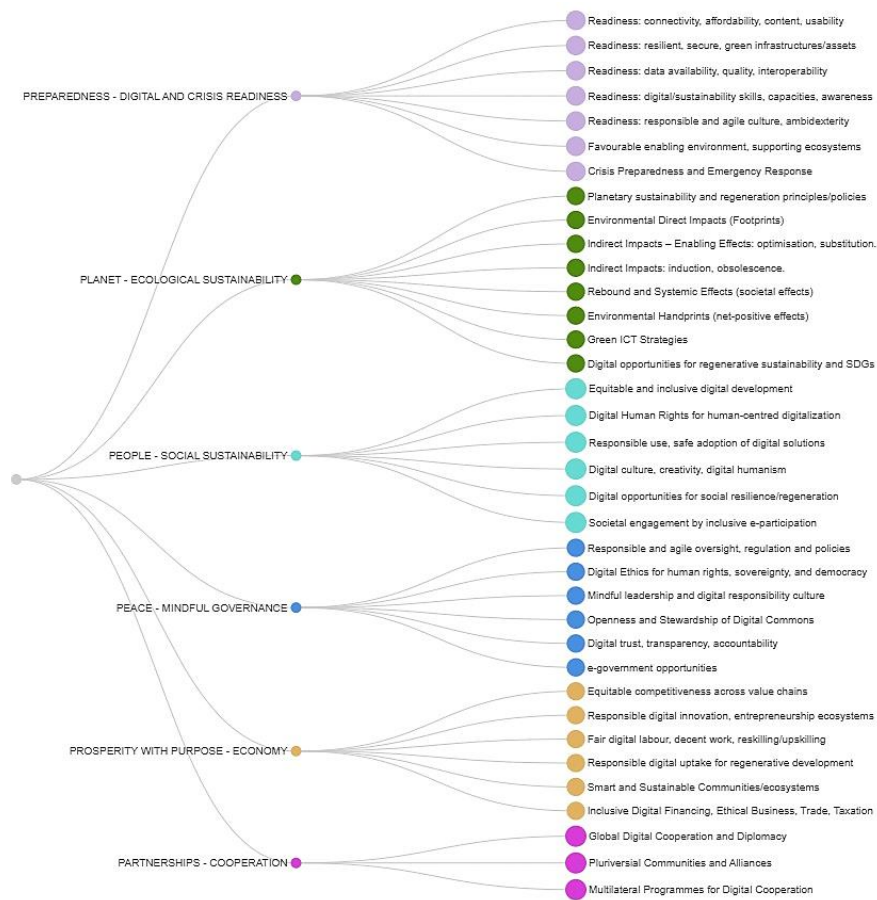
3.b. ¿Considera que integrar los restantes pilares de la Agenda 2030 en los marcos de transformación digital, es coherente y relevante para dar respuesta a la actual falta de sincronización entre la transformación digital y la sostenibilidad?

C.1.2. SUBDIMENSIONES DE LA TAXONOMÍA PROPUESTA

En relación con los dominios propuestos (ver Figura 3) como aportación de esta investigación, cabe destacar que han sido formuladas considerando los huecos de investigación actuales y la necesaria reorientación de la transformación digital hacia una sostenibilidad regenerativa. Esto es, lograr la convergencia entre las agendas digital y de sostenibilidad, para generar oportunidades y mitigar los riesgos hacia una triple transición. Entre ellas, destacan especialmente, las correspondientes al pilar de preparación, para fomentar la resiliencia, la respuesta a crisis, la sostenibilidad y la inclusión.

Asimismo, destacan las relativas al pilar de la sostenibilidad ambiental, dado que es la dimensión más débil y peor representada en los marcos digitales. En gran parte, esta circunstancia se debe a una falta de concienciación sobre los riesgos ambientales, pero también, a notables controversias y complejos retos, para los que actualmente no existe una respuesta consensuada, representando un área prometedora de investigación.

Figura 3: Esquema de los dominios propuestos para la taxonomía.



PREGUNTA 4.

En lo que respecta a las 7 subdimensiones propuestas para el pilar de Preparación (ver tabla 1 y figura 3):

¿Considera que esta propuesta es coherente, relevante y aporta valor a la conceptualización de esta dimensión para promover una transformación digital sostenible y regenerativa?

