applied sciences

MDPI

Review

Automation and Robotics Pilot Lines in the Context of Industry 5.0

Rubén Alonso [1,2,*], Tomás F. Sánchez [1], Diego A. Alfaro [1], Yarens J. Cruz [1], Alberto Villalonga [1] and Fernando Castaño [1]

[1] Centro de Automática y Robótica, CSIC-Universidad Politécnica de Madrid, 28500 Madrid, Spain
[2] ICT & Robotics, R2M Solution s.r.l., 27100 Pavia, Italy
* Correspondence: ruben.alonsoh@alumnos.upm.es

Abstract: Pilot lines have become a key element in modern industry. The demands for resilience, human-centricity, and sustainability in Industry 5.0, combined with technological innovations, highlight the critical role of these lines in the new industrial paradigm. Pilot lines facilitate the validation of processes and the reduction in uncertainties, making them essential tools for future industries. This article examines the current state of pilot lines and evaluates their alignment with Industry 5.0 principles. As part of this analysis, the GAMHE 5.0 pilot line is presented as a line designed with a focus on automation and robotics, meeting the requirements of the industries of the future. This article also details a series of case studies conducted on the pilot line, demonstrating its flexibility and adaptability. Finally, the advantages and disadvantages of small-scale lines are analyzed within the context of Industry 5.0, emphasizing their importance in balancing technology, human factors, and sustainability.

Keywords: pilot lines; Industry 5.0; automation; robotics; sustainable manufacturing

Academic Editors: Yutaka Ishibashi and Paolo Tripicchio

Received: 18 January 2025
Revised: 14 February 2025
Accepted: 23 February 2025
Published: 26 February 2025

Citation: Alonso, R.; Sánchez, T.F.; Alfaro, D.A.; Cruz, Y.J.; Villalonga, A.; Castaño, F. Automation and Robotics Pilot Lines in the Context of Industry 5.0. *Appl. Sci.* **2025**, *15*, 2510. https://doi.org/10.3390/app15052510

1. Introduction

In its 2025 manufacturing industry sector outlook report (https://www.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-outlook.html (accessed on 27 December 2024)), Deloitte points out that despite financial uncertainty, rising costs and the complex economic and business landscape, the industry continues investing in digital solutions.

Nevertheless, this transition towards digitalization introduces new challenges. On the one hand, there are challenges associated with the rapid pace of technological evolution and the need for a skilled workforce [1]. On the other hand, the complexity of these new technologies, along with issues of interoperability and integration with the industry's existing processes [2], pose significant difficulties.

In recent years, discussions about Industry 4.0, and more recently Industry 5.0, have gained relevance as paradigms to address these and other issues [3]. Specifically, Industry 4.0 aimed to reduce production times and enhance quality, flexibility, and interoperability [4]. Meanwhile, the new Industry 5.0 extends these concepts by focusing on greater collaboration between human operators and machines, while also emphasizing waste reduction and sustainability [5].

The concept of Industry 5.0 is linked to the idea of Society 5.0: a society that extends beyond industrial- or information-based societies to find a balance between technology, economic development, social progress, and environmental sustainability [6]. Likewise, if Industry 4.0 was primarily focused on digitalization and productivity, the Industry 5.0 paradigm builds on these aspects while adding a social and responsible dimension. Human-centricity, along with resilience and sustainability, are the core pillars of Industry 5.0. Specifically, the human-centric aspect places humans at the center of the production process, guiding them, easing their workload, and supporting decision-making. The resilience aspect refers to a more adaptable and flexible production system that also enhances quality. Lastly, the sustainability aspect focuses on optimizing resources, reducing environmental impact, and minimizing waste.

When discussing sustainability and, in particular, waste reduction, it is often useful to start from simpler and more production-related concepts, for example, "Right First Time" and "Zero Defect Manufacturing". Right First Time (RFT), often referred to as First Time Right, is a production strategy based on quality improvement movements from the 1960s and the Japanese philosophy of continuous quality processes known as Kaizen [7]. The strategy emphasizes the concept that there should be no defects throughout the entire production process, thus avoiding unnecessary rework and waste. In the 1980s, it was used as a slogan in mass-production factories to encourage workers to stop the line and solve problems as soon as they were detected [8].

Zero Defect Manufacturing (ZDM) is another concept related to the quality of processes and products. Although it originated in the 1960s, ZDM remains a trend in Industry 4.0. Typically, ZDM combines both a product-oriented and a process-oriented approach. The product-oriented approach focuses on studying defects in parts and pieces, and finding solutions, while the process-oriented approach focuses on equipment and processes to identify issues in how products are manufactured [9].

Both approaches need to be validated, preferably in non-productive environments before being implemented. This is especially critical in an ecosystem where the offering of solutions and technologies, which are sometimes immature, is broad and constantly evolving. These changes, in hardware, and particularly in software, are becoming even faster and more impactful due to the rapid evolution of AI and robotics [10]. Therefore, it is necessary to have methods, strategies, and tools that help reduce uncertainty on such innovations and serve as a bridge between research and market needs.

Often, Technology Readiness Levels (TRLs) are presented as a measure of maturity and as a scale to evaluate the degree of development of a technology. These levels, which originated from NASA [11], range from identifying basic principles to operating the technology in real-world environments. Between these two extremes, there are several intermediate steps that include scientific risk reduction, proof of concepts, laboratory tests, and validation and demonstration in relevant settings such as pilot lines or pilot plants.

Pilot lines are a relevant element in this advance along the TRL scale, particularly when developing solutions that facilitate quality improvement and waste reduction. A pilot line is a small-scale version of a production system used to test, evaluate, adapt, or even refine products, processes, or technologies. It serves as an intermediate step between research and full-scale production, facilitating the research and development (R&D) and serving as a test-before-invest environment [12], all without disrupting ongoing production processes.

Pilot lines play a crucial role in validating the technical viability and reducing risks. They are also a valuable tool for experimentation during the early stages of product design and for rapid prototyping [13]. Furthermore, pilot lines facilitate the production of proof-of-concept batches, enabling their use in refining the designs. Additionally, they serve as tools for technology adaptation and optimization, and represent a valuable complement in the human–technology–sustainability aspects of Industry 5.0.

In this context, this article aims to understand the usefulness of pilot lines as an intermediate step between research and production, while analyzing the status of pilot lines in Industries 4.0 and 5.0. It also seeks to detail how the "Group of advanced Automation of Machines, Highly complex processes and Environments" (GAMHE) 5.0 pilot line has been designed and implemented. Additionally, it presents, from an applied perspective, a collection of case studies where this pilot line has been used in the industrial field. To achieve these objectives, the following points are addressed:

- Analysis of the state of the art related to pilot lines in different industries;
- Critical comparison of pilot lines for automation and robotics;
- Design and implementation of the GAMHE 5.0 pilot line;
- Demonstration of the use of the pilot line in several industrial cases studies;
- Discussion on the benefits and possible negative impacts of pilot lines.

These points are detailed in the following sections. Section 2 details the state of the art and provides an extensive review of automation and robotics pilot lines. Section 3 presents the GAMHE 5.0 line and details how it addresses the needs of Industry 5.0. Section 4 provides the information of case studies developed and validated on the pilot line. Finally, Sections 5 and 6 provide the discussion, the conclusions, and future work.

2. Pilot Lines in the Literature

The significant demand for variability and adaptability has led to a shift from mass production to the production of smaller batch sizes tailored to individual customer needs [14,15]. This has led to significant efforts in various sectors to design and implement pilot lines with the goal of staying aligned with technological advancements and meeting customer needs.

As stated previously, pilot lines are scaled-down versions or replicas of installations used in productive processes. These pilot lines may be larger in scale and then referred to as pilot plants. Regardless of their size, the objective of both pilot lines and pilot plants is to reduce unpredictability and risks, and serve as tools for development, testing, adaptation, or improvement of a production environment [16].

The concept of pilot lines originated during the rise of mass production as a method for testing alternatives and optimizing processes without impacting ongoing production. Today, these pilot lines are crucial elements in industry due to the need to adapt to new technologies, meet market requirements for continuous quality and process improvement, and serve as training tools.

This section is aimed to provide an overview of the literature related to pilot lines, starting with general approaches and moving on to those in Industry 4.0 contexts, and finally focusing on those most relevant to automation and robotics. Additionally, the objective is to examine the key features of the analyzed pilot lines and their contributions.

2.1. Methodology

The methodology applied for selecting the relevant literature involved searching for the term "Pilot line" across various academic indexers and search engines. Specifically, the following databases were used: ScienceDirect, Scopus, OpenAlex, and Google Scholar.

In ScienceDirect, the search was conducted using the phrase "pilot line", in quotation marks, to ensure that both singular and plural forms were included. This search yielded 1559 results as of 9 December 2024. In Scopus, an "Article title, abstract, keyword" search was performed for the term "pilot line". Since this search does not differentiate between singular and plural forms, it also included searches for "pilot lines". The result in Scopus was a total of 912 publications.

The bibliographic catalogue of open scientific articles, OpenAlex, was also used in the state-of-the-art analysis. For OpenAlex, the used search terms were "pilot line | pilot lines" to include both singular and plural forms using the "|" (OR) operator. In this case, OpenAlex returned 6444 publications.

Lastly, Google Scholar was used due to its extensive coverage. The search term employed was "pilot line | lines" to ensure that both singular and plural forms were included. The search returned a result that Google Scholar estimates to be approximately 15,900 publications.

As shown in Figure 1, the interest in pilot lines has remained relatively stable over recent years on both Scopus and ScienceDirect, with slight increases in the number of publications. In OpenAlex, there was a peak in 2019, which declined in 2020 but then steadily increased again, surpassing the level of 2019 in 2023. For 2024, the number of publications is lower due to it being the current year and probably incomplete indexing. On Google Scholar, the level of publications remained relatively similar between 2019 and 2021, with a growth in 2022. Since 2022, the numbers have been slightly increasing.

