TRABAJO FIN DE MASTER

La Intercomunicación de Gemelos Digitales: Estado del arte sobre la conexión de entidades de gemelos digitales

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Digital Twin Intercommunication: State-of-the-art on connecting digital twin entities

TESI DI LAUREA MAGISTRALE IN MECHANICAL ENGINEERING

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Resumen en español

1. Introducción: Relevancia del tema

El concepto de Gemelos Digitales se ha convertido en una de las tecnologías más relevantes de la era digital. Introducido en la primera década del 2000, este concepto ha revolucionado la forma en que los activos físicos son gestionados, optimizados y monitorizados en tiempo real. Los gemelos digitales son representaciones virtuales de objetos físicos, sistemas o procesos, que permiten monitorear, simular y analizar el rendimiento y el comportamiento de los activos, y generar optimizaciones. Esta tecnología se ha expandido rápidamente a diversas industrias como la manufactura, la automatización de procesos, la gestión de la cadena de suministro y la ingeniería.

Una de las grandes promesas de los gemelos digitales es la interoperabilidad: la capacidad de diferentes sistemas y plataformas para compartir datos y actuar en conjunto. Sin embargo, alcanzar una interoperabilidad completa ha sido un desafío, ya que los gemelos digitales deben poder comunicarse entre sí de manera eficiente, incluso cuando pertenecen a diferentes proveedores o plataformas tecnológicas. Este desafío se vuelve aún más complejo cuando consideramos la diversidad de los entornos industriales actuales, que incluyen desde sensores en equipos físicos hasta plataformas de análisis basadas en la nube.

La Asset Administration Shell (AAS), un marco estandarizado desarrollado bajo el concepto de Industria 4.0, se ha destacado como una solución clave para garantizar la interoperabilidad de los gemelos digitales. Este marco ofrece una representación digital estandarizada de los activos industriales y permite la comunicación fluida entre sistemas dispares. El AAS facilita la integración de máquinas, software y otros componentes dentro de una planta industrial, utilizando submodelos que encapsulan toda la información relevante de los activos.

La creciente importancia de la interoperabilidad en los gemelos digitales es evidente en las publicaciones académicas. Un análisis de la base de datos ScienceDirect muestra un aumento significativo en el número de artículos relacionados con "Gemelos Digitales" e "Interoperabilidad". En 2019 se registraron solo 4 artículos sobre el tema, mientras que en 2024, la cifra alcanzó los 62. Esto refleja el creciente interés y la atención que la comunidad científica está dedicando a resolver los desafíos de la conectividad entre gemelos digitales.

2. Revisión Literaria: Desafios y avances

La revisión de la literatura revela que, aunque el concepto de interoperabilidad de gemelos digitales está ganando popularidad, todavía se encuentra en sus etapas iniciales de desarrollo. La mayoría de los estudios sobre este tema se han presentado en conferencias académicas, lo que indica que las soluciones aún no están completamente consolidadas. Sin embargo, se espera que con el tiempo, a medida que los estándares y tecnologías se maduren, haya una adopción más amplia.

Existen varios desafíos técnicos que deben ser resueltos para lograr la interoperabilidad entre los gemelos digitales. Entre ellos, los más importantes incluyen:

- Compatibilidad tecnológica: Los gemelos digitales, que se desarrollan en diversas plataformas y utilizan distintas tecnologías, deben poder comunicarse entre sí sin problemas. Este es uno de los problemas más tratados en la literatura y la industria. La solución ha sido desarrollar modelos de transformación que permitan la conversión de los datos entre diferentes plataformas, o bien crear un “puente” común, como el AAS, que facilite esta comunicación.
- Armonización semántica: Los datos compartidos entre los sistemas deben ser entendidos de manera coherente, lo que requiere que los distintos sistemas utilicen un lenguaje común. Esto se refiere a la necesidad de que todos los sistemas tengan una semántica común, que garantice que los datos sean interpretados de la misma manera, independientemente de la plataforma.
- Calidad de los datos: Los gemelos digitales dependen de datos precisos y de alta calidad para realizar simulaciones y generar predicciones. Si los datos no son precisos o están incompletos, las decisiones basadas en estos modelos pueden ser erróneas, lo que puede afectar a la eficiencia de los procesos y generar costos adicionales.
- Seguridad de los datos: En la interconexión de los gemelos digitales, los datos se comparten entre múltiples agentes y plataformas. Esto plantea riesgos de seguridad, ya que los datos deben ser protegidos para evitar

accesos no autorizados, alteraciones o pérdidas. La implementación de protocolos de seguridad robustos es esencial para garantizar la integridad de la información compartida entre los gemelos digitales.

En particular, se ha estudiado a fondo uno de los desafíos más críticos para lograr la interoperabilidad: la compatibilidad tecnológica. El proceso de conectar diferentes gemelos digitales está siendo abordado desde diversas perspectivas en la investigación, y se han propuesto enfoques clave para resolver esta incompatibilidad. Las conclusiones obtenidas de diversas publicaciones apuntan a que la tarea de conectar gemelos digitales es un tema que sigue ganando importancia, pero que aún enfrenta retos complejos.

Enfoques para Superar la Compatibilidad Tecnológica

Se han propuesto dos enfoques principales para mejorar la conectividad entre gemelos digitales:

- Modelos de transformación directa: Este enfoque busca mapear los diferentes modelos de información para crear reglas de transformación que permitan que los datos fluyan entre plataformas incompatibles. Esto implica la creación de marcos comunes que permitan la interoperabilidad directa entre los sistemas existentes.
- Desarrollo de una tecnología puente: En lugar de transformar los sistemas, este enfoque aboga por el desarrollo de una solución de interoperabilidad universal que actúe como un "puente" entre diversas plataformas tecnológicas. Aquí es donde el Asset Administration Shell (AAS) ha sido identificado como una solución clave.

3. El Papel del Asset Administration Shell (AAS)

El AAS ha sido identificado como una solución prometedora para lograr la interoperabilidad entre los gemelos digitales. Un estudio realizado por Siemens define cómo la estructura de los activos en el formato AAS mejora el intercambio de datos entre socios y sus respectivos gemelos digitales. Este formato estandarizado facilita la comunicación entre plataformas dispares y, por lo tanto, supera las barreras tecnológicas existentes.

Por otro lado, ABB ha explorado el desarrollo de reglas de transformación entre diferentes modelos de información para AAS, lo que ha permitido avanzar en la implementación de gemelos digitales más compatibles y efectivos dentro de sus plataformas.

El AAS está demostrando su efectividad para integrar los elementos del Internet de las Cosas (IoT), asegurando que los datos compartidos sean interpretados de manera coherente en diferentes sistemas. Este enfoque ayuda a resolver uno de los principales problemas de interoperabilidad: la falta de coherencia en los datos interpretados por distintas plataformas tecnológicas.

En cuanto a la interoperabilidad semántica, se ha identificado que el AAS está aumentando su compatibilidad con mecanismos para adjuntar semántica a los modelos de información. Esto es crucial para garantizar que todos los sistemas involucrados interpreten los datos de la misma forma. En este sentido, ECLASS ha sido reconocido como el diccionario semántico oficial, aunque alternativas como MaRCO, que utiliza ontologías basadas en el entorno de manufactura, también están ganando popularidad.

Comparativa de Modelos de Datos y Estándares

El AAS destaca en el ámbito de la interoperabilidad debido a su capacidad para manejar datos de series temporales (timeseries), que son esenciales para el funcionamiento de los gemelos digitales. Según [4], el formato NGSI-LD ofrece capacidades limitadas para la comunicación bidireccional en comparación con AAS y DTDL. Esta capacidad para manejar datos de largo plazo es una característica clave de los gemelos digitales, ya que muchos de los procesos que monitorizan y simulan requieren almacenar y procesar datos durante largos períodos de tiempo.