PREPAREDNESS - DIGITAL AND CRISIS READINESS	Readiness: connectivity, affordability, relevant content, and usability
	Readiness: resilient, secure, green infrastructures/assets/systems
	Readiness: data availability, quality, interoperability, and openness.
	Readiness: digital and sustainability skills, capacities, and awareness
	Readiness: responsible and agile culture, ambidexterity for tackling transformations
	Favourable enabling environment and supporting ecosystems
	Crisis Preparedness and Emergency Response

Tabla 1. Subdimensiones correspondientes al pilar de Preparación.

PREGUNTA 5.

En lo relativo a las 8 subdimensiones propuestas para el pilar de sostenibilidad planetaria o ecológica (ver tabla 2 y figura 3): ¿Considera que esta propuesta es coherente, relevante y aporta valor a la conceptualización de esta dimensión para promover una transformación digital sostenible y regenerativa que promueva las oportunidades y mitigue los riesgos en el medio ambiente?

PLANET – ENVIRONMENTAL SUSTAINABILITY	Planetary sustainability and regeneration principles and policies
	Environmental Direct Impacts (first-order effects – footprints, e.g. direct GHG emissions or electronic waste)
	Indirect Impacts (second-order desirable enabling effects: optimisation, substitution).
	Indirect Impacts (second-order undesirable effects: induction, obsolescence).
	Rebound and Systemic Effects (unintended high-order effects, societal effects)
	Environmental Handprints (net-positive effects within or beyond the ICT sector)
	Green ICT (mitigation strategies for greening the ICT sector and raising awareness)
	Digital opportunities for regenerative sustainability and SDGs (e.g. digital tools for monitoring biodiversity or climate change effects).

Tabla 2. Subdimensiones correspondientes al pilar de Planeta.

PREGUNTA 6.

En relación con el resto de los pilares propuestos (paz, personas, prosperidad y partenariados), y según su área de conocimiento y/o experiencia, por favor indique a continuación: Su valoración general de la coherencia, relevancia y valor aportado por los dominios propuestos para la conceptualización de una transformación digital sostenible y regenerativa (ver tabla 3 y figura 3).

PILLAR/DIMENSION	THEME
PARTNERSHIPS - COOPERATION	Global Digital Cooperation and Diplomacy
	Multi-stakeholder communities and alliances for inclusivity and diversity
	Multilateral programmes for integrating sustainability within digital cooperation mechanisms
PEACE - MINDFUL GOVERNANCE	Responsible and agile oversight, regulation, and policies
	Digital Ethics for human rights, sovereignty, and democracy
	Mindful leadership and digital responsibility culture
	Openness and Stewardship of Digital Commons
	Digital trust, transparency, and accountability
	e-government opportunities
PEOPLE - SOCIAL SUSTAINABILITY	Equitable and inclusive digital development
	Empowerment for Digital Human Rights and human-centred digitalization
	Responsible use and safe adoption of digital solutions
	Digital culture, creativity, and digital humanism
	Digital opportunities for social resilience/regeneration
	Societal engagement by inclusive e-participation
PROSPERITY WITH PURPOSE - ECONOMY	Equitable competitiveness across value chains
	Responsible digital innovation and entrepreneurship ecosystems
	Fair digital labour, decent work, reskilling/upskilling
	Responsible digital uptake for regenerative development
	Smart and Sustainable Communities/ecosystems
	Inclusive Digital Financing, Ethical Business, Fair Trade and Taxation

Tabla 3. Subdimensiones correspondientes a los pilares de partenariados (cooperación), paz (gobernanza), personas (sostenibilidad social) y prosperidad (dimensión socioeconómica).

C.2. OBJETIVOS PARA MOVILIZAR LA TRANSFORMACIÓN DIGITAL SOSTENIBLE Y REGENERATIVA HACIA LA TRIPLE TRANSICIÓN

A continuación, se presentan las metas y objetivos estratégicos propuestos para transitar desde la conceptualización lograda mediante la taxonomía propuesta a la implementación. Por tanto, estas metas y objetivos configuran la agenda estratégica para avanzar hacia una transformación digital sostenible y regenerativa para una triple transición.