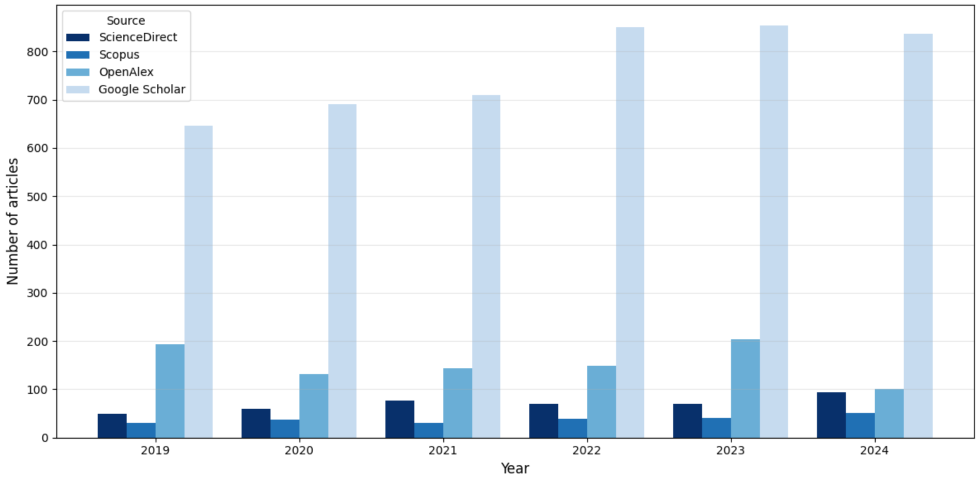

Figure 1. Articles including the term "Pilot Line".

Once the list of articles was retrieved, and given the large number of articles mentioning pilot lines in different ways, the search was refined using terms related to the scope of this article. Specifically, terms such as "industry", "robotics", "automation", "manufacturing" or "artificial intelligence". During the selection of articles, priority was given both to maintaining variety across different areas where pilot lines are used and to selecting publications highly related to Industry 4.0/5.0 concepts.

To identify ongoing projects and pilot line initiatives, the primary sources were the findings from the analysis of state-of-the-art articles and the additional information obtained through general search engine queries.

2.2. Industrial Pilot Lines

Regarding the academic literature, one relevant paper is [17]. In their research on industrial cyber–physical systems, particularly those involving milling processes, the authors identified several challenges such as the difficulty in configuring parameters to guarantee the required surface roughness and the absence of procedures for predicting surface roughness at both micro and macro scales. For this reason, Villalonga et al. developed a machine learning-based system to analyze and configure these parameters, testing and validating it on an Industry 4.0 pilot line. The authors report achieving positive results regarding response times and facilitating optimal settings.

Aligned with pilot line initiatives for Industry 4.0, the authors in [16] present a multi-technology sensorized Digital Twin of a line used to assemble medical devices. Their pilot line includes a linear motion platform and a sensor system, performing assembly steps while verifying results. The case study addresses the need for accuracy in an assembly process that has a critical point where two components must engage precisely. The pilot line also enabled the experimentation with data augmentation and fault injection, generating large volumes of information from each assembly step, and facilitating the modeling of the Digital Twin. Additionally, it enabled testing processes at speeds valid for high-volume production.

In [18], the authors present a pilot line for computing chip manufacturing, specifically, an Extreme Ultraviolet Lithography (EUV) mask pilot line used at Intel Corporation. This pilot line is characterized by its reliance on a standard toolset, with a particular emphasis on high-definition and high-speed inspection tools. The use of the pilot line is justified through the conduct of studies and validation of approaches to address defect detection and process simplification challenges. In [19], another case study is presented for a line designed to detect and analyze defects on EUV masks, which is a crucial process in small-chip manufacturing. This pilot line is based on electron microscopes or other tools utilizing extreme ultraviolet light and it supports various types of inspection activities. The authors also present the pilot line as useful for benchmarking activities and have designed it in such a way that beta pilot line tools can be replaced with production tools when they become available.

Without leaving the field of electronic components and systems, ref. [20] presents an initiative associated with an innovation project that introduces a multi-stakeholder pilot line including producers of 8-inch silicon carbide (SiC) substrates and equipment developers, as well as SiC process technologists, Research and Technology Organizations (RTOs), and end-users. This consortium introduced the world's first 200 mm silicon carbide pilot line for power technology, targeting applications in the automotive power electronics sector. The research and development activities conducted in this pilot line focused on enhancing competitiveness, energy savings, and reducing CO_2 (carbon dioxide) emissions.

The field of electronics offers many other examples of activities utilizing pilot lines. For instance, in their analysis of trends in microelectronic technologies within the context of Industry 4.0 [21], the authors mention the European Union's "Two-Dimensional Experimental Pilot Line" project as one of the enablers for new research and call for a more mature Industry 4.0 that addresses changing market needs, increased control requirements, and automation advancements.

Likewise, ref. [22] focuses on operational optimization and upscaling pilot lines in the semiconductor industry. The authors integrated logistics simulation with discrete event simulation for production planning and control, demonstrating their solution through a pilot line. The article highlights complexity, investments for machine acquisition and operation, product variety, and short product life cycles as some of the challenges faced by the sector, and where pilot lines can be particularly useful. Their publication also conveys an interesting message that emphasizes the importance of pilot lines: "Due to the capital-intensive equipment required for semiconductor production, companies often use low-volume manufacturing to validate market demand, optimize production processes, and mitigate risks before scaling up to full production". These small-scale activities where technology validation, process optimization, and uncertainty reduction can occur are precisely where pilot lines prove valuable.

The idea of using small-scale and pilot lines for "what-if" analyses while avoiding disruptions on main production lines is discussed in [16]. These "what-if" scenarios also use pilot lines as a tool for generating information to support decision-making and serve as a data source for Digital Twins and dashboards.

Another pilot line, which focuses more on evaluating workstation setups rather than technologies, is presented in [23]. This pilot line facilitates tests aimed at reducing dead times, unnecessary inventories, and bottlenecks in production processes within the clothing industry. In their work, the authors analyzed variations in efficiency when switching from a conventional production system to one that is modular and aligned with lean manufacturing principles. They suggest using mobile workstations in a modular system, allowing operators to perform multiple tasks, and present positive indicators related to improved production efficiency.

The intersection of lean manufacturing and pilot lines is also explored in the works presented in [24]. The authors adopted an automation and robotics approach in a pilot line for battery module production, specifically focusing on modules that use cylindrical cells. This pilot line incorporates the use of a cell testing system along with a pick-and-place robot, referred to as a “cell loading system” and a pulse-arc welding robot. These elements are used to validate a Six Sigma-based sustainable manufacturing approach. The sustainability in production is associated with the concept of the 6Rs: Rationalize, Reduce, Redesign, Reuse, Repair, and Recycle.

A relevant pilot line in this context is one of those used within the same research project to calculate station processes, supporting the transition from pilot line to production and reducing time-to-market [25]. The authors aimed to address the lack of a well-defined methodology for scaling up pilot lines and present an eight-workstation pilot line designed to demonstrate a virtual modeling tool integrated with an ontology model for calculating station process times.

Following the topic of battery production, an article that covers this subject along with pilot lines and sustainability is presented by von Drachenfels et al. [26]. The article is based on the idea that it is complex to scale environmental impact data measured in pilot lines to full-scale production environments. Specifically, they suggest that while pilot lines are common for increasing understanding of environmental impacts when producing battery cells, scaling these data to large-scale production systems is challenging. This situation becomes even more complicated with emerging technologies, due to which the data at the pilot line level needed for a life cycle assessment (LCA) are scarce. The authors highlight pilot lines as a key element in improving awareness of the environmental impact of various technologies. They conclude by suggesting that, to some extent, pilot lines can be used to estimate production environmental impacts but emphasize the importance of recognizing that certain variables will require specific methodologies.

The environmental impact, along with challenges in profitability and motivating new young employees is addressed in [27]. From an Industry 4.0 perspective and supported by pilot lines, the authors present a flexible, interoperable end-of-line solution specifically designed for the ceramic tile sector. The pilot line contributes to the development of new optimization tools, creation of new machinery, and integration of technical modules into existing solutions. In their article, they also present tests of new waterproofing treatments and an improved process control, detailing outcomes such as a 25% reduction in development time, a 25% decrease in development costs, and a 20% increase in efficiency and production capacity.

In the photovoltaic panel production industry, pilot lines have been used as development platforms and as tools for monitoring single processes [28]. Specifically, pilot production of hundreds of units of high-efficiency solar cells has provided relevant data and insights for future production scaling analysis. Another example is a multi-process, multi-manufacturing-tool pilot line approach for the rapid technological development of flexible and lightweight displays [29], which enabled a rapid and cost-effective method for process development and the fabrication of limited-size Thin-Film Transistor (TFT) arrays. This approach helped break down technological barriers to commercialization, as in many cases detailed previously.

The need to make manufacturing more autonomous by providing capabilities in perception, prediction, optimization, and control has also facilitated the creation of a pilot line and its associated Digital Twin in the field of polymer processing [30]. The pilot line includes an injection molding machine, robotic arms, conveyor belts, and inspection cameras. The Digital Twin is utilized for real-time monitoring, movement optimization (for both the robotic arm and the conveyor belt), and predictive maintenance.

Even in the aerospace sector, there are examples of pilot lines. The European Space Agency (ESA), under the PIOTS project, developed photonic packaging technologies meeting space requirements, as well as the packaging line process controls, and deployed a pilot line for the packaging of photonic integrated circuits [31]. Shifting from aerospace to aviation, this field has also examined the potential benefits of Industry 4.0 and how pilot lines can help mitigate investment risks and uncertainties. Specifically, in [32], the authors note that "no matter how good a technology is, if the companies do not feel that they can get the benefits from their huge investment, they will be reluctant to invest".

Adapting facilities to varying production volumes is also one of the challenges in the automotive sector. For this reason, in [33], the authors built customized low-cost robots for different scenarios. These robots consist of plug-and-produce robotic modules that can be composed in a design platform. In their case studies, they demonstrated the scenario of physical cooperation and task sharing between humans and robots on a car assembly pilot line, underlining improved usability and sensing capabilities.

Lastly, there are several articles in which the pilot line is not centered on a specific sector but rather serves to validate approaches and technologies across various fields. One such article discusses designing reconfigurable modular production systems to improve human–system integration [34]. The pilot line presented spans across diverse industries, including automotive, wood products, bicycles, bearings, and metal manufacturing. Specifically, the article showcases pilot lines equipped with agents supporting artificial intelligence (AI), the semantic web, machine learning, and flexible planning as part of a framework for agile and smart manufacturing.