Adicionalmente, [13] aboga por el AAS como el modelo de datos estandarizado para la provisión de información, ya que, a diferencia de DTDL y TD, el AAS es el único modelo de información estandarizado oficialmente en el contexto de los gemelos digitales. Esta estandarización permite una mayor fiabilidad y consistencia en el intercambio de datos.

Un análisis realizado en [8], que evaluó 29 arquitecturas de gemelos digitales en el ámbito manufacturero, concluyó que el AAS es una posible solución para la normalización de la comunicación entre gemelos digitales. Este estudio se basa en una revisión sistemática de 140 publicaciones revisadas por pares, donde se identificó que, entre las arquitecturas de gemelos digitales de código abierto más utilizadas, solo el AAS es un estándar oficial.

AAS y su Impacto en las Regulaciones Europeas

En cuanto al marco regulatorio, AAS ha sido contemplado como el estándar principal para la estructuración semántica de la información de los productos en un formato de datos interoperable, lo cual es un requisito esencial para el

Digital Product Passport (DPP). Este concepto es parte de los nuevos requisitos regulatorios de la Unión Europea, que se implementarán en diversos sectores en los próximos años para facilitar la transición hacia una Economía Circular.

¿Por qué el Asset Administration Shell es Relevante en la Interoperabilidad de los Gemelos Digitales?

La revisión de la literatura ha demostrado que tanto los investigadores como las industrias y las organizaciones de normalización han reconocido al AAS como un habilitador clave para garantizar la interoperabilidad de los datos de los gemelos digitales y la interacción de las entidades. Las razones principales para esta relevancia son las siguientes:

- Inversión de empresas relevantes como ABB y Siemens: Empresas como Siemens y ABB están invirtiendo recursos sustanciales para hacer que sus productos sean compatibles con la tecnología AAS. Un ejemplo claro de esta integración es el Digital Product Passport, basado en la interoperabilidad de datos, que Siemens está liderando en su investigación. Además, se organizan reuniones anuales entre los líderes de la industria manufacturera y de automatización para discutir los avances de esta tecnología.
- Adopción y consenso en la comunidad investigadora: Aunque varias tecnologías y arquitecturas están siendo exploradas en la comunidad investigadora, existe un consenso creciente de que el AAS es el principal habilitador para las plantas de manufactura de la Industria 4.0. Grandes proyectos de investigación patrocinados por el gobierno alemán, como Manufacturing-X y Catena-X en la industria automotriz, están construidos alrededor del AAS y lo consideran un estándar en los ecosistemas de datos a lo largo de las cadenas de suministro.
- Desarrollo de estándares internacionales: La Comisión Electrotécnica Internacional (IEC) está desarrollando un estándar sobre esta tecnología, reconociéndola como un habilitador clave para el Digital Product Passport y la Product Carbon Footprint, dos marcos regulatorios de la UE que afectarán a todos los niveles de la industria de producción a partir de 2027.

En resumen, el AAS no solo está demostrando ser una tecnología esencial para la interoperabilidad de los gemelos digitales, sino que también está ganando aceptación y prominencia como un estándar internacional que solucionará muchos de los problemas de conectividad en la Industria 4.0.

4. Comunicación de gemelos digitales: Requisitos de conectividad basados en arquitecturas AAS

El Asset Administration Shell (AAS), como arquitectura estándar para la interoperabilidad de los componentes de la Industria 4.0, está captando la atención de académicos e investigadores de todo el mundo. Un análisis de las publicaciones académicas en el repositorio Scopus ha revelado una tendencia interesante en la cantidad de artículos publicados sobre AAS. Entre 2017 y 2019, se publicaron 18 artículos, cifra que se mantuvo constante durante 2020. Desde 2021, la cantidad de publicaciones ha aumentado de manera significativa a una tasa anual superior al 50%. En 2023, se publicaron 52 artículos de investigación sobre el AAS, lo que refleja un notable crecimiento en el interés por esta tecnología.

Este aumento en la cantidad de publicaciones sobre el Asset Administration Shell no es una coincidencia, ya que el AAS se ha identificado como una tecnología clave para habilitar la interoperabilidad entre los gemelos digitales (DTs) y para permitir el Digital Product Passport (DPP), una iniciativa regulatoria fundamental para los componentes de la Industria 4.0. La creciente adopción del AAS está vinculada a su capacidad para resolver problemas de interoperabilidad entre diferentes plataformas tecnológicas, facilitando la creación de una red interconectada de gemelos digitales que operen de manera fluida y coordinada.

AAS como Habilitador en Otros Sectores

Una de las preguntas de investigación más relevantes es si la tecnología del Asset Administration Shell se está aplicando en otros sectores fuera de la manufactura. La Industrial Digital Twin Association (IDTA), que gestiona el desarrollo del AAS, ha definido la planta de manufactura e industria 4.0 como una red de entidades que forman un Sistema de Sistemas (SoS), donde las aplicaciones basadas en AAS interactúan entre sí. Esto ha sido crucial para impulsar la adopción de esta arquitectura en diversas aplicaciones industriales.

La relevancia del AAS no se limita a la manufactura. Los sectores que están comenzando a explorar el AAS incluyen logística inteligente, smart cities, y gestión avanzada de la cadena de suministro, donde la interoperabilidad de los gemelos digitales desempeña un papel central. En estos sectores, el AAS permite no solo la gestión de activos físicos sino también la integración de sistemas de información complejos que operan a través de plataformas heterogéneas. Esta capacidad de integración expande el potencial del AAS, llevando su aplicación más allá de la manufactura hacia otras áreas críticas de la industria.

Revisión de la Literatura sobre el Asset Administration Shell

Para comprender mejor las tendencias de investigación sobre el AAS, se consultaron dos fuentes de información clave:

- Publicaciones en el sitio web de Plattform Industrie 4.0: Este repositorio enumera un total de 31 documentos relacionados con el AAS. Estos documentos proporcionan una base sólida para entender el impacto y la evolución de la tecnología en el sector industrial.
- Scopus: Utilizando una búsqueda refinada con el término "Asset Administration Shell" en el título, abstracto y palabras clave, se obtuvieron 11 documentos hasta octubre de 2024. Estos artículos proporcionan una visión más detallada de cómo se está utilizando el AAS en diferentes industrias y la investigación académica más reciente sobre su implementación.

Documentos Relevantes en Scopus

Uno de los documentos clave en la literatura revisada es el estudio de 29 artículos que analizan cómo el AAS puede ser utilizado en el campo de la manufactura. De estos estudios, se llegaron a dos conclusiones principales:

Diversidad en la interpretación del AAS: Mientras algunos investigadores consideran al AAS como el modelo de información del gemelo digital, otros lo ven como el hilo digital que conecta todas las partes de un sistema, y algunos lo identifican como el gemelo digital del activo en sí mismo. Es crucial que los lectores comprendan estas distinciones al abordar diferentes publicaciones sobre el AAS.

Propósitos de aplicación: Alrededor del 40% de los artículos revisados exploraron las capacidades del AAS en modelado de datos, adquisición de semántica y la conexión de diferentes instancias de AAS. Los demás estudios se centraron en aplicaciones concretas, como el mantenimiento predictivo, la interfaz humano-máquina (HMI) y la producción en sí.