PREGUNTA 7.

7.a. En relación con la meta y objetivos propuestos para el pilar de preparación (ver tabla 4), por favor indique su valoración cualitativa respecto a su coherencia, relevancia y potencial de implementación para avanzar hacia la visión de una transformación digital sostenible y regenerativa.

7.b. En su opinión, el enfoque regenerativo propuesto para esta meta ¿es coherente y relevante o sería necesario reforzarlo?

7.c. Asimismo, por favor, puntúe la relevancia de esta meta y objetivos propuestos, siguiendo la siguiente escala: Muy relevante (5); Relevante (4); Neutral (3); Poco relevante (2); nada relevante (1).

PILAR	META Y OBJETIVOS
1. PREPARACIÓN RESPUESTA A CRISIS Y PREPARACIÓN PARA LA TRIPLE TRANSICIÓN REGENERATIVA	META 1: Lograr una Conectividad Significativa y Preparación frente a Crisis para 2035, para aprovechar las oportunidades digitales para la humanidad y el planeta. Objetivo 1.1: Asegurar el acceso universal, asequible y seguro a la conectividad, servicios digitales y contenido significativo para todas las personas. Objetivo 1.2: Desarrollar infraestructuras y sistemas seguros, sostenibles, resilientes e interoperables para una transformación digital regenerativa (priorizando la soberanía, la sobriedad y el ecodiseño). Objetivo 1.3: Desarrollar arquitecturas de datos y sistemas de administración resilientes, interoperables, abiertos y sostenibles que protejan y maximicen su valor social. Objetivo 1.4: Cultivar habilidades y capacidades digitales y de sostenibilidad, para cerrar brechas y aumentar la concienciación sobre riesgos y oportunidades de la triple transición. Objetivos 1.5: Promover una cultura consciente, ágil y ambidiestra para maximizar las oportunidades digitales y mitigar sus riesgos, para un desarrollo regenerativo. Objetivo 1.6: Impulsar un entorno facilitador y ecosistemas favorables para el florecimiento de una transformación digital consciente, sostenible y regenerativa. Objetivo 1.7: Desarrollar capacidades robustas de respuesta a crisis a través de soluciones digitales sostenibles e inclusivas.

Tabla 4. Metas y objetivos relativos al pilar de preparación.

PREGUNTA 8.

Los aspectos ambientales son los menos integrados en los marcos digitales y los que mayores controversias y retos de investigación presentan, según la literatura. En la actualidad, no existe una clasificación consensuada en relación con los posibles impactos de la transformación digital en el ámbito ambiental, aunque habitualmente se catalogan en directos (ciclo de vida de las TIC), indirectos (positivos y facilitadores; o negativos ligados a la obsolescencia o la inducción del consumo), y efectos rebote ligados a la paradoja de Jevons para la eficiencia energética. No existe clasificación consensuada en relación con posibles efectos netos positivos, ni para aplicaciones digitales para el sector ambiental. Según lo expuesto:

8.a. En relación con la meta y objetivos propuestos para el pilar de sostenibilidad planetaria (ver tabla 5), por favor indique su valoración cualitativa respecto a su coherencia, relevancia y potencial de implementación para avanzar hacia la visión de una transformación digital sostenible y regenerativa.

8.b. En su opinión, el enfoque regenerativo propuesto para esta meta ¿es coherente y relevante o sería necesario reforzarlo?

8.c. Asimismo, por favor, puntúe la relevancia de esta meta y objetivos propuestos, siguiendo la siguiente escala: Muy relevante (5); Relevante (4); Neutral (3); Poco relevante (2); nada relevante (1).