In [35], the researchers present a study that will be validated across several multi-sectoral pilot lines. The study focuses on the concept of Zero Defect Manufacturing and quality control. The authors begin by acknowledging that legacy IT systems and a low level of digitization make technology integration challenging, and that some new technologies require investment when their benefits are uncertain. To address this challenge, they designed a multilayer Data Quality Management (DQM) architecture to deploy cyber–physical production systems for digitally enhanced quality management, ready to be tested in various pilot lines ranging from automation to healthcare. Similarly, ref. [36] presents a study on AI technologies and applications for production, and highlights the need for test beds, pilot lines, and factory lines as research and demonstration facilities.

Focusing on the generation of AI solutions and models, such as those related to human–AI collaboration, the authors in [37] address challenges associated with changing customer needs, which require agile and flexible strategies within the industry, to present solutions applicable across various sectors—such as food, plastic automotive components, and gear-box machinery. The authors aimed to demonstrate and validate these solutions on reduced-scale production lines.

The ODIN Project has published articles focusing on Open, Digital, Industrial, and Networking pilot lines as a means to research and validate modular and reconfigurable production systems based on robots. Specifically, ref. [38] aims at efficient and sustainable robotics for immediate implementation on the shop floor, detailing challenges related to manufacturing high volumes and diverse parts, operational complexity, and the necessity of flexible monitoring. The article demonstrates safe human–robot collaboration, perception capabilities, decision-making, and planning across various sectors, including automotive, white goods, and aeronautics. Regarding the white goods sector, this is further elaborated in [39], where challenges associated with interoperability with legacy systems, flexibility, and efficiency are extended. The authors present a use case for semi-automated quality control of washing machine control panels, achieving improved results in error detection, logging, and human–robot collaboration.

2.3. Pilot Lines for Workforce Skilling

Pilot lines are not only being deployed as tools for technology development and validation, or for mitigating technical and investment uncertainties. The idea of using pilot lines as a formative element and facilitator for capacity building is discussed in multiple articles.

A relevant perspective is provided by the authors of [40], who emphasize that new technologies are emerging faster than workers' ability to adopt them and use pilot lines for validating one of these technologies. They specifically focus on an educational teleoperation platform as a learning environment for heavy industrial robotics. The challenges identified during the pilot line validation include data transfer issues between the robot and user interface as well as ensuring the safety of laboratory staff while remotely teleoperating the equipment. Additionally, they highlight a challenge applicable to other teleoperated lines used for training: the need for mechanisms to recover from common errors that occur when learning.

A similar case related to education and training is presented in [41]. The authors rely on a human–robot collaboration pilot line designed for diesel engines to present a test case for Virtual Reality-based safety training. The article confirms the usefulness of the pilot line for evaluating the case study and suggests the value of Virtual Reality, at least at the pilot line level, for training operators on safety.

When discussing the digitalization of manufacturing Small and Medium Enterprises (SMEs), cost-related obstacles, as well as challenges associated with hardware and software investments, technological and implementation difficulties, and skills and knowledge gaps are often cited [42]. In their work, the authors summarize the industrial R&D needs for testing before investment and the lifelong learning, evaluating how pilot lines can be helpful. Their research focuses on three different pilot lines: Robolab Tampere, human–robot collaboration (HRC) pilot line, and the Tampere University of Applied Sciences (TAMK) fieldlab. In their analysis, they concluded that skills and technologies related to human–machine collaboration, robotics, cybersecurity, machine learning (ML), and artificial intelligence are the most relevant.

Expanding on the subject of pilot lines for training, ref. [43] emphasizes the role of learning factories in supporting digitalization and the adoption of artificial intelligence. The high demand for automation and new technologies also implies a need for new workforce skills, and pilot lines and learning factories facilitate AI training through practical tasks and applications. Specifically, the article focuses on additive manufacturing, human–robot collaboration, and Digital Twins. The perspective on pilot lines as a training tool is also linked to the concepts of "test-before-investment" and pre-production validation, ensuring that the workforce is adequately trained when investments in technologies for production are made.

Additionally, the article details specific objectives for learning pilot lines and factories, such as (i) strengthening technological and business competencies; (ii) developing AI-based Industry 4.0 applications; (iii) demonstrating and validating Industry 4.0 technologies; and (iv) facilitating the rapid implementation and application of results.

A somewhat different approach to workforce capacity building is presented in [12]. This article addresses the definition of requirements for Reconfigurable Pilot Lines (RPLs), which can be used for skill development and adapted to future training needs. The authors present various surveys conducted with industrial stakeholders and detail cybersecurity, robotics, human–machine collaboration, flexible manufacturing, and digital design and optimization as essential competencies in future industries. On this matter, they mention that, in addition to Learning Factories (LFs) and Teaching Factories (TFs) traditionally used to develop skills, RPLs enable a rapid and efficient way to introduce the workforce to new technologies and acquire knowledge.

2.4. Innovative Activities and Digital Factories

The trends towards supporting the research and development of pilot lines by the European Commission (EC) have facilitated the launch of several projects emphasizing the idea of using pilot lines as elements to bridge the gap between research and industrial production. For example, H2020 Pillar 2: Industrial Leadership defined six Key Enabling Technologies (KETs) in manufacturing (nanotechnology, micro- and nanoelectronics, photonics, advanced materials, industrial biotechnology, and advanced manufacturing systems) and promoted the idea of multi-KET pilot lines [44]. Within the Digital Europe Program, which aims to bring digital technologies and infrastructure to citizens, public administrations, and industry, the EC has specific calls in which pilot lines are fundamental components. The Chips Joint Undertaking, an initiative seeking to strengthen the European semiconductor industry, organized a call for the setup of pilot lines on advanced photonic integrated circuits and another call for proposals on operational activities of these pilot lines during 2024. In this way, they are stimulating innovation through pilot lines and experimental facilities in the field of semiconductors.

Some of the projects detailed in the state-of-the-art review are framed within these calls and similar initiatives. For instance, FAMES (https://fames-pilot-line.eu/ (accessed on 27 December 2024)) is a project and a pilot line aimed at developing more efficient and sustainable semiconductor technologies, or NanoIC (https://www.nanoic-project.eu/ (accessed on 27 December 2024)). The project led by the center for nanoelectronics and digital technology research, IMEC, together with a consortium of companies, tackles the efficiency, affordability, and sustainability in chip manufacturing. Another example is PhotonHub (https://www.photonhub.eu/pilot-lines/ (accessed on 27 December 2024)), which serves as an innovation hub for photonics and covers the concepts of "test-before-invest" and upskilling opportunities discussed throughout this work. PhotonHub presents seven different pilot lines where technologies such as chemical sensors or medical applications can be validated. Also, the AMPLiFII2 (https://gtr.ukri.org/projects?ref=104175 (accessed on 27 December 2024)) project, funded by the UK Research and Innovation program, leverages the concept of pilot lines to validate some of its developments and begin producing battery modules at small scales, but ready for high-scale production.

When analyzing public and private initiatives related to pilot lines, it is possible to find a wide variety with objectives and characteristics adapted to different specific needs. Some examples launched in recent years are the pilot line production services offered by RISE (Research Institutes of Sweden), covering a full addition manufacturing development cycle (https://www.ri.se/en/am-center/our-offer/pilot-line-production (accessed on 27 December 2024)), or the pilot line for manufacturing coatings, including different equipment and which is adaptable to the specific needs of industrial applications, presented by the SPRI Development Agency and the Tekniker research center (https://bdih.spri.eus/en/pvd-pilot-line-coating-facilities-for-industrial-components/ (accessed on 27 December 2024)).

Regarding the lines most related to automation and robotics, it is worth referencing the pilot line of the Booster Manufacturing Lab at CTAG (Automotive Technology Center of Galicia), which was used in works such as [45]. This line is part of an Industry 5.0-oriented laboratory and consists of two vehicle stations equipped with collaborative robots, mobile robots, and machine vision systems.

In [46], the pilot line from the Bi-Rex Competence Center (Big Data Innovation and Research Excellence) was used. The article presents a reconfigurable mobile robotic manipulator that relies on the hardware and workspaces of the Bi-Rex pilot line. Bi-Rex is presented as a pilot line integrating innovative technologies and traditional solutions within an interconnected ecosystem. The line focuses on the implementation of advanced collaborative robotics, leveraging IoT, Big Data, and AI technologies to support tasks in smart and additive manufacturing. Another infrastructure similar to Bi-Rex is MADE, a competence center focused on Industry 4.0. In [47], MADE integrates training, technology, serious games and Lean 4.0 principles to facilitate the digital transformation of manufacturing companies.

In [48], the Competence Industry Manufacturing 4.0 (CIM4.0) digital factory pilot line is involved in cybersecurity-related research, including testing Secure Quantum Key Distribution over fiber optic networks and using elements of the pilot line as endpoint for secure data communication when connecting with edge nodes. The CIM4.0 digital factory is designed for organizations to test innovative technologies that can improve business competitiveness, with advanced robotics being one of those included in this group of novel technologies.

Improving quality in Industry 4.0 and Zero Defect Manufacturing are concepts being addressed in innovation projects like Qu4lity (https://qu4lity-project.eu/ (accessed on 27 December 2024)). In Qu4lity, multinational companies like Philips present their OneBlade pilot line (https://digitalfactoryalliance.eu/progress-on-the-philips-oneblade-pilot-line/ (accessed on 27 December 2024)) as a tool for enhancing production efficiency and product quality. For achieving these objectives, they use, for example, AI applications for visual quality control and machine learning applied to the movements of robots on the pilot line. The extracted data are exported to dashboards for decision-making and improvement of production processes.

Lastly, it is worth mentioning the human–robot collaboration pilot line at Tampere University, an active line that has been utilized in some of the articles referenced in the state-of-the-art section [40,49]. This line incorporates robots, AR/VR, Digital Twins, and computer vision systems, and serves both as a reconfigurable system for research purposes and as a showroom environment.