Avances y Aplicaciones del AAS en la Producción

El AAS se está aplicando principalmente en el campo de la producción y manufactura. En particular, los estudios de [24] y [25] destacan la creación y gestión de AAS en un entorno con múltiples partes interesadas. Un enfoque interesante es el uso de herramientas como AASX Package y Eclipse BaSys, que simplifican la creación de AAS para aquellos sin experiencia técnica avanzada. Esto ha permitido que más actores dentro de la industria adopten el AAS, facilitando la interoperabilidad entre sistemas y tecnologías dispares.

En entornos con múltiples agentes, se ha propuesto el marco OAASIS [26], que permite el acceso y la modificación de los AAS en función de los permisos de propiedad y edición del activo. Además, otros estudios como el de [30] proponen herramientas basadas en Papyrus4Manufacturing para modelar AAS utilizando ontologías, lo que permite una mejor gestión de los datos a lo largo del ciclo de vida del producto.

Investigación sobre la Gobernanza de Datos y Ciberseguridad

Una de las áreas de investigación que aún presenta vacíos importantes es la gobernanza de datos y los aspectos de ciberseguridad en el uso del AAS. Un estudio clave [29] reveló una brecha significativa en los principios de gestión de datos, como el control de acceso y la gestión de derechos. Se espera que la IDTA publique un enfoque oficial para abordar estas cuestiones, lo que fortalecerá la seguridad de las interacciones entre gemelos digitales.

Conclusiones de la Revisión de la Literatura

A partir de la literatura revisada, se puede concluir lo siguiente:

- Enfoque principal en el modelado de datos: La mayoría de las investigaciones sobre AAS se centran en sus capacidades para modelar datos y cómo facilitar la interoperabilidad a través de diferentes plataformas.
- Aplicación predominante en manufactura: La industria manufacturera sigue siendo el sector principal en el que se aplica el AAS, especialmente en el contexto de mantenimiento predictivo y gestión de activos.
- Desarrollo de herramientas de usuario: El progreso en herramientas como AASX Package y Eclipse BaSys está facilitando la adopción del AAS, incluso en entornos con múltiples partes interesadas y sin experiencia técnica avanzada.
- Futuro prometedor: La creciente publicación de investigaciones sobre el AAS, junto con el avance de normativas y estándares, como el Digital Product Passport (DPP), posiciona al AAS como un elemento central en la evolución de la Industria 4.0 y la transformación digital global.

Requisitos de Conectividad entre los Gemelos Digitales

Con base en la revisión realizada, se han establecido varios requisitos técnicos para asegurar la conectividad efectiva entre los gemelos digitales basados en AAS. Estos incluyen:

1. Propósito: Es esencial que las funcionalidades para procesar, almacenar y transmitir datos entre gemelos digitales estén bien definidas. Además, debe establecerse el valor que se obtiene al permitir la interacción de los gemelos, como la optimización de procesos o el monitoreo en tiempo real.
2. Adquisición de Datos: Los mecanismos para generar las representaciones virtuales de los activos deben estar claros, permitiendo tanto la entrada automática como manual de datos. Esto incluye la integración de datos de sensores, sistemas de control y otros dispositivos en tiempo real.
3. Entradas de Datos: Es necesario especificar las interfaces de comunicación entre los activos y los distintos agentes involucrados. Además, debe definirse la propiedad de los datos y cómo se manejarán las operaciones de creación, acceso, modificación y generación de modelos virtuales.
4. Verticalidad: Los datos deben estar en un formato común que facilite la integración de activos desde el nivel de campo (sensores y máquinas) hasta el nivel de gestión (sistemas ERP y MES). Esto es crucial para crear una visión unificada de los activos y permitir su control a nivel empresarial.
5. Enlace de Datos: Los mecanismos de transacción de datos deben ser claros y garantizar que los datos intercambiados sean fácilmente comprendidos por todos los sistemas involucrados. Esto incluye la especificación de cómo los activos físicos se vinculan a sus representaciones virtuales.
6. Sincronización: Los datos generados en el equipo de manufactura deben ser sincronizados en tiempo real con los gemelos digitales, permitiendo que las actualizaciones y cambios se reflejen de inmediato en los sistemas de control. Además, la retroalimentación de los modelos virtuales debe alimentarse de vuelta en los activos físicos.
7. Seguridad de Datos: La transmisión de datos entre gemelos digitales debe ser segura, utilizando canales de comunicación protegidos y garantizando que los datos estén cifrados y protegidos contra accesos no autorizados.

8. Trazabilidad: Asegurar que los datos de los activos sean trazables a lo largo de todo su ciclo de vida, desde su fabricación hasta su desecho o reciclaje. Esto es particularmente relevante en el contexto de las normativas de economía circular.

5. Conclusión: Aplicación de los Requisitos en un Entorno de Fabricación Dinámico

La interoperabilidad de los gemelos digitales, facilitada por el Asset Administration Shell (AAS), ha demostrado ser una tecnología clave para la transformación digital en diversas industrias, especialmente en el sector de la manufactura. A lo largo de este informe, se ha explorado cómo el AAS no solo habilita la conexión entre diferentes gemelos digitales, sino que también garantiza la integridad, seguridad y consistencia de los datos intercambiados.

Como punto final, y disponible en la version en ingles, se ha explorado aplicar los requisites a un entorno de fabricación.

Executive Summary

Digital Twins, first introduced in the early 2000s, have consistently been a prominent focus of research, particularly within the manufacturing sector, where approximately 80% of studies are concentrated. Originally, the concept centered around gathering data and information throughout the entire Product Life Cycle. Over time, Digital Twin technology has expanded into various fields, including Health and Safety, Virtual Commissioning, and further developments within manufacturing. A significant milestone in this area was the introduction of the ISO 23247 standard, which provides guidelines for integrating Digital Twins in manufacturing. However, as it will be detailed throughout the report, although it defines a specific framework for implementing the digital twin technologies in manufacturing environments, it falls short in specific relevant topics like the connectivity of digital twins between them.

This thesis reviews recent publications on the topic of interconnecting Digital Twins to identify commonalities and the most effective technologies for enabling such connectivity. Notably, it starts with exploring the concept of "interoperability" in Digital Twin environments, a topic that has been under discussion within standardization organizations. Interoperability, as defined by the ISO 21823 standard, involves the ability of two or more systems or applications to exchange and mutually utilize information.

Several sources of information have been consulted to form an accurate state-of-the-art about Digital Twin Interoperability. Specialized academic search engines with advanced search string filters have been used to retrieve specific papers on the topic. **The main target was to identify weather or not industry was dealing with the challenge of connecting digital twins, and if so, the approach that it was taken**, that being, the main topics explored by researchers and the most named technologies, frameworks and methodologies.

In that aspect, **the Asset Administration Shell**, a framework first conceived in 2015 by Plattform Industrie 4.0, led by the German Federal Ministry of Education and Research, **has been acknowledged to be a key enabler for interoperability in the Industry 4.0 Environment**. Several papers analyzing this technology have been commentated in the report, highlighting the research conducted on it, and the complementary technologies that support the interoperability aspect of Digital Twins. The spread of this technology is prominent in research, and currently an international standard, supervised by the International Electrotechnical Commission, is under production.