PILAR	META Y OBJETIVOS
2. PLANETA REGENERACIÓN AMBIENTAL PARA LA TRANSICIÓN ECOLÓGICA	META 2: Lograr una Transformación Digital Regenerativa, Circular, Climáticamente Neutra, y dentro de los Límites Planetarios para 2035 Objetivo 2.1.: Promover principios y políticas de sostenibilidad regenerativa en las estrategias digitales de todas las organizaciones para promover sus beneficios y mitigar los riesgos para el medio natural y la salud humana. Objetivo 2.2.: Establecer incentivos para reducir la huella ambiental y fomentar la sobriedad de las infraestructuras, sistemas y dispositivos digitales, hacia un desarrollo digital circular, climáticamente neutro y regenerativo. Objetivo 2.3.: Desarrollar metodologías y estándares para evaluar los efectos (directos, indirectos y rebote) asociados a las soluciones digitales. Objetivo 2.4: Desarrollar inventarios de datos abiertos para monitorizar los impactos ambientales y efectos facilitadores de las infraestructuras, soluciones y sistemas digitales. Objetivo 2.5.: Establecer un mecanismo de reporte socioambiental (ESG) y rendición de cuentas específico a las necesidades del sector digital, para promover transformaciones eco-sociales. Objetivo 2.6.: Priorizar incentivos para prácticas sostenibles de “Green ICT” que mitiguen los efectos negativos de la digitalización, promoviendo el ecodiseño, el aprovisionamiento responsable y la sobriedad digital. Objetivo 2.7.: Sensibilizar sobre las prácticas de consumo y producción sostenibles en el sector digital y desarrollar habilidades verdes para mitigar prácticas dañinas y falsos reclamos verdes. Objetivo 2.8: Fomentar el desarrollo de aplicaciones digitales para la protección de la biodiversidad y los ecosistemas frente al cambio climático, con el fin de generar impactos netos positivos para el planeta y las personas, hacia el cumplimiento de los ODS.

Tabla 5. Metas y objetivos relativos al pilar de sostenibilidad planetaria.

PREGUNTA 9

Finalmente, en relación con su ámbito de conocimiento sobre los siguientes pilares y dimensiones temáticas (ver tabla 6) relativas a personas (aspectos sociales), prosperidad (aspectos socioeconómicos), paz (gobernanza) y partenariados (cooperación global), por favor indique:

9.a. Valoración cualitativa respecto a su coherencia, relevancia y potencial de implementación para avanzar hacia la visión de una transformación digital sostenible y regenerativa para la triple transición.

9.b. Asimismo, por favor, puntúe la relevancia de estas metas y objetivos propuestos, siguiendo la siguiente escala: Muy relevante (5); Relevante (4); Neutral (3); Poco relevante (2); nada relevante (1).

PILAR	METAS Y OBJETIVOS
3. PERSONAS TRANSICIÓN JUSTA PARA LA REGENERACIÓN SOCIAL	META 3: Realizar una Transformación Digital Inclusiva, Segura y Socialmente Resiliente para 2035, fomentando Oportunidades Positivas para Todos. Objetivo 3.1: Salvaguardar la inclusividad, la equidad y los derechos humanos en todas las iniciativas digitales y mundos virtuales para una transformación digital centrada en valores humanos. Objetivo 3.2: Empoderar y capacitar a las personas y comunidades para un uso y adopción seguros de soluciones y contenido digitales que respeten los derechos humanos y contribuyan a un desarrollo regenerativo. Objetivo 3.3: Promover soluciones digitales con impacto positivo, para abordar desafíos eco-sociales y fomentar oportunidades regenerativas para las personas (por ejemplo, e-educación, e-salud, acceso a espacios de participación o cultura). Objetivo 3.4: Crear espacios virtuales seguros para la e-participación que promuevan el humanismo digital y la regeneración social. Objetivo 3.5: Concienciar a nivel social acerca de los derechos humanos digitales y dotar de herramientas accesibles para su protección a todas las personas y en especial a los más vulnerables.