2.5. Key Features and Comparison

The most obvious feature of pilot lines is their scale. They are all scaled-down representations of production lines or complete factories. This scale also implies a cost control aspect, as it provides a controlled, cost-efficient, environment to identify improvements and detect issues. When referring to scale, production capacity is also considered. Part of the lines analyzed produce small batches or limited quantities to understand how they will behave in the market or to validate them before larger-scale production.

Not only is the scale common, but the scalability is also a key characteristic. The analyzed lines are, in general, modular, adaptable, or designed to be reconfigurable. This allows for flexibility both in the processes applied and target outcomes, on one hand, and on adaptation to production needs by scaling up and replicating the pilot line, on the other.

Regarding the flexibility, it is worth noting how several of these pilot lines serve general purposes or support various applications. General-purpose lines allow for testing technologies and processes across sectors, for example, human–machine collaboration, data augmentation mechanisms, safety methods, and fault injection approaches. Lines with various applications are designed to address multiple uses cases, usually also covering a few different sectors.

Another common characteristic is their use for risk mitigation and for reducing uncertainty. The concept of "test-before-invest" mentioned multiple times in the state of the art is closely related to this point. A smaller scale implies lower costs and allows for replicating parts of a production process where technologies and approaches can be tested without impacting factory production.

In some cases, generating data is costly; in others, data generation directly produces waste, such as when creating reference datasets for training quality control models. In other instances, the small-scale model enables anticipating how a larger system will behave and, thus, make decisions related to sustainability. The generation of these datasets, the preliminary development of scalable models, and the understanding of critical aspects and monitoring needs are additional capabilities provided by many pilot lines.

Regarding automation and robotics, as well as Industry 4.0 and Industry 5.0 concepts discussed in this article, it is important to note that a significant number of the works analyzed are based on Industry 4.0 or at least linked to manufacturing innovations. In terms of Industry 5.0, there is more diversity. If Industry 5.0 is understood as the integration of technologies, human-centric approaches and collaboration with skilled workforces, and sustainable practices aimed at reducing waste, the coverage varies widely.

Regarding technology, several analyzed lines either have robotic components or include AI agents and models. It is also worth noting that other technologies, like Digital Twins and Big Data, are mentioned across many analyzed works. At the human-centric level, human–machine collaboration and human-in-the-loop approaches are the most common. Within this human element of Industry 5.0, it is important to highlight the use of lines as training and capacity building tools. In terms of sustainability, concepts such as zero defects, quality control, reducing waste, and improving efficiency in time and resource usage are commonly found across the articles reviewed.

Table 1 presents a comparative analysis of the articles reviewed. This comparison shows the primary area of each article. In certain cases, the differences may not be significant, for example, in the semiconductor or electronics sectors. On the other hand, some articles mention generic pilot lines that are not sector-specific. These are marked as "general" to differentiate them from those mentioning multiple sectors, which are labeled with the term "various". The table also highlights the relationship with Industry 4.0 and the key concepts of Industry 5.0, including the connection to automation and robotics (A&R), the integration of AI technologies, and the focus on human-centric approaches and sustainability.

Table 1. State-of-the-art comparison.

				Industry 5.0		
Article	**Area**	**I4.0**	**A&R**	**AI**	**Human**	**Sustain.**
[12]	General	X	X	X	X	X
[16]	General	X	X	X		
[17]	General	X	X	X	X	X
[18]	Semicond.		X			
[19]	Semicond.		X			
[20]	Electronics	X				X
[21]	Microelec.	X	X			
[22]	Semicond.	X				
[23]	Clothing				X	
[24]	General	X	X			X
[25]	Batteries	X				
[26]	Batteries	X				X
[27]	Ceramics	X	X	X	X	X
[28]	Solar					X
[29]	Electronics				X	
[30]	Polymers	X	X			
[31]	Space		X			
[32]	Aviation	X			X	
[33]	Automotive	X	X			X
[34]	Various	X	X	X	X	
[35]	Healthcare	X	X		X	
[36]	General	X	X	X		
[37]	Various	X		X	X	
[38]	Various	X	X	X	X	X
[39]	White g.	X	X		X	
[40]	General	X	X	X	X	X
[41]	Training	X	X		X	
[42]	General	X	X	X	X	
[43]	Training	X	X	X	X	X
[48]	Security	X				
[50]	General	X	X		X	X

3. GAMHE Pilot Line

The GAMHE 5.0 pilot line (Figures 2 and 3) was established thanks to the research and development in artificial cognitive control systems and reference architectures within the framework of Industry 5.0. The system focuses on integrating computer numerical controls (CNCs) for machine tools, including a Deckel Maho DMC 75 V Linear high-speed machining center equipped with a Siemens 840D CNC, and a Kern-Evo ultraprecision micro-machining center featuring a Nano NT laser control and Heidenhain CNC.

To simulate a manufacturing production line, additional components were incrementally incorporated. These include two conveyor belts, a Universal Robots UR5e collaborative robotic arm, and a Han's Robot Elfin 10L-PRO collaborative robotic arm, both used for part handling alongside the machining centers. For inspection and quality control, an Allied Vision Mako G-192 camera was connected to a Raspberry Pi 4 Model B with 8 GB of RAM, enabling the development and testing of artificial vision routines. The system's most recent integration involved an AMR ROSbot XL HUSARION, equipped with a RPLIDAR A2 LiDAR sensor and an Intel RealSense stereoscopic camera, facilitating the transportation of manufactured components across different workstations.

Each element of the pilot line is equipped with an Internet of Things (IoT) node capable of communicating with its respective machine through various industrial protocols. The CNC Deckel Maho uses Open Platform Communications Data Access (OPC DA); the CNC

Kern Evo employs Language for Service and Visualization version 2 (LSV-2); both UR5e robotic arm and the Allied Vision Mako G-192 camera use TCP-IP; finally, EtherCAT is utilized for the Elfin 10L-PRO robotic arm. All these IoT nodes communicate with one another through a central server functioning as an MQTT broker. This configuration enables each machine to interact with other IoT nodes within the pilot line, transmit sensor data, report operational states and alarms, and receive operation commands. The IoT nodes run on two Raspberry Pi 3B+, two Raspberry Pi 4B with Raspbian/Linux, and two MSI Core i3 mini-computers with Windows operating systems.

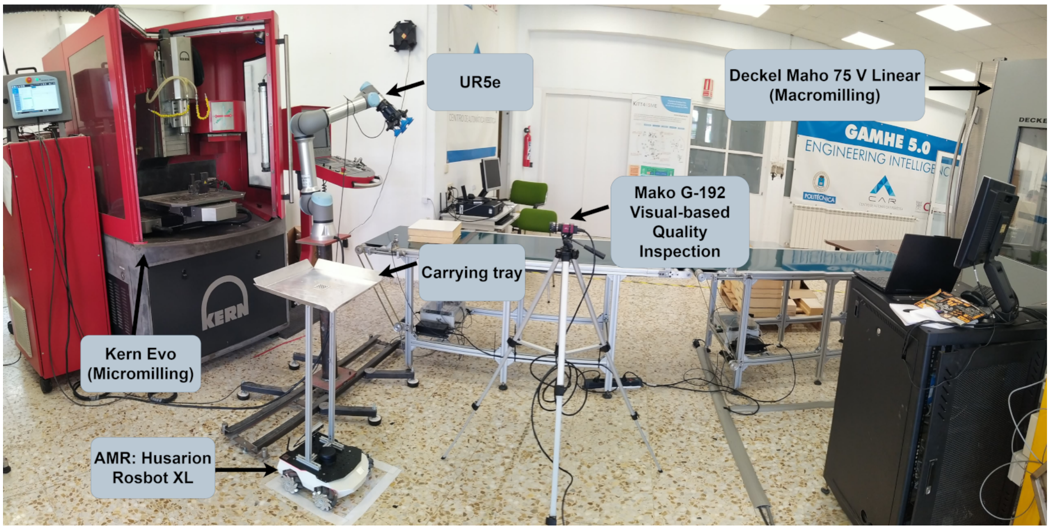

Figure 2. GAMHE 5.0 pilot line I.

Figure 3. GAMHE 5.0 pilot line II.

The GAMHE 5.0 pilot line is distinguished by integrating systems operating under different protocols and from various technological eras, combining early 2000s machining centers with state-of-the-art collaborative robots. Thus, this configuration serves as a case study on implementing digital transformation in established manufacturing plants. The system enables bidirectional communication among all elements of the pilot line, facilitating performance optimization through precise coordination of its various components. Additionally, the versatility of the CNC machines allows for the execution of diverse manufacturing operations, making it possible to adapt the line for producing a wide range of products. Within this interconnected environment, the pilot line is both flexible and scalable, with the capability to integrate new systems and adapt to different purposes or use cases.

Another notable feature of the pilot line is the integration of artificial vision systems for both inspection and quality control, as well as for enabling robotic arms to interact with workpieces. The UR5e robotic arm is equipped with a conventional camera mounted on its wrist for object detection. Additionally, an Intel RealSense stereoscopic camera was incorporated to the Elfin 10L-PRO robotic arm. For this robot, custom software was developed to identify various workpieces and determine their position and orientation relative to a predefined coordinate system.

Another advantage of the pilot line is its reconfigurability and adaptability to different use cases. For example, a typical setup used in quality control processes is detailed in Figure 4. In this setup, all nodes of the GAMHE 5.0 pilot line (A1, A2, A3, A4, A5, A6, A7, I) are capable of sending and receiving messages using the MQTT protocol. These messages contain status information and operation commands for the respective nodes. The process starts with the first message sent from a human–machine interface to node A1 to pick up the part and position it in node A2. Each node then reports the end of its operation and sends a message to the next node to continue the process or notify the operator of any anomalies. At node I, quality control is performed, resulting in three outputs: (i) O1: the process continues at node A6; (ii) O2: the part is transferred to the storage of damaged parts; and (iii) O3: the part is marked for reprocessing. The output of the inspection stage determines the destination to which AMR A7 should transport the part.