Keeping the focus on the Asset Administration Shell technology, specific architectures available in research are analysed to **conceive a list of requirements that characterize connecting digital twins between them. In addition, the Product Carbon footprint estimation is presented as a relevant topic**, due to future regulatory requirements that

will be imposed by the European Union. In that regard, a **reference architecture to enable the Product Carbon Footprint by connecting digital twin entities among them based on the Asset Administration Shell is presented.**

In conclusion, the main goal achieved by the production of this report has been double: First, a research activity was performed to describe the research environment in the interoperability between Industry 4.0 Components. Relevant advancements made both by researchers and standardization organizations in the task of conceiving a technological solution to connect digital twins are compiled in this document. Secondly, the Asset Administration Shell was acknowledged as an interesting technical tool to succeed in connecting digital twins. This is shown by the fact that standardization organizations and the consensus of specialized scholars have appointed the technology as a key player in the interoperability environment of Digital Twins. **To contribute to the existing body of knowledge on the topic, papers presenting architectures that enabled digital twin connectivity were analyzed, to propose a list of requirements. Lastly, a diagram showing the communication points for enabling the product carbon footprint calculation was conformed**. Specific literature was appointed relevant to the task, as it treated in one way or another the communication between the different agents involved.

Key-words: Digital Twin, Interoperability, Asset Administration Shell

Table of Contents

1. Introduction

a. Background Information

The digital twin technology has concentrated substantial attention over the past two decades. Initially conceived to enhance product lifecycle management, digital twins have expanded their theoretical applicability across diverse sectors including intelligent manufacturing, smart cities and complex supply chains management. The core functionality of digital twins relies in the creation of a virtual replica of physical entities, with a capability to establish a bidirectional communication flow between both domains, thereby enabling real-time monitoring, simulation, and optimization of processes.

The realization of this master thesis began with the following context:

> *"A unifying theory that systematically defines the core functions bridging the gap between the digital and physical entities is missing. A thesis is proposed to aim to partially fill this gap by helping to identify and develop models and methods underlying digital twin fundamental functions"*

In that aspect**, the field identified to fill the gap present in the unifying theory was** the topic of digital twin interoperability. In other words, **connecting digital twin entities between them** in a way that they are capable of exchanging information efficiently.

The true potential of digital twins is realized when these virtual models can consistently communicate and collaborate with each other. In this field is where the concept of Digital Twin Interoperability (DTI) becomes indispensable, as it is pivotal to guarantee that digital twins can share information effectively but more important, interpret in an exact way an identical fragment of information [1].

With that as starting point, the next group of questions arose:

i. Why is digital twin interoperability relevant? What problem does it address?
ii. Which are the research trends on the topic?

iii. Is there any technology in the DT field that specifically identifies this gap? If so, is this technology an open-source alternative? Are there any standardization organizations involved in its development?

b. Main Target and Methodology

This report aims to delve deeper into the current state of digital twin interoperability, providing a description on the current state-of-the-art by identifying the key research topics the sector is facing and to explore the strategies proposed to achieve that Digital Twins can effectively communicate between them.

Considering the three-research questions stated in the previous section, a comprehensive literature review was conducted using scientific-specific academic repositories to explore the state of interoperability within the current context of digital twins. For that, carefully selected papers, and any relevant cited documents included in them were analyzed to provide a state-of-the-art overview, reflecting the current scenario of interoperability between digital twins.

c. Report Structure

Chapter one, which ends with this section, deals with the context in which the project is framed. The main objectives are presented, and the methodology followed for the literature review is introduced.

Chapter two briefly introduces the need for interoperability in the Digital Twin environment. Secondly it presents an overview and analysis of the literature reviewed, trying to build a narrative between the different methods, techniques and frameworks presented in each work. Its main goal is to present the main methodologies, frameworks and technologies that are present in specialized literature and that aims to solve the interoperability problem between digital twins. Additionally, the efforts performed by the main standardization organizations is compiled. The main conclusions on the literature review are collected at the end of the section in which a specific reference architecture is presented, and which will be covered in the rest of the report.

Chapter three will be entirely dedicated to presenting the technology. The main characteristics of the referenced architecture will be detailed. In addition, specific research fields in which the technology will play a significant role are presented. Alongside, architectures in research covering the connection of digital twins and their data are presented.

Chapter four contains the main contribution done by the Thesis to the existing body of knowledge of the technology. Several relevant papers covering the technology will be analysed to depict a list of requirements that characterize the architectures that enable digital twin connectivity. In addition, an analysis of the different interactions needed between field-level assets to calculate the product carbon footprint of a manufacturing process is performed.

Finally, **chapter five** will summarize the main findings and implications of the report as a hole. Future work guidelines will be defined to keep contributing to the interoperability paradigm in the Digital Twin Research Field.

2. Literature Review

2.1 The need for Digital Twin Interoperability

Interoperability among digital twins is the pivotal challenge currently faced by industry for enabling effective integration and management of complex systems, such as manufacturing processes or supply chains, where multiple actors and processes are involved. High interoperability between industrial assets through their digital twins would ensure efficient information sharing and processing, thereby optimizing overall system performance.

It is important to distinguish digital twins from traditional computational modelling and simulation techniques like finite element analysis and discrete event simulation. While both use digital models to replicate products and processes, digital twins create a virtual environment capable of studying multiple simulations, backed by synchronized real data and a two-way flow of information between the digital twin and the sensors collecting this data. This bidirectional synchronization, which can be event-based or time-based, is a key feature of digital twins, setting them apart from conventional offline modelling and simulation. It increases the accuracy of predictive analytical models, offering greater understanding for the management and monitoring of products, policies, and procedures.

In smart manufacturing, for instance, interoperable digital twins of different machines and systems within a production line would enable real-time monitoring and optimization, leading to greater efficiency in scheduling predictive maintenance operations and reducing overall downtime. Supply chain management is another field where the advantages are significant. Enabling connectivity between digital twins of products, warehouses, and transportation systems would provide end-to-end visibility, facilitating better inventory management, demand forecasting, and route optimization, collectively reducing costs and improving delivery times. Furthermore, in the context of product lifecycle management, communication between digital twins of design, manufacturing, and in-use phases could lead to rapid iterations and improvements, accelerating innovation and reducing time-to-market for new products.

Accurate and reliable information exchange between sensors, physical plant resources like machines and conveyors, manufacturing execution systems, and enterprise resource planning systems are capabilities that would collectively contribute to process optimization, improved efficiency, and innovation across industries. Currently, this exchange of information is not standardized at all, as each system counts with its own communication interfaces [1].

In essence, enabling digital twin interoperability would enhance data sharing and reuse across different systems and industries, increasing the value of data when utilized in multiple contexts. This advanced level of integration and real-time synchronization positions digital twins as powerful tools for managing and optimizing complex industrial systems in ways that traditional modelling and simulation techniques cannot match.

2.1.1 Retrieving relevant documentation

The relation between the concepts of “Digital Twin” and interoperability has become an increasingly popular research topic. The result of a simple search of the terms “Digital Twin” and “Interoperability” **as keywords** in the scientific repository Science Direct shows an interesting trend: Those keywords were included in 4 papers in 2019, 10 in 2020, 6 in 2021, 17 in 2022, jumping to 44 in 2023, and 40 just in the first half of 2024. Consequently, it can be stated that digital twin interoperability is a topic attracting attention from specialized scholars.

An academic search using academic search engines like Scopus and Consensus was performed. Throughout the research, several search strategies were defined: Filtering by keywords, by words contained in the Article Title or the abstract, etc. These general strategies typically retrieved documents that tackled the topic of digital twin interoperability in a very theoretical manner, without specifically pointing out relevant technologies, frameworks or methodologies that solved the challenge of connecting digital twins between them.

As a result, the search was explicitly **targeted at titles** explicitly containing the words "Digital Twin" and "Interoperability” resulting in 27 documents. Of them, twelve papers were selected for detailed analysis as they treated, in one way or another, the concrete manner of the ability to connect digital twins between them. The exclusion of the remaining fifteen documents was in relation to the lack of emphasis on this matter, as they focused on describing the main advantages interoperability would introduce in different industrial sectors but fall short on providing frameworks or technological solutions to such topic. The exclusion criteria followed for the specific search string mentioned above can be consulted in Annex I.