	Objetivo 3.6: Proteger la cultura inclusiva, la creatividad humana y los valores humanistas ante los desafíos de la Inteligencia Artificial Generativa y los Mundos Virtuales.
4. PROSPERIDAD CON PROPÓSITO TRANSICIÓN SOCIOECONÓMICA REGENERATIVA	META 4: Impulsar una Economía Digital Equitativa, Competitiva e Innovadora para 2035, cultivando oportunidades hacia un desarrollo regenerativo Objetivo 4.1.: Fomentar la innovación responsable, la transferencia de conocimiento y el emprendimiento con propósito para ofrecer nuevas soluciones digitales que prioricen los valores sociales y ecológicos. Objetivo 4.2.: Promover condiciones equitativas e incentivos para una competencia justa y sostenible en el mercado digital y sus cadenas de valor, mitigando el colonialismo digital y la concentración de poder. Objetivo 4.3.: Fomentar el desarrollo y la adopción responsable de tecnologías digitales sostenibles que permitan responder a retos sociales y ecológicos. Objetivo 4.4.: Impulsar inventivos y marcos para una financiación inclusiva y sostenible, modelos de negocio éticos para plataformas digitales y “Fintech”, así como comercio y fiscalidad justos. Objetivo 4.5.: Abordar el futuro del trabajo promoviendo empleos formales decentes, mejora de habilidades y oportunidades para un desarrollo digital equitativo. Objetivo 4.6.: Impulsar comunidades inteligentes y sostenibles que favorezcan una transformación digital sectorial con impacto positivo para un desarrollo regenerativo que empodere a las personas y favorezca la corresponsabilidad social.
5. PAZ GOBERNANZA CONSCIENTE Y RESPONSABLE PARA LA REGENERACIÓN	META 5: Impulsar una Gobernanza Ética y un Liderazgo Consciente para 2035 hacia una Transformación Digital Regenerativa e Inclusiva Objetivo 5.1.: Instituir una supervisión sólida, marcos regulatorios y estándares para garantizar una gobernanza ética, promoviendo la soberanía, la democracia y la protección de los derechos humanos en el ámbito digital. Objetivo 5.2: Establecer un marco global eficiente para la Ética Digital que integre sólidamente la sostenibilidad regenerativa y promover incentivos para su implementación universal. Objetivo 5.3.: Fomentar un liderazgo consciente y políticas de responsabilidad digital que promuevan la regeneración eco-social y el pluralismo en las estrategias digitales. Objetivos 5.4.: Desarrollar políticas y mecanismos que aseguren un gobierno electrónico ético, inclusivo y sostenible con fuerte involucración de la sociedad civil y las empresas para una administración accesible. Objetivos 5.5.: Asegurar el acceso abierto y una adecuada administración de los bienes digitales comunes para abordar los desafíos eco-sociales, fomentando la convivencia y comunalidad. Objetivos 5.6.: Mejorar la confianza digital a través de mecanismos reforzados de rendición de cuentas equitativos que incentiven la transparencia.
6. PARTENARIADOS COOPERACIÓN DIGITAL PARA LA REGENERACIÓN	META 6: Promover la Cooperación y Participación Digital Global para 2035, a través de asociaciones pluriversales y multiactor Objetivo 6.1.: Establecer una estructura multilateral óptima y un marco de políticas universal para reforzar la cooperación global y la diplomacia para abordar desafíos geopolíticos y la promoción de la triple transición a nivel mundial. Objetivo 6.2.: Forjar alianzas multiactor, multidisciplinares y pluriversales, para impulsar la cooperación tecnológica, el intercambio de conocimiento y la co-creación de soluciones para impulsar la transformación digital regenerativa a nivel mundial. Objetivo 6.3.: Reforzar programas multilaterales para la cooperación y la creación de capacidades específicas a la transformación digital sostenible y regenerativa, asegurando espacios digitales seguros y resilientes, así como combatiendo prácticas insostenibles y amenazas cibernéticas.

Tabla 6. Metas y objetivos relativos a los pilares: personas, prosperidad, paz y partenariados.

RESPUESTA 9:**9.a. PERSONAS - TRANSICIÓN JUSTA, REGENERACIÓN SOCIAL:**

- **VALORACIÓN DESCRIPTIVA**
- **PUNTUACIÓN**

9.b. PROSPERIDAD CON PROPÓSITO - TRANSICIÓN SOCIOECONÓMICA:

- **VALORACIÓN DESCRIPTIVA**
- **PUNTUACIÓN**

9.c. PAZ - GOBERNANZA CONSCIENTE Y RESPONSABLE:

- **VALORACIÓN DESCRIPTIVA**
- **PUNTUACIÓN**

9.d. PARTENARIADOS -COOPERACIÓN DIGITAL:

- **VALORACIÓN DESCRIPTIVA**
- **PUNTUACIÓN**

D. INTEGRACIÓN DE LA TRANSFORMACIÓN DIGITAL EN EL MARCO DE LA AGENDA 2030 DE NACIONES UNIDAS PARA EL DESARROLLO SOSTENIBLE

De forma análoga a lo que sucede con la insuficiente integración de la sostenibilidad en la transformación digital, los marcos de sostenibilidad (o desarrollo sostenible) no disponen de una integración sólida de los riesgos y oportunidades que entraña la disrupción digital. Esto puede dificultar la oportunidad de reorientar ambas agendas, la de sostenibilidad y digital, para lograr un desarrollo regenerativo. En el actual contexto de la Agenda 2030 para el Desarrollo Sostenible (ONU, 2015), los indicadores para la dimensión digital resultan insuficientes:

- *Indicador 4.4.1: Proporción de jóvenes y adultos con habilidades en TIC, por tipo de habilidades*
- *Indicador 5.b.1: Proporción de individuos que poseen un teléfono móvil, por sexo*
- *Indicador 9.c.1: Proporción de la población cubierta por una red móvil, por tecnología*
- *Indicador 17.6.1: Suscripciones de banda ancha fija a Internet por 100 habitantes, por velocidad*
- *Indicador 17.8.1: Proporción de individuos que utilizan Internet*

Según datos de ITU (2022), los países desarrollados y muchos de los emergentes, disponen de coberturas de conectividad cercana al 100% de redes móviles y superior al 91% de acceso a Internet de alta velocidad. Por tanto, en la comunidad internacional se está debatiendo hasta qué punto los actuales indicadores digitales de la Agenda 2030 son representativos del progreso en el desarrollo digital y su impacto en materia social y ambiental. Asimismo, se debate en qué medida omitir enfoques más representativos y ambiciosos, puede estar obstaculizando una adecuada monitorización de los riesgos y oportunidades de la transformación digital en la esfera del desarrollo sostenible.

PREGUNTA 10.

En el camino hacia una integración más sólida de la transformación digital dentro del marco de la Agenda 2030 y sus futuras sucesoras, quisiéramos conocer su perspectiva sobre varios enfoques objeto de debate en foros internacionales. Por favor, especifique su opinión acerca de los mismos o proponga un enfoque alternativo.

- 1) *Mejorar el esquema actual de ODS incorporando **indicadores adicionales** relacionados con la dimensión digital en aquellas temáticas donde sea especialmente relevante a la luz de las tendencias mundiales (Fuso-Nerini et al., 2024).*
- 2) *Considerar la digitalización como una **transformación transversal** (Sachs et al., 2019), que influye en todos los ODS (este enfoque es conceptual y necesitaría el desarrollo de metodologías complementarias para la evaluación de dicha transformación).*
- 3) *Proponer el establecimiento de un **nuevo ODS18** en futuras Agendas de Desarrollo Sostenible, específicamente centrado en promover una transformación digital sostenible y la triple transición: digital, verde y socialmente equitativa (Montreal Declaration, 2020; Future Earth, 2020).*

- 4) Construir un **ecosistema** para impulsar la transformación digital sostenible y regenerativa a través de un **modelo de innovación de hélices**, para promover el diálogo multiactor, la co-creación de soluciones, así como la transferencia responsable de tecnología, conocimiento y capacidades.
- 5) Formular y consolidar una **agenda paralela independiente** para la transformación digital sostenible, como la que plantea el próximo Pacto Global Digital de la ONU, pero con un enfoque más sólido de sostenibilidad regenerativa (ONU, 2021).
- 6) Por favor, sugiera cualquier otro enfoque alternativo que considere relevante: _____

CONCLUSIÓN

PREGUNTA 11

Por último, ¿le gustaría aportar alguna sugerencia o comentario adicional que aporte valor a esta investigación sobre la transformación digital sostenible y la triple transición, y no se haya contemplado en este cuestionario?

Por favor, describa a continuación su comentario o sugerencia: _____

Ha llegado al final del cuestionario. Muchas gracias por su colaboración.