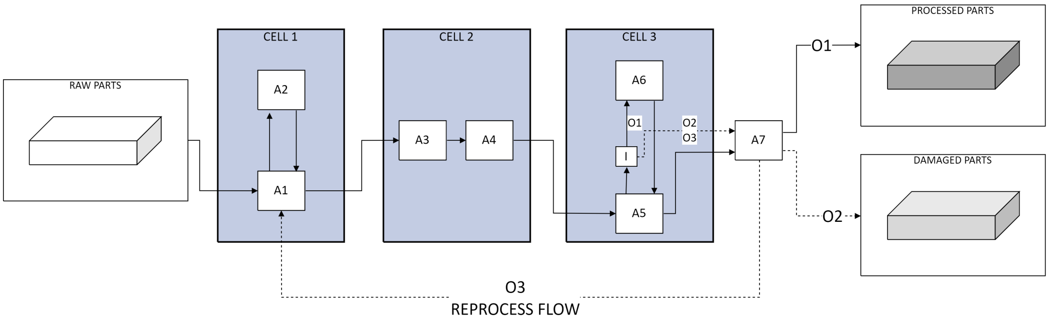

Figure 4. GAMHE 5.0 functional diagram: (A1) Hans Robot Elfin 10L-PRO robotic arm; (A2) Deckel Maho DMC 75V Linear high-speed machining center; (A3) conveyor belt; (A4) conveyor belt; (A5) Universal Robots UR5e robotic arm; (I) Inspection Allied Vision Mako G-192 camera; (A6) Kern Evo ultraprecision micro-machining center; (A7) AMR 460 ROSbot XL HUSARION; (O1) output 1, processed parts; (O2) output 2, damaged parts; and (O3) output 3, reprocessed parts.

3.1. Development and Continuous Improvement of the Pilot Line

Currently, data acquisition software is under development to facilitate the collection of data required for experimental designs. These programs enable real-time data capture and analysis, with the option of local storage at each IoT node or centralized database management. Additionally, they incorporate advanced tools for time-series data analysis and visualization. These data acquisition systems form the foundational infrastructure for developing Industry 5.0 applications such as predictive maintenance, machine and process optimization, quality control, modeling, simulation, and Digital Twin development.

In addition to the automated elements of the line, data are also collected from human operators. Developing a Human Digital Twin (HDT) is a crucial step towards harnessing the full potential of Industry 5.0. In this context, data are gathered from wearable devices that connect and transmit sensor readings via MQTT for processing. The primary objective is to use these metrics to adjust task and resource allocation, minimizing operator fatigue and stress. It is essential to establish correlations between sensor-generated data and workers' self-assessments of task performance. These Human Digital Twin and human-in-the-loop experiments enable addressing part of the requirements related to human-centricity. Specifically, the information obtained from sensors and wearables enables adapting processes to operator needs. The human-in-the-loop in the pilot line also facilitates the empowerment of the operator in terms of machine supervision and control, which is one of the key elements of the human-centricity. These points, along with adaptive interfaces and explainability in AI models, allow for balancing technology with workforce needs.

3.2. Integration with the Legacy Systems

The GAMHE 5.0 pilot line includes both legacy and modern systems. Some of the older systems, over 15 years old, include the Deckel Maho DMC 75 V Linear high-speed machining center and the Kern Evo ultraprecision micro-machining center. On the other hand, state-of-the-art technologies such as the UR5e robotic arm, ARM ROSbot, and machine vision systems for quality control are also integrated. To ensure seamless communication between these diverse systems, specialized nodes were developed to translate MQTT messages into each system's respective communication protocol.

For example, for the Kern Evo integration (Figure 5), an MSI Core i3 mini-computer with Windows operating systems is used as IoT Node. This node has a software written in C++ with a library for MQTT messaging and a library for communication through the Language for Service and Visualization version 2 protocol of the Heidenhain SDK to execute direct numerical control operations such as starting or stopping a machining program. This node connects directly to the Heidenhain iT530 CNC via an ethernet cable, in parallel, the wireless network adapter is used to connect to the local network of the MQTT Broker.

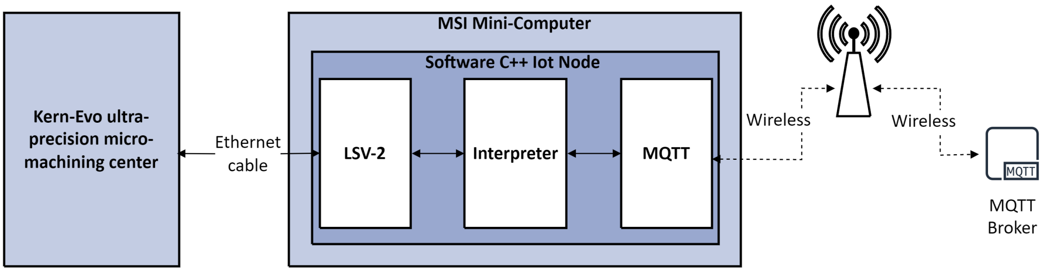

Figure 5. Kern Evo ultraprecision micro-machining center integration.

A similar approach is used to integrate the Deckel Maho DMC 75 V Linear high-speed machining center (Figure 6). In this case, the communication protocol with the machine is OPC DA-integrated in a software written in Python 3.9+ programming language.

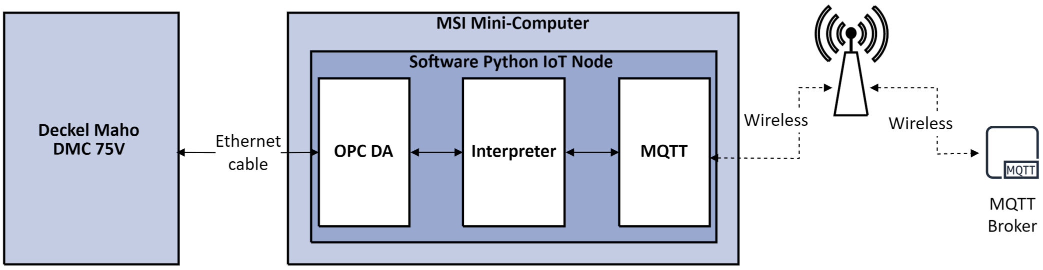

Figure 6. Deckel Maho DMC 75 V integration.

In general, IoT nodes are composed of a machine/system protocol, an interpreter, and the MQTT protocol. In this way, the MQTT protocol provides a common communication layer for all nodes in the pilot line, including those proxying legacy systems.

3.3. Comparative Analysis

Consistent with the majority of lines previously analyzed, GAMHE has a clear focus on Industry 4.0. Due to its generic nature and adaptability, it can be classified as a general pilot line with a clear emphasis on automation. Regarding Industry 5.0, the key technology aspects focus on robotics, artificial intelligence, IoT, and communications. This makes GAMHE similar to the lines discussed in [16,36,50].

In terms of human aspects, GAMHE places significant emphasis on human-centric design, being prepared for validation of human-in-the-loop cases and Human Digital Twins. It also serves as a valid educational tool and is fully replicable as a capacity-building asset, like those mentioned in [40,43].

GAMHE focuses on predictive maintenance and quality control, prioritizing early defect detection and reducing waste at the end of production lines. This aligns the line closely with the examples provided in [24,26]. All these lines highlight sustainability as a key element of the new industrial paradigm.

In terms of hardware, GAMHE shares certain similarities with [30,33,34,38,40]. It aligns with [30] in the use of robots, conveyor belts, and vision systems, and with [40] in its focus on human–robot collaboration, robotic arms, and IoT protocols. With [33,38], it shares similarities in mobile platforms and AMRs (Autonomous Mobile Robots). Like [34], GAMHE focuses on Digital Twins, cyber–physical systems, and the acquisition and generation of data. In turn, GAMHE includes CNC machinery for macro- and micro-milling.

Its modularity and scalability are comparable to those found in [33]. Reconfigurability and flexibility are highly demanded in manufacturing industries and are therefore fundamental requirements when designing lines like GAMHE. This flexibility and scalability enable the line to validate multiple technologies and processes. Additionally, it offers the capability to generate and manage data for subsequent analysis or integration into models, in a similar manner to [26,28].

Lastly, a key aspect of GAMHE 5.0, also highlighted as a key feature in other works [35], is its ability to integrate legacy equipment with innovative technologies. This capability enables the line to support a broad range of devices and technologies and adapt to various use cases.

4. Case Studies

As mentioned previously, flexibility and adaptability are two of the key aspects of GAMHE 5.0. This section presents a summary of relevant case studies that the pilot line has supported in recent years.

4.1. Digital Twin-Based Optimization for Ultraprecision Motion Systems with Backlash and Friction (2019)

The study focuses on developing a Digital Twin for modeling and optimizing an ultraprecision motion system with backlash and friction, commonly found in CNC machining centers. The primary objective is to minimize the maximum positioning error without significantly increasing control effort. The Digital Twin (DT) includes a virtual representation of mechanical and electrical components, models of nonlinearities such as backlash and friction, and integration of a cascaded P-PI control system. Four methods were used to optimize the controller parameters: a standard industrial procedure (FT) and three gradient-free heuristics (SA, GA, and CE). The study demonstrates the DT's effectiveness in improving control system behavior and highlights the superiority of gradient-free heuristics over the FT method, with the cross-entropy (CE) method standing out for its speed and efficiency.

In particular, improvements in the maximum absolute errors of 28% (GA), 26% (CE), and 20% (SA) with respect to the FT method were demonstrated. Considering the integral time absolute error the improvements were 21% (GA), 23% (CE) and 19% (SA). The parameters obtained through the optimization heuristics did not result in an increase of more than 3% in the control effort, as measured by the Integral of the Absolute Control Signal. These results validate the feasibility of DT-based optimization for improving ultraprecision motion systems, paving the way for industrial implementation [51].

4.2. Cloud-Based Industrial Cyber–Physical System for Data-Driven Reasoning: A Review and Use Case on an Industry 4.0 Pilot Line (2020)

The paper describes a cloud-based Industrial Cyber–Physical System (ICPS) designed for smart manufacturing, validated on an Industry 4.0 pilot line. Its main objective was to present a cloud-based data-driven reasoning process for reparametrizing predictive models in edge modules. Specific goals included improving surface roughness quality prediction, implementing a monitoring and prediction system in smart manufacturing scenarios, and surpassing the performance of standalone predictive models. The methodology involved describing the pilot line, generating and training data models, configuring the cloud-based ICPS, and validating the system. The study advances the state of the art by proposing a cloud-based ICPS, demonstrating the effectiveness of reinforcement learning through the Q-Learning method, and validating the system on a pilot line, showing improved prediction accuracy and reduced computational load. For example, in the case of computational load, the latency for the best model selection with the reasoning module was 0.085 s, compared to 1.10 s for the brute-force search. Limitations include the need for adaptation to other processes and the representativeness of the dataset used [17].