The papers selected conformed the starting main pool of information consulted for the documentation about the topic. Its review and main findings can be consulted in the following chapter. To further refine and complement the literature review, a citation analysis was conducted, including additional specific relevant documentation to the informational source pool.

To find an always consistent narrative between the different case studies analyzed and the technologies presented has been the main challenge faced by the author. For that purpose, the chapter is split in two differentiated parts. The first one contemplates the analysis of the papers that specifically aim at industrial companies. Surprisingly, some of the papers analyzed came from research groups from R&D departments of relevant industrial companies, which was interesting to analyze as it showed which technologies were being used in the industrial sector. The second part shows the most relevant conclusions found in specialized literature. Some of the papers contemplated were literature reviews themselves, and the findings shared came from analyzing the existing literature at the time of publication. The complete documentation can be consulted in the Bibliography section.

In conclusion, the main goal of this literature analysis is to analyze which technological options are spread across industry and research to enable digital twin interoperability. The main conclusions of the complete literature review can be found at the end of the chapter.

2.2 Industry Leaders' approach

Industries are characterized by being multi-agent networks. Materials and resources are exchanged between the different players throughout the different life cycle stages. As part of the digital transformation the industry is dealing with, information in digital form is also shared.

For example, in the initial phase of requirements definitions related to the design and engineering phases, digital models (CAD, ECAD) are created and exchanged typically with established product data management solutions, like Siemens PLM, or SAP. These solutions enable the share of static digital data. However, in further lifecycle phases, like the data generated in the manufacturing process or operation, other systems like Manufacturing Execution Systems play a significant role. This lack of standardization makes interoperability a major challenge.

This challenge can be assessed from different perspectives and analyzing how different key players of the industry are dealing with them might be beneficial to assess if different agents follow a common strategy.

In this first part, the approach followed by two leaders in the automation industry like Siemens and ABB will be carefully analyzed. The main goal is to breakdown the challenges mentioned in their published research they consider pivotal to solve in the digital twin interoperability problem and identify the technologies they use and the future topics the aim to tackle.

2.2.1 Expert's knowledge to define the Research Problem: Siemens

Related to the background information provided in the previous section, Siemens stated that the task of improving the interoperability in exchange of digital twin data had different challenges to address. In December 2022 they started a project in which they aim to implement a specific technology for enabling reusability and interoperability of the data.

To establish a standardized data exchange and collaboration concept, they gathered a working group of thirty engineers and digital twin experts from eight companies to define the requirements and measurement criteria the solution should be characterize with.

The full list of requirements and evaluation items can be consulted in [2]

Specifically, they considered the Asset Administration Shell technology as an enabler of digital twin data and its shared use. To support that statement, they present several references to papers that study how the AAS technology meet some of the requirements they present. However, they assess that the research reviewed only meet the requirements to a very limited extend, neglecting the aspect of implementation in a cross-company context, and the consequent validation of the technology. That is precisely what led them to enunciate the specific research gap they aim to adress: The development of a prototype platform to merge the static digital twin data from a Product Lifecycle Management system (Siemens Teamcenter) towards an AAS server/repository.

The results published study how the information included in their PLM software solution would be included in the metamodel of the Asset Administration Shell. For future updates of the work under production, they recognize that the topic of sharing data of digital twins is being triggered by coalitions at both the company level and the institutional level. In that regard, they expect that interactions in technological events like the Hannover Fair, where yearly the latest findings of the Asset Administration Shell are shared, will help them to define new requirements and evaluation items to their work.

The work analysed in this section belongs to the results of the on-going research published by Siemens themselves as a research paper. However, it is not the only source of information that can be consulted to analyze the approach Siemens is taking in the topic of digital twin interoperability.

In April 2024, at the Hannover Messe 2024, Siemens presented its latest specific development on AAS, aligned with the roadmap presented in the academic paper, being the most relevant the software integration of the Asset Administration Shell into the main solutions and products offered by Siemens: Teamcenter, TIA Portal and Battery Passport.

> *"The administration shell (AAS) is a key technology for the seamless exchange of digital twin data along the entire value chain. The AAS implements all principles of Xcelerator and is therefore ideal for tracking the entire product lifecycle. Within Manufacturing-X, the AAS is set as a basic technology and anchored across all use cases. That's why we actively promote the application of AAS in the industry as one of the consortium leaders in the Factory-X project." CEO of Factory Automation at Siemens, Rainer Brehm*

Another topic in which Siemens is leading the research is in the relationship between the Asset Administration Shell and the Digital Product Passport. At the fair, specific advancements were pointed at the how the Digital Product Passport for Industry 4.0 Components, part of a new regulatory requirements of the European Union as part of the Eco-design for Sustainable Products Regulation (ESPR) and the Green Deal, could be composed of the reference architecture available in the Asset Administration Shell.

In conclusion, it can be affirmed that **Siemens has strategically acknowledge the Asset Administration Shell as the main technology for the Digital Twins of the Industry 4.0.**

2.2.2 Experts' Knowledge to define the Research Problem: ABB

With the publication of an article in 2020 [3], ABB took the lead in demonstrating that a transformation system simplifies the standardized provision of information on devices via digital twins. Their focus was to study the interoperability of digital twins for information exchange. That means transforming information models of digital twins into a common target format that ensured interoperability. The approach was like that of Siemens but was not focused on the cross-exchange of information, rather it was focused to show digital twin connectivity within a single company environment. Foe that, the German Company ABB enabled a system to transform its Digital Twins in ABB Ability™ format to Asset Administration Shell. This demonstrates that transformation of the information models is a viable solution when it comes to enabling the exchange of comprehensible information in a bidirectional way between agents (in this case, provider and customer).

In addition, a literature analysis performed using the Scopus database showed that ABB kept researching the functionalities of the Asset Administration Shell technology. Since 2020, nine publications affiliated to any of the ABB Groups were published with Asset Administration Shell being mentioned in the title of the work published.

2.3 Researchers' efforts

The second part of the literature analysis continues exploring the research trends on digital twin interoperability. The topics contemplated include comparison between different architectures and information models for asset representation, specific translation models between digital twin architectures, as well as concrete efforts made by researchers to quantify the most used technology for dealing with the task of connecting digital twin entities.

2.3.1 Transformation models between Digital Twin Architectures

The work performed by Schmidt et al [4] continued the work led by ABB [3] in enabling digital twin interoperability by a transformation system between different architectures.

Briefly describing the added value of Schmidt's work, a mapping in the metamodel level is proposed to transform DTDL-compliant Digital Twins into AAS-compliant Digital Twins, enabling communication and integration between systems that use these well-spread architectures. It is worth noting an important restriction of the paper, that being, that it solely studies the substitutability of the architectures, without entering concrete relevant aspects of the implementation such as communication protocols or security aspects.

In particular, the following architectures for asset representation are contemplated:

- Plattform Industrie 4.0 with AAS
- Microsoft Azure with DTDL
- ETSI with NGSI-LD
- Eclipse Foundation with Vorto
- World Wide Web Consortium with TD

By nature, these architectures are incompatible with each other as they do not share the same syntax, properties and behaviour representation mechanisms, communication systems and or semantics and properties. In addition, it cannot be expected that in the future there will be only one dominant international standard used to implement digital twins, so a paradigm needs to be resolved.

Different efforts from the academic community show that one of the possible paths towards interoperability remains in the transformation of digital twin architectures into each other, when possible. [3] [5] [6] [7].

To compare different architectures, a list of set of requirements to compare against is needed. Schmidt uses the following:

Requirement	Description
1. Models	Assets are represented in a structured way using models
2. Product Life Cycles	The entire PLC of the asset must be supported with the DT representation
3. Portability, Reusability and Scalability	These capabilities must be supported
4. Interaction	Instances of digital twins must be able to interact.
5. Composition	Hierarchical relations must be supported
6. Interchangeability	Interchangeability of digital twin instances of the same model must be supported. (An instance is a digital twin of the model already in use)
7. Standardized definition and capabilities	Structure must be standardized for different assets
8. Taxonomy	Terms and definitions of the descriptors must be provided

Table 2.1: Requirements to compare the architectures against

[4] reaches the decision of providing a transformation framework between DTDL → AAS analyzing the already available options in other papers and discussing the most promising architectures among the five mentioned above.

NGSI-LD is identified to be limited in its ability to communicate with the asset due to the lack of functions as a model element, and Vorto does not support relationships and compositions of twins which is an important element for digital twins in the context of Industry 4.0.

Pakala et al [5] proposed a transformation of TD into AAS, and Microsoft's option contemplates the transformation of AAS into DTDL. As a result, the feasible advanced needed is the creation of a transformation model of DTDL into AAS.

Research like the ones performed in [3] and [6] propose a transformation model based on the metamodel level. The metamodel refers to the highest level of abstraction of the architectures and defines how the information is structured. In other words, it is the systematic organization, exchange and retrieval of the data.

The work performed in [6] tackles the task of overlapping the systematic organization of the data between AAS and DTDL to make available the transfer of compliant from AAS to DTDL.

2.3.1.1 Mapping Rules definition

The main goal of the mapping rule is to find an equivalent between how information is registered in both architectures.

Each element of the DTDL environment was mapped to an element of the metamodel proposed by AAS. In this task, the following were the main ideas considered:

- DTDL Interface is considered as the superordinate element and the remaining are divided into data elements and other types.

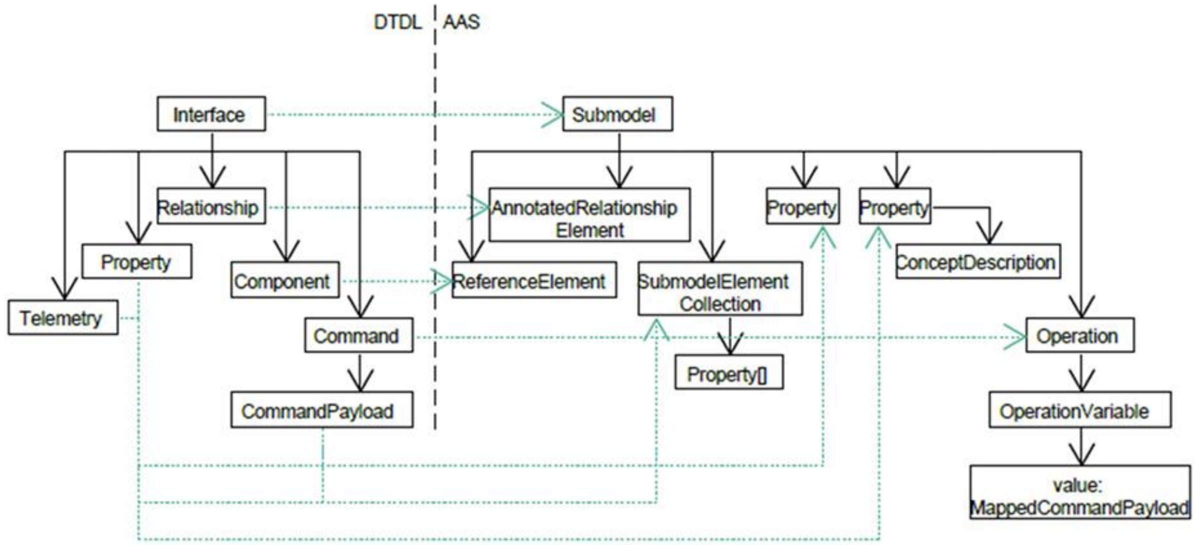

Figure 2.1: Metalevel mapping of DTDL architecture and AAS standard [6]

The main achievement by the transformation model in Figure 2.1 is that it enables that an AAS output file can be generated from the DTDL model.

2.3.2 The predominant technology in research

As presented in the previous section, several digital twin's architectures have been consistently used in research. With this section, specific papers in the form of literature reviews will be analyzed to disseminate if any of the digital twin architectures is preferred in research, and if so, the field in which it is used.

In [8], the research question of the preferred technologies for data exchanged within a digital twin and among digital twins is addressed. The final pool of information consisted of twenty-one primary studies. From that pool thirty percent of the research analysed selected the Asset Administration Shell as the main architecture to enhance data exchange. . [9] mentions how digital twin models cannot achieve interoperability when designed and implemented independently. In that aspect, it mentions AAS as a unified architectural framework to achieve interoperability between Industry 4.0 Components. [10] appoints that only four digital twin architecture technologies (AAS, DTDL, NGSI-LD, OPC UA) support multivariant timeseries, which is a data structure needed to allow digital twins to operate and exchange data among them. For standardization purposes, AAS is appointed as the preferred technology because it is the only one that is considered a standard, and more importantly, because the European Green Deal, on its sustainability efforts, also recognizes this categorization of standard.

2.4 Standardization efforts in Digital Twin Intercommunication

To identify methodologies, frameworks and technologies that support this interoperability, the efforts performed by the main standardization organizations will be reviewed next. It is important to highlight that most of this effort is work under production, so conclusions might not have been published yet. However, identifying where the efforts are being directed is worth noting, as it might show similarities and discrepancies between different organizations and the research analysed.

Formally, the concept of interoperability is a very discussed topic on the Industrial Internet of Things (IIoT) domain, with established standards specifically addressing interoperability. However, the concept of Digital Twin Interoperability, understood as the capability of digital entities to communicate seamlessly, remains an emerging field with no specific standards published yet.

This gap has been highlighted by the American National Institute of Standards and Technology (NIST) [11] which suggested in an analysis published on early 2023, on the series of standards that deals with a digital twin framework for manufacturing, that, quoting literally, “future standards should consider the integration and communication between Digital Twins. The need for interoperability is crucial to extract the full potential of Digital Twins, enabling them to interact, share data, and function cohesively within diverse digital ecosystems”.

However, as it will be detailed in the next section, not all the standardization organizations have approached the challenge in the same way. The efforts made by ISO/IEC and ETSI will be reviewed.

2.4.1 ISO/IEC

2.4.1.1 Interoperability Standard: IEC 21823

The JTC1 SC41 Work Programme created by ISO and IEC is dedicated to enhancing IoT interoperability by developing comprehensive standards that ensure integration and communication across diverse systems. In particular, the ISO/IEC 21823 series addresses various aspects of interoperability such as: framework, transport connectivity, semantics and syntactic and behavioral policies.

2.4.1.2 Digital Twins Architecture: IEC 62832 and ISO 23247

IEC 62832, titled "Industrial process measurement, control and automation – Digital Factory framework," is a standard that provides a framework for the digital representation of industrial processes, systems, and equipment. The standard is critical in enabling the development and implementation of the "Digital Factory" concept, which is integral to Industry 4.0 and smart manufacturing

The ISO 23247 standard, titled “Automation systems and integration — Digital twin framework for manufacturing”, lays the foundations for using Digital Twins in the manufacturing sector, which accounts for nearly 70% of Digital Twin research.