4.3. Industry 5.0 Pilot Line Digital Twin (2024)

The study focuses on the design, development, and evaluation of Digital Twins for modeling operator, robot, and interaction behaviors in an experimental pilot line. The main goal was to optimize the production line within the Industry 5.0 context, which advocates a human-centered approach by integrating human intelligence and skills with advanced technologies. The study sought to establish safe and efficient human–robot interactions in a collaborative manufacturing environment. Contributions include integrating Digital Twin technologies with human–robot interaction, creating a virtual space for optimizing collaboration between humans and machines, demonstrating the use of FlexSim and Gazebo for decision-making and resource allocation in manufacturing systems, implementing communication protocols such as TCP/IP, ROS2, and MQTT for IoT nodes, machine tools, and wearable devices, and incorporating physiological data from wearables into human Digital Twins to enhance human–robot interaction and improve worker well-being [52].

4.4. Self-Reconfiguration for Smart Manufacturing Based on Artificial Intelligence (2024)

The study evaluates the integration of an AI-based solution for visual inspection, determines the optimal line parametrization using AutoML, and uses a fuzzy-logic-based reconfigurator to manage performance degradation. The methodology includes deep learning-based visual inspection, automated machine learning (AutoML) workflow automation, and development of a fuzzy-logic-based reconfigurator. The study demonstrates the feasibility of integrating AI solutions for self-reconfiguration in production lines, presents an end-to-end AutoML approach, and develops a fuzzy-logic-based reconfigurator.

In this case study, two segmentation models were trained for the inspection task, with the best one achieving an accuracy of 0.995 and an F1 score of 0.992. This model was deployed in the pilot line for product handling. Additionally, an AutoML approach was used to determie the optimal parametrization of the line, resulting in a model with an

R^2 of 0.963. This led to an expected 55.1% improvement in throughput compared to the training data, which aligned with the values achieved in real production at maximum capacity. Limitations include result generalization and hyperparameter optimization. Overall, the study suggests that self-reconfiguration can significantly improve the efficiency and flexibility of production systems [53].

4.5. Quality Inspection of Prefabricated Panels Made for Construction (2024)

This case study focuses on quality control from a Zero Defects Manufacturing perspective. Specifically, the pilot line is used to inspect the quality of thermal-insulating panels for the construction sector. The system relies on several components of the pilot line, including the manipulator robot, the industrial camera, and the AI IoT node running a segmentation algorithm. In this case, the system is complemented by a human operator and an Autonomous Mobile Robot, which ensures the operator's safety.

The results demonstrated improvements in various aspects related to Industry 5.0. For example, in the technological domain, quality control achieved a validation precision of 98.3% and a recall of 94.7%. Regarding the human aspect, the average operator physical activity time during quality control was evaluated across the three possible panel routes. Specifically, the time the operator was physically involved in the process was analyzed in relation to the total quality control process time. This time decreased from 14.46% to 8.69%, thereby reducing the operator's workload [54].

5. Discussion

Throughout this article, many of the advantages of pilot lines have been presented, and even some disadvantages have been detailed. This section aims to review these advantages and disadvantages, and to analyze the approach from a critical point of view.

The advantages of pilot lines are clear: having an at-scale line where organizations can investigate, test, validate, generate data, and even produce on a small scale is already interesting in itself, particularly because this can be performed without impacting the production or affecting critical processes.

In relation to this, the concept of "test-before-invest" has been mentioned throughout this article. This possibility is also one of the positive points, as pilot lines offer an efficient way to test technology, processes, communication, sustainability, or human operations in controlled environments and can later be applied to production or scaled up to more complex lines.

The reconfigurability and modularity of pilot lines are another advantage. This makes the lines flexible and adaptable to different cases, and also allows for independent component replacement with higher TRL solutions as they become available.

Small-scale production is another strength of this concept. In many cases, small batches need to be produced and it would not be profitable to adapt or reconfigure an entire production line. It also allows for predicting how a larger-scale production might work and evaluating methods of quality and efficiency.

The ability to mitigate risks and clear uncertainties regarding technology is another significant advantage, especially in an environment where advances in artificial intelligence have substantial impacts on different aspects of the production processes. Pilot lines facilitate research and development of new technologies, and most importantly, they allow for validation in environments close to operational ones. Related to this, the ability to generate data enables model training, decision-making, and analysis for efficient scaling.

Another clear advantage is the possibility of using pilot lines for technology transfer and facilitating workers' training on technologies that will soon be deployed in production. Capacity building, upskilling or reskilling workers can benefit from these small-scale controlled environments. Lastly, pilot lines serve as demonstration and showcase elements, allowing stakeholders to view prototypes and innovations at early stages.

Regarding the challenges faced when scaling-up pilot lines, it is important to mention that while the initial cost may not be as high as implementing the changes on a full production line, costs can still be significant and may not be profitable in all cases. In some instances, considering virtual pilot lines, as presented in [41], or focusing on Digital Twins is a valid alternative.

The costs associated with maintaining and operating the pilot line can be substantial. Given the availability of pilot-line-as-a-service offerings and funded projects for their use, it might be worth exploring these options instead of setting up an in-house solution.

Modularity offers flexibility and helps mitigate the potential issues of obsolescence in rapidly changing technologies. However, a modular and adaptable pilot line may not be as efficient as one specifically designed for a particular process.

Regarding the efficiency, the yield achieved in pilot lines does not always hold in full-scale production. This can be due to the increased complexity of processes or potential bottlenecks when handling large volumes. Additionally, efficiency is also impacted by machine downtimes in production. While these stoppages in production are common for maintenance, they are usually not considered in pilot lines. Therefore, it is important not to assume that production in a pilot line scales linearly to full-scale production.

Finally, a critical point is the reliability and variability of results when moving from small-scale to large-scale production and across different levels of technological maturity. Von Drachenfels et al. highlight this issue, providing an example of the differences in environmental impact analysis results in the battery production sector [26].

Regarding the alignment with the principles of Industry 5.0 and zero defects, pilot lines demonstrate a perfect fit. While pilot lines experienced a surge during the era of Industry 4.0, under the new paradigm of Industry 5.0, they have the potential to become key elements. The Industry 5.0 component related to technology is evident in the relevance of pilot lines. General technologies and manufacturing-specific advancements are constantly evolving. Having an environment for prototyping, interoperability, and validation is crucial for advancing on the TRL scale. The human-centricity promoted by Industry 5.0, which is expected to arrive to production lines, also has an opportunity for testing and validation in pilot lines. In fact, many concepts of human-centricity, human–machine collaboration, and explainability are being evaluated in pilot lines.

Lastly, although some challenges have been mentioned regarding the scalability of certain sustainability analyses from pilot lines to full-scale production lines, it is clear that pilot lines can be used to obtain some indicators and facilitate decision-making. Pilot lines also allow for the development of quality control models and predictive maintenance tools, aligning with zero defects and first-time-right principles, thereby reducing times, consumption, and waste.

It is important to mention that in certain cases, there is little distinction between pilot lines and testbeds. In theory, pilot lines are more focused on industrial environments, emphasizing integration, scaling, and production-oriented viability analysis. Testbeds, on the other hand, are primarily oriented towards experimenting with technologies in somewhat controlled settings. Pilot lines would be at higher Technology Readiness Levels and closer to production, whereas testbeds would be nearer to laboratory validation stages. Due to rapid technological evolution and availability of different technical solutions, pilot lines are often being used for experimentation and quick technological validation. As a result, there is some overlap between the two concepts. Sometimes, there is also some overlapping with research and development showrooms. In principle, pilot lines are focused on validating production-related processes, while showrooms are more oriented towards showcasing products or proof of concepts for commercial purposes. However, the configurations of these showrooms tend to be scaled-down systems where technologies can be validated.

This overlapping also occurs when talking about competence centers. Both have equipment for research and development, and interest in the skilling of workers. Pilot lines are usually smaller in scale and focus more on validating technologies and processes, while competence centers are typically organizations for driving innovation. In many cases within the competence centers, there are pilot lines as detailed in [43,48].

In general, these overlaps do not reduce the importance of the pilot lines, but rather contextualize them and place them in broader ecosystems.

6. Conclusions

Industry 4.0 is evolving into Industry 5.0. Pilot lines have been one of the main elements of the modern industry. In the paradigm of Industry 4.0, they were key elements due to the needs for shorter production times and interoperability, and the expectations in terms of quality. In Industry 5.0, these needs are expanded to include new technologies, with a focus in human- and sustainability-related objectives.

The interest in pilot lines, their link with Industry 5.0, and understanding how automation and robotics fit in these ecosystems has led us to analyze the state of the art and evaluate different approaches to highlight advantages and disadvantages when designing and deploying lines on a reduced scale.

To this end, articles focused on pilot lines were searched in some of the main academic indexers and search engines, and we obtained thousands of results and observed how the works related to pilot lines increase slightly or are maintained year after year. From these articles, a subset was selected, refining the search by key terms related to Industry 4.0/5.0 concepts. These articles were analyzed, detailed, and compared. Once analyzed, the modular and scalable design followed in the GAMHE 5.0 pilot line was presented, in addition to a series of case studies carried out in the line. Also, the GAMHE line was compared with the ones detailed in the state of the art, to certify certain similarities in terms of approaches and trends.

Finally, the aforementioned advantages and disadvantages of pilot lines are presented, whereby the main advantages are the ability to reduce risks and eliminate uncertainty before investing, and as an element of testing and validation of technologies without impacting main production. Regarding the disadvantages, issues related to the scaling of sustainability indicators and also potential initial, maintenance, and operating costs are mentioned.