The main contribution of the standard is defining four main entities in the digital twin framework: The user entity, like human-machines interfaces for example, the digital twin entity, which virtually represents the assets, the device communication entity, for ensuring two-way communication, and the cross-system entity, providing common functionalities such as security support. It is worth noting that the standard also specifies what resources can be virtually represented. For that purpose, Observable Manufacturing Elements (OMEs) are defined. In total eight types of elements are defined, each characterized by seven attributes. To our needs, this descriptive approach is interesting but fall short on proposing specific technologies for virtual asset representation.

In relation to interoperability, part 4 of this standard specifically tackles the topic of the technical requirements for the information exchange between the entities described in the reference architecture defined.

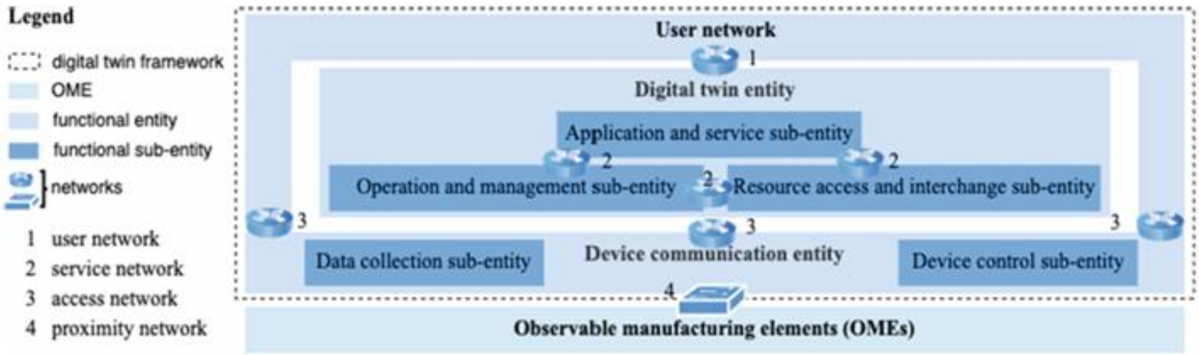

Figure 2.2: Communication framework between entities in ISO 23247 [12]

The communication framework of ISO 23247 assumes the following types of interactions: The access network and the proximity network are responsible for connecting the digital twin with its physical counterpart. The service network is responsible for connecting the different information models that together conform the digital twin. In the AAS environment, the service network would be the internal mechanism that connects the different submodel elements. Finally, The user network connects the DT entity with third-party systems such as Enterprise Resource Planning (ERP) or Manufacturing Execution System (MES), allowing them to use the services provided by the DT. Consequently, it can be stated that ISO 23247 does not directly contemplates any type of communication between digital entities, therefore not assessing the interoperability gap between digital twins' entities, which is the main target of the literature review.

2.4.1.3 Information Model: IEC 63278

Technical Committee 65 of the International Electrotechnical Commission and more specifically the Working Group 24 is working on the standardization of the Asset Administration Shell for Industrial Applications. The complete IEC 63278 Standard will be compiled by the following documents:

- Asset Administration Shell for Industrial Applications – Part 1: AAS Structure (Published)
- Asset Administration Shell for Industrial Applications – Part 2: Information metamodel (Draft for public comment, final publication expected for 08/2025)
- Asset Administration Shell for Industrial Applications – Part 3: Security Provisions for AASs (Exp 08/2025)

- Asset Administration Shell for Industrial Applications – Part 4: Use Cases and modelling examples (Draft for public comments, final publication expected for 10/2025)
- Asset Administration Shell for Industrial Applications – Part 5: Interfaces (Exp 12/2026)

The Asset Administration Shell (AAS) architecture significantly contributes to addressing interoperability challenges within digital twin ecosystems by providing a standardized digital representation of assets. This standardization is vital in facilitating seamless integration and communication among various digital twins, which is a primary concern highlighted in [11].

In addition, it perfectly complementizes the ISO 23247 standard outlining a reference architecture for digital twins in manufacturing, emphasizing the need for consistent data formats to ensure interoperability, offering a structured framework that encapsulates the asset's data and functionalities into a standardized format. This framework theoretically allows for easier data exchange and interaction between different systems and digital twins. Moreover, it supports data accuracy and integrity, which aligns with the data assurance of ISO 23247. By standardizing how data is represented, stored, and accessed, AAS helps maintain consistency and reliability across different digital twins. This is crucial for ensuring that the information used for decision-making and process optimization is accurate and trustworthy.

In essence, AAS enables the creation of a unified digital twin framework by providing standardized interfaces and protocols, which align with the interoperability support and peer interface functional entities described in ISO 23247. On paper, it enables that DTs can communicate effectively, share data, and work together without the need for extensive customization or additional integration efforts.

The Industrial Digital Twin Association (IDTA) aims to make sure that all these theoretical capabilities of the standard are demonstrated in the industry. As a result, it is the organization responsible for providing the concrete specification of the referenced architecture.

2.4.2 ETSI

The European Telecommunications Standards Institute (ETSI) also has identified the need for enabling the integration of data sources and systems in an interoperable way. Even though the organization itself is not focus intensively on the Industry 4.0 (as it is Plattform Industrie 4.0, the enabler platform of the Asset Administration Shell), it has formed a working group (Reference Body SmartM2M and Project Number 628) to specifically analyse the standardization opportunities in ETSI in the Digital Twin field.

In particular, the idea is to provide a referenced architecture for Digital Twins mapped within the oneM2M framework.

Currently, the published documentation only mentions the digital twin reference architecture theoretically, and does provide a concrete specification, as AAS currently has, as explained in the previous section. In addition, in the specific literature reviewed in Chapters 3 and 4, AAS has shown to be more appropriate that NGSI-LD (the ETSI data format) for the Industry 4.0 and manufacturing environment.

In conclusion, as the Asset Administration Shell is the reference architecture that owns the category of international standard, it is expected to be the a relevant technology and framework used for enabling interoperability in the Industry 4.0.

2.5 Main conclusions of the literature review

The task of connecting DTs between them is a growing topic in the research field, and the publication trend of works tackling that topic is considerably increasing. The papers specifically mentioning in their title the words "Digital Twin" and "Interoperability" present an annual growth rate of 50%.

In an on-going research project [2], Siemens defined the structure of the assets in AAS format that enhanced significant data exchange between partners and their respective digital twins. On the other hand, ABB [4] explored defining transformation rules from different information models to AAS and continue to explore the Asset Administration Shell technology in their research agenda.

The work performed by scholars is focused on allowing the integration of IoT elements ensuring that shared data is interpreted consistently across different systems. [7] [8] and [9] identify creating intermediate transformation models between well-established architectures as an effective approach to reach interoperability.

Specifically related to semantic interoperability, [11] points out that the Asset Administration Shell is increasing its compatibility with ways to attach semantic to the information models. In that regard, ECLASS has been acknowledged as the official semantic dictionary, but other alternatives are gaining popularity, like the semantic dictionary MaRCO, based on ontologies of the manufacturing environment.

In the realm of data formats, [4] states that NGSI-LD offers limited capabilities in bidirectional communication compared with AAS and DTDL. [10] appoints AAS as a technology that excels in the timeseries data, comparing it to NGSI-LD and DTDL. This data format is very relevant in the digital twin interoperability paradigm, as for DTs to operate, the exchanged data must cover long time horizons, which is possible only with timeseries structures. Lastly, [13] advocates for the AAS as the standardized data model for the provision of information as compared to DTDL and TD, it is the only officially standardized information model referenced architecture for digital twins.