The scaling of sustainability indicators is an area of ongoing research, as several of the parameters used in life cycle assessments do not scale linearly [26]. Initial costs and operational costs may be justified by the benefits obtained. Some of these initial costs can be mitigated through the use of modular pilot lines, which can grow based on available funding. Additionally, a mix of models or Digital Twins can be used to replace some components and machines. Lastly, as discussed, pilot-line-as-a-service models can assist in reducing initial costs.

The pilot lines are also framed in the context of Industry 5.0 and quality concepts, such as Zero Defect Manufacturing. Also, the lines are compared with slightly overlapping concepts such as testbeds and competence centers.

The conclusion is that the pilot lines are relevant to adapt the organizations to the new Industry 5.0 and play a key role for validating technologies and processes. These lines could be key to the three pillars of the new industrial paradigm: regarding resilience, by enabling more robust, adaptable, and innovative production; in human-centricity, by supporting the training of operators and testing approaches where humans are enhanced by machines; and lastly, in sustainability, by focusing on process and energy efficiency, as well as improving quality control processes to avoid waste.

The GAMHE 5.0 line, as a flexible and modular automation and robotics line, is an exponent of the pilot lines for Industry 5.0, and will facilitate new case studies related to technology, humans, and sustainability. Among these future cases, human-centricity and human–machine interaction are some of the activities that the authors are actively involved in. In particular, Human Digital Twins, to analyze data on fatigue, posture, and ergonomics, as well as human-in-the-loop approaches to empower the operator and enhance decision-making, are some of the main aspects planned to be addressed in future works.

Author Contributions: Conceptualization, R.A.; methodology, R.A.; software, T.F.S., D.A.A., Y.J.C. and A.V.; investigation, R.A., T.F.S., D.A.A., Y.J.C., A.V. and F.C.; resources, T.F.S. and D.A.A.; writing—original draft preparation, R.A.; writing—review and editing, R.A., T.F.S., D.A.A., Y.J.C., A.V. and F.C.; supervision, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the project "Digitalization of Power Electronic Applications within Key Technology Value Chains (PowerizeD)", ID 101096387, funded by the European Union HORIZON FP and Chips JU, and PCI2022-135004-2 funded by MICIU/AEI/10.13039/501100011033 by the "European Union NextGenerationEU/PRTR". The work is also funded by the project "Self-reconfiguration for Industrial Cyber–Physical Systems based on Digital Twins and artificial intelligence. Methods and application in Industry 4.0 pilot line", Spain, grant ID PID2021-127763OB-100, and supported by MICIU and NextGenerationEU/PRTR. This work is also supported by iGENZERO project with reference TED2021-131921A-I00, funded by MCIN/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR.

Conflicts of Interest: Author Rubén Alonso was employed by the company R2M Solution s.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AMR	Autonomous Mobile Robot
A&R	Automation and Robotics
AutoML	Automatic Machine Learning
CE	Cross-Entropy
CNC	Computer Numerical Control
CSIC	Consejo Superior de Investigaciones Científicas. Spanish National Research Council
CTAG	Centro Tecnológico de Automoción de Galicia. Automotive Technology Center of Galicia
DA	Data augmentation
DQM	Data Quality Management
DT	Digital Twin
EC	European Commission
ESA	European Space Agency
EUV	Extreme Ultraviolet Lithography
FP	Framework Program
FT	Fine-Tune
GA	Genetic Algorithm
GAMHE	Group of advanced Automation of Machines, Highly complex processes and Environments
HDT	Human Digital Twin
HRC	Human–Robot Collaboration
I4.0-I5.0	Industry 4.0. Industry 5.0
ICPS	Industrial Cyber–Physical System

ICT	Information and Communication Technology
IP	Internet Protocol
JU	Joint Undertaking
KETs	Key Enabling Technologies
LCA	Life Cycle assessment
LFs	Learning Factories
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
RAM	Random Access Memory
RFT	Right First Time
RPLs	Reconfigurable Pilot Lines
RTO	Research and Technology Organizations
R&D	Research and Development
SA	Simulated Annealing
SiC	Silicon Carbide
SME	Small and Medium Enterprise
TCP	Transmission Control Protocol
TFs	Teaching Factories
TFT	Thin-Film Transistor
TRL	Technology Readiness Level
VR	Virtual Reality
ZDM	Zero Defect Manufacturing

References

1. Kumar, R.; Singh, R.K.; Dwivedi, Y.K. Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *J. Clean. Prod.* **2020**, *275*, 124063. [CrossRef]
2. Zeid, A.; Sundaram, S.; Moghaddam, M.; Kamarthi, S.; Marion, T. Interoperability in smart manufacturing: Research challenges. *Machines* **2019**, *7*, 21. [CrossRef]
3. Lasi, H.; Fettke, P.; Kemper, H.G.; Feld, T.; Hoffmann, M. Industry 4.0. *Bus. Inf. Syst. Eng.* **2014**, *6*, 239–242. [CrossRef]
4. Yin, Y.; Stecke, K.E.; Li, D. The evolution of production systems from Industry 2.0 through Industry 4.0. *Int. J. Prod. Res.* **2018**, *56*, 848–861. [CrossRef]
5. Leng, J.; Sha, W.; Wang, B.; Zheng, P.; Zhuang, C.; Liu, Q.; Wuest, T.; Mourtzis, D.; Wang, L. Industry 5.0: Prospect and retrospect. *J. Manuf. Syst.* **2022**, *65*, 279–295. [CrossRef]
6. Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; European Commission, Directorate-General for Research and Innovation: Luxembourg, 2021; Volume 46.
7. Gregoire, C. Understanding and Increasing Right First Time (RFT) Performance in a Production Environment: A Case Study. Ph.D. Thesis, Kansas State University, Manhattan, KS, USA, 2017.
8. Poppendieck, M. Principles of lean thinking. *IT Manag. Sel.* **2011**, *18*, 1–7.
9. Psarommatis, F.; May, G.; Dreyfus, P.A.; Kiritsis, D. Zero defect manufacturing: State-of-the-art review, shortcomings and future directions in research. *Int. J. Prod. Res.* **2020**, *58*, 1–17. [CrossRef]
10. Liu, J.; Jiang, X.; Shi, M.; Yang, Y. Impact of artificial intelligence on manufacturing industry global value chain position. *Sustainability* **2024**, *16*, 1341. [CrossRef]
11. Mankins, J.C. Technology readiness levels. *White Pap.* **1995**, *6*, 1995.
12. Siivonen, J.; Pöysäri, S.; Hakamäki, A.M.; Lanz, M.; Salminen, K.; Ijas, M.; Aho, M.; Nieminen, H. Reconfigurable pilot lines enabling industry digitalization: An approach for transforming industry and academia needs to requirements specifications. *Procedia CIRP* **2022**, *107*, 1226–1231. [CrossRef]
13. Saffaro, F.A.; Trescastro, M.G.; Rodriguez, A.; Schramm, F.; Formoso, C.; Heineck, L. Prototyping contributions for production management in construction. In *Proceedings of the 14th Annual Conference of the International Group for Lean Construction, Santiago, Chile, 25–27 July 2006*; International Group for Lean Construction: Santiago, Chile, 2006; pp. 25–27.
14. Unger, H.; Börner, F.; Müller, E. Context related information provision in Industry 4.0 environments. *Procedia Manuf.* **2017**, *11*, 796–805. [CrossRef]
15. Kletti, J.; Schumacher, J. *Die Perfekte Produktion*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 1–10.