In [8], with the analysis of 29 digital twin architectures in the manufacturing domain resulting from a systematic literature review of 140 peer-reviewed publications, Asset Administration Shell is revealed as a possible solution for standardising communication between Digital Twins. Another aspect that backs this idea is that out of the most used open-source digital twin architectures, only the Asset Administration Shell is a standard.

In the regulatory framework, Asset Administration Shell has been contemplated as the main standard for semantic structuring of product information in an interoperable data format, required characteristics for the Digital Product Passport (DPP). This concept is part of the new regulatory requirements the European Union will instate to implement in multiple sectors in the next years to facilitate the shift from a linear to a Circular Economy.

2.5.1 Why the Asset Administration Shell is relevant in Digital Twin Interoperability

The literature review has disseminate how researchers, industry and standardization organizations are handling the topic of interoperability. In particular, the major conclusion is that the Asset Administration Shell technology is appointed as specialized institutions and among the consensus of the publications as the key enabler for ensuring digital twin data interoperability and entity interaction, due to, among others, the following reasons:

1. Relevant companies like ABB and Siemens, for example, are investing resources in making their products compatible with the Asset Administration Shell technology. A specific example is that Siemens leads the research in integrating the Digital Product Passport, based on data interoperability. In addition, yearly meetings are held between the leaders in the manufacturing and automation industries to discuss the advancements of the technology.
2. Although several technologies and architectures are being explored in the researcher community, there is consensus in appointing this technology as the key enabler for Industry 4.0 Manufacturing Plants. Large research projects sponsored by the German government are built around the AAS and consider it as a standard in data ecosystems along the supply chains of manufacturing (Manufacturing-X) and the automotive industry (Catena-X) to achieve interoperability. This additionally reflects the relevance of the research and the

suitability of the AAS concept for resolving interoperability problems in a digital twin environment.

3. The International Electrotechnical Commission is developing a standard about the technology and has been appointed as the main enabler for the Digital Product Passport and the Product Carbon Footprint, EU Regulatory Frameworks that will affect all levels of the production industry from 2027 onwards.

A relevant milestone will occur with the publication of the new version of the reference architecture expected in the next months (as of September 2024), as it will be an official document produced by the user organization of the technology stating the specific framework for peer-to-peer interaction.

In other words, what has been assessed with the compilation of this report is dissecting how the Asset Administration Shell technology is relevant compared to existing options, and how it enables interoperability between different Industry 4.0 Components.

2.5.2 Next steps

As digital twins aim to create value managing the information gathered from its physical counterpart, the fact that data exchange is not standardized is a major challenge. This problem is being tackled by companies, academia and specialized research.

Two main acknowledgements arise from the first literature review performed: (i) The Asset Administration Shell is a very relevant technology in enabling digital twin interoperability. (ii) [2] and [14] concluded that there is a research gap in the aspect of implementation of DTs architectures: they should be created for specific use cases. On contrary, most research focuses on modelling a concrete system in its entire complexity. In that regard, they propose the question that should be answered is what the concrete information that should be provided and shared is. For that reason, they compiled a list of requirements that should characterize the architecture that enables sharing the data of DTs.

The next chapter will be differentiated in two parts. Firstly, the Asset Administration Shell will be presented theoretically, highlighting the importance of its user organization, The Industrial Digital Twin Association, and the information published. Secondly, a review of the existing literature conceiving AAS architectures and its specific use cases will be performed. In that regard, special attention will be put in the cases that contemplates DTs being linked to other DTs.

3. The Asset Administration Shell

3.1 Plattform Industrie 4.0 & IDTA

Asset Administration Shell (AAS) appeared to establish a standardized framework for enabling communication and data exchange in the increasingly interconnected and complex landscape of Industry 4.0. Industrial processes were being digitized both in the plant (with increasing sensor's implementation, data generation and automation) and in the research field, were scholars and researchers were mentioning the interesting capabilities of digital twins. Consequently, there was a pressing demand for a universal architecture that could facilitate seamless interoperability between diverse systems, components, and stakeholders across different sectors. In that context, the AAS was conceived as a digital representation of physical and nonphysical assets, enabling these assets to interact, share data, and operate cohesively within a common ecosystem.

Since its inception in 2015 [15], the AAS has undergone significant development. Over the years, the specification has evolved through the incorporation of feedback from industry experts and the adaptation to the needs of a rapidly evolving industrial environment. The Industrial Digital Twin Association (IDTA) has been a crucial force in promoting and disseminating AAS technology. It has set the perfect environment to foster collaboration between stakeholders from industry, academia, and government. To cite several examples, France, Italy and Germany signed an agreement to form a Trilateral cooperation alliance to support the digitalization of the Industry in a European level. A major achievement of the Trilateral cooperation alliance was achieved in 2022, with the publication of the first part of the document series IEC 63278, making the Asset Administration Shell the relevant standard for digital twins in industrial applications. Outer continent collaborations have also occurred, highlighting a collaboration project between the German and Korean government [16], focused on setting a common strategy for the interoperability of I4.0 Components.

As of August 2024, the AAS specification has solidified its role as a central element in the digital transformation of industry, particularly in enabling digital twins and smart system integration. However, some crucial aspects of the AAS framework are still under development. Notably, official documentation on the security aspects of the information handled by the AAS, which is essential for protecting industrial data, has not yet been fully published. Additionally, detailed guidelines on peer-to-peer interactions, which are key for direct communication between AAS instances, are also pending. These gaps indicate that the development of the AAS is an ongoing process, with further publications expected to address these important areas

3.1.1 Industrial Digital Twin Association

The Industrial Digital Twin Association (IDTA), as the user organization for the Asset Administration Shell, is the main reference in compiling the knowledge available about the standard.

In this section, the available documentation as of August 2024 will be listed, pointing out missing knowledge gaps and the expectancy of future documentation covering those topics will be commented.

3.1.1.1 AAS Specifications

Specifications define the software structure, interface and semantics of the Asset Administration Shell and create the basis for the standardized Digital Twin. The latest update was published in June 2024 and conformed the following topics:

- Part 1: Metamodel
- Part 2: Application Programming Interfaces
- Part 3a: Data Specification – IEC 61360
- Part 5: Package File Format

The published information covers the topics of presenting the information model' data formats (Part 1), attaching the semantic dictionary compliant with the IEC 61360 standard (Part 3) and enabling the interaction of the data included in the AAS in two ways: (i) enabling the file exchange (Part 2) and (ii) accessing the AAS through an API (Part 5).

In that regard, two pivotal topics are missing: Cybersecurity and AAS interaction. Both are mentioned by IDTA as relevant aspect of the architecture that has been carefully assessed, so expectably, specific documentation will be available soon.

3.1.1.2 Content Hub

As complementary documentation to the specification of the AAS itself, twenty-six specifications of submodel templates are published. The full list of published submodel's specification as of August 2024 can be consulted in [22]. To name a few: Submodel template of Provision of 3D Models, Time series data, Provision of simulation models or Technical Data for Industrial Equipment in Manufacturing. Each submodel's specification details an intended-use case to better frame its utilization. Alongside the specification itself, IDTA offers additional documentation in the form of discussion papers and white papers, where findings and collaborations with other companies and organizations are reflected. For example, IDTA eventually publishes reviews of the latest advancements of the trilateral cooperation agreement.

All things considered, the Industrial Digital Twin Association (IDTA) significantly contributes to promoting AAS technology by developing best practices, and guidelines through white papers and use cases that demonstrate AAS applications in real-world scenarios. By advocating for interoperability and fostering