16. Kakavandi, F.; Gomes, C.; de Reus, R.; Badstue, J.; Jensen, J.L.; Larsen, P.G.; Iosifidis, A. Towards developing a digital twin for a manufacturing pilot line: An industrial case study. In *Digital Twin Driven Intelligent Systems and Emerging Metaverse*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 39–64.
17. Villalonga, A.; Beruvides, G.; Castano, F.; Haber, R.E. Cloud-based industrial cyber–physical system for data-driven reasoning: A review and use case on an industry 4.0 pilot line. *IEEE Trans. Ind. Inform.* **2020**, *16*, 5975–5984. [CrossRef]
18. Stivers, A.R.; Yan, P.Y.; Zhang, G.; Liang, T.; Shu, E.Y.; Tejnil, E.; Lieberman, B.; Nagpal, R.; Hsia, K.; Penn, M.; et al. EUV mask pilot line at Intel Corporation. In Proceedings of the 24th Annual BACUS Symposium on Photomask Technology, Monterey, CA, USA, 14–17 October 2004; SPIE: Bellingham, WA, USA, 2004; Volume 5567, pp. 13–22.
19. Chan, Y.D.; Rastegar, A.; Yun, H.; Putna, E.S.; Wurm, S. EUV mask defect inspection and defect review strategies for EUV pilot line and high volume manufacturing. In Proceedings of the Extreme Ultraviolet (EUV) Lithography, San Jose, CA, USA, 22–25 February 2010; SPIE: Bellingham, WA, USA, 2010; Volume 7636, pp. 454–469.
20. Messina, A.A.; Imbruglia, A.; Calabretta, M.; Vinciguerra, V.; Moise, C.C.; Sitta, A.; Enachescu, M.; Roccaforte, F. The "first and euRopEAn siC eighT Inches pilOt liNe": A project, called REACTION, that will boost key SiC Technologies upgrading (developments) in Europe, unleashing Applications in the Automotive Power Electronics Sector. In Proceedings of the 2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Catania, Italy, 23–25 September 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–6.
21. Wang, Y. Research Progress on Key Technologies of Microelectronics for Industry 4.0. *Acad. J. Sci. Technol.* **2022**, *2*, 4–6. [CrossRef]
22. Preising, H.; Gutmann, D.; Wolf, M. Application of Logistics Simulations for Scaling Up a Semiconductor Pilot Line: A Case Study. In Proceedings of the Conference on Production Systems and Logistics 2024, Honolulu, HI, USA, 9–12 July 2024; publish-Ing.: Hannover, Germany, 2024; pp. 563–572. Available online: https://repo.uni-hannover.de/items/6b6dfc6a-18d6-4868-8592-494c52929b98 (accessed on 22 February 2025).
23. Flores, A.; Aguilar, J.; Choque, R. Implementing of a pilot line of clothing industry under the philosophy lean manufacturing. *Int. J. Mater. Mech. Manuf.* **2014**, *2*, 214–228.
24. Titmarsh, R.; Assad, F.; Harrison, R. Contributions of lean six sigma to sustainable manufacturing requirements: An Industry 4.0 perspective. *Procedia CIRP* **2020**, *90*, 589–593. [CrossRef]
25. Chinnathai, M.K.; Al-Mowafy, Z.; Alkan, B.; Vera, D.; Harrison, R. A framework for pilot line scale-up using digital manufacturing. *Procedia CIRP* **2019**, *81*, 962–967. [CrossRef]
26. von Drachenfels, N.; Engels, P.; Husmann, J.; Cerdas, F.; Herrmann, C. Scale-up of pilot line battery cell manufacturing life cycle inventory models for life cycle assessment. *Procedia CIRP* **2021**, *98*, 13–18. [CrossRef]
27. Raffaeli, R.; Pazzi, L.; Pellicciari, M. Industry 4.0 Solutions as Enablers for the Sustainability of the Italian Ceramic Tiles Sector. *Sustainability* **2024**, *16*, 4301. [CrossRef]
28. Engelhart, P.; Wendt, J.; Schulze, A.; Klenke, C.; Mohr, A.; Petter, K.; Stenzel, F.; Hörnlein, S.; Kauert, M.; Junghänel, M.; et al. R&D pilot line production of multi-crystalline Si solar cells exceeding cell efficiencies of 18%. *Energy Procedia* **2011**, *8*, 313–317.
29. Raupp, G.B.; O'Rourke, S.M.; Moyer, C.; O'Brien, B.P.; Ageno, S.K.; Loy, D.E.; Bawolek, E.J.; Allee, D.R.; Venugopal, S.M.; Kaminski, J.; et al. Low-temperature amorphous-silicon backplane technology development for flexible displays in a manufacturing pilot-line environment. *J. Soc. Inf. Disp.* **2007**, *15*, 445–454. [CrossRef]
30. Singh, M.; Srivastava, R.; Lee, S.; Murray, N.; Qiao, Y.; Devine, D. Digital Twin of Polymer Processing Pilot Line. In Proceedings of the 37th International Manufacturing Conference by Irish Manufacturing Council, Athlone, Ireland, 7–8 September 2021; pp. 7–8.
31. Rotta, D.; Preve, G.; Rodrigo, A.S.; Chiesa, M.; Cucinella, G.; Bogoni, A. The ESA project PIOTS: Setting up a complete pilot line for the packaging of photonic integrated circuits for space applications. In Proceedings of the International Conference on Space Optics—ICSO, Virtual, 30 March–2 April 2020; SPIE: Bellingham, WA, USA, 2021; Volume 11852, pp. 2259–2270.
32. Ghafar, N.; Harun, K.; Lailawati, M.; Rahman, N. Preliminary investigation of Industry 4.0 readiness among small and medium aviation companies in Malaysia. In *Journal of Physics: Conference Series*; IOP Publishing: Bristol, UK, 2020; Volume 1573, p. 012030.
33. Wögerer, C.; Bauer, H.; Rooker, M.; Ebenhofer, G.; Rovetta, A.; Robertson, N.; Pichler, A. LOCOBOT-low cost toolkit for building robot co-workers in assembly lines. In Proceedings of the Intelligent Robotics and Applications: 5th International Conference, ICIRA 2012, Montreal, QC, Canada, 3–5 October 2012; Proceedings, Part II 5; Springer: Berlin/Heidelberg, Germany, 2012; pp. 449–459.
34. Sidorenko, A.; Motsch, W.; van Bekkum, M.; Nikolakis, N.; Alexopoulos, K.; Wagner, A. The MAS4AI framework for human-centered agile and smart manufacturing. *Front. Artif. Intell.* **2023**, *6*, 1241522. [CrossRef]
35. Caccamo, C.; Eleftheriadis, R.; Magnanini, M.C.; Powell, D.; Myklebust, O. A hybrid architecture for the deployment of a data quality management (DQM) system for zero-defect manufacturing in industry 4.0. In Proceedings of the Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems: IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, 5–9 September 2021; Proceedings, Part III; Springer: Berlin/Heidelberg, Germany, 2021; pp. 71–77.

36. Nolan, A. Artificial intelligence and the technologies of the Next Production Revolution. In *OECD Science, Technology and Innovation Outlook 2018*; Organisation for Economic Co-operation and Development: Paris, France, 2018; pp. 51–74.
37. Alvarez-Napagao, S.; Ashmore, B.; Barroso, M.; Barrué, C.; Beecks, C.; Berns, F.; Bosi, I.; Chala, S.A.; Ciulli, N.; Garcia-Gasulla, M.; et al. Knowledge project–concept, methodology and innovations for artificial intelligence in industry 4.0. In Proceedings of the 2021 IEEE 19th International Conference on Industrial Informatics (INDIN), Palma de Mallorca, Spain, 21–23 July 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 1–7.
38. Makris, S.; Michalos, G.; Kousi, N.; Papavasileiou, A.; Campos, U.E.; Bravo, J.O.; Cueva, H.H.; Siltala, N.; Wang, L.; Suppa, M.; et al. Open-Digital-Industrial and Networking pilot lines using modular components for scalable production–ODIN project approach. *Procedia CIRP* **2022**, *106*, 162–167. [CrossRef]
39. Karagiannis, P.; Xanthakis, V.; Apostolopoulos, G.; Michalos, G.; Makris, S. Quality control of white goods parts using robotic technologies. *Procedia CIRP* **2021**, *104*, 1759–1764. [CrossRef]
40. Pöysäri, S.; Kaarlela, T.; Dianatfar, M.; Lanz, M. Educational teleoperation platform for heavy industrial robotics as a learning environment. In Proceedings of the 13th Conference on Learning Factories (CLF 2023), Reutlingen, Germany, 9–11 May 2023; Elsevier BV: Amsterdam, The Netherlands, 2023.
41. Dianatfar, M.; Heshmatisafa, S.; Latokartano, J.; Lanz, M. Feasibility analysis of safety training in human-robot collaboration scenario: Virtual reality use case. In Proceedings of the International Conference on Flexible Automation and Intelligent Manufacturing, Detroit, MI, USA, 19–23 June 2022; Springer: Berlin/Heidelberg, Germany, 2022; pp. 246–256.
42. Lanz, M.; Latokartano, J.; Järvenpää, E.; Pöysäri, S.; Dianatfar, M.; Siltala, N.; Salminen, K.; Hilman, L.; Siivonen, J.; Aho, M. Development and deployment of services based on D-BEST methodology for robotics and production automation related pilot lines. In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2024; Volume 2989.
43. Gyulai, T.; Viharos, Z.J.; Kása, F.; Wolf, P. Upskilling SME Workforce by Learning Factories. In Proceedings of the 13th Conference on Learning Factories (CLF 2023), Reutlingen, Germany, 9–11 May 2023.
44. Butter, M.; Fischer, N.; Gijsbers, G.; de Heide, M.; Hartmann, C. *Horizon 2020: Key Enabling Technologies (KETs), Booster for European Leadership in the Manufacturing Sector*; Publications Office of the European Union: Luxembourg, 2014.
45. Regalado, S.; Pereira Domínguez, A.; Marchi, S.D.; Dacal-Nieto, A.; Triviño-Tonato, E. Design and validation of a knee exoskeleton prototype for squatting operations. *Int. J. Eng. Technol.* **2024**, *16*, 130–135. [CrossRef]
46. Baldassarri, A.; Bertelli, M.; Carricato, M. Design of a Reconfigurable Mobile Collaborative Manipulator for Industrial Applications. *J. Comput. Nonlinear Dyn.* **2023**, *18*, 091006. [CrossRef]
47. Masoero, L.; Moreta Maldonado, C.M. *Proposal for the Implementation of a Lean 4.0 Teaching Factory Inside the New MADE Competence Center of the Politecnico di Milano*; POLITesi, Politecnico di Milano: Milano, Italy, 2019.
48. Corrias, N.; Vagniluca, I.; Francesconi, S.; De Lazzari, C.; Biagi, N.; Menchetti, M.; Lombardi, G.; Scordato, A.; Gionco, V.; Mercinelli, R.; et al. Implementation of Italian industry 4.0 quantum testbed in Turin. *IET Quantum Commun.* **2024**, *5*, 46–51. [CrossRef]
49. Dianatfar, M.; Pöysäri, S.; Latokartano, J.; Siltala, N.; Lanz, M. Virtual reality-based safety training in human-robot collaboration scenario: User experiences testing. In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2024; Volume 2989.
50. Lutters, E. Pilot production environments driven by digital twins. *S. Afr. J. Ind. Eng.* **2018**, *29*, 40–53. [CrossRef]
51. Guerra, R.H.; Quiza, R.; Villalonga, A.; Arenas, J.; Castaño, F. Digital twin-based optimization for ultraprecision motion systems with backlash and friction. *IEEE Access* **2019**, *7*, 93462–93472. [CrossRef]
52. Alfaro, D.; Castaño, F.; Cruz, Y.J.; Villalonga, A.; Haber, R.E. Human-Centric Approach for the Digital Twin of Human-Machine/Robot Collaboration in an Industry 5.0 Pilot Line. *Rev. Iberoam. Automática Informática Ind.* **2025**, *22*, 1–5.
53. Cruz, Y.J.; Castaño, F.; Haber, R.E.; Villalonga, A.; Ejsmont, K.; Gladysz, B.; Flores, Á.; Alemany, P. Self-Reconfiguration for Smart Manufacturing Based on Artificial Intelligence: A Review and Case Study. In *Artificial Intelligence in Manufacturing: Enabling Intelligent, Flexible and Cost-Effective Production Through AI*; Springer: Cham, Switzerland, 2024; pp. 121–144.
54. Villalonga, A.; Cruz, Y.J.; Alfaro, D.; Haber, R.E.; Martínez-Lastra, J.L.; Castaño, F. Enhancing Quality Inspection in Zero-Defect Manufacturing Through Robotic-Machine Collaboration. In Proceedings of the 2024 7th Iberian Robotics Conference (ROBOT), Madrid, Spain, 6–8 November 2024; IEEE: Piscataway, NJ, USA, 2024; pp. 1–6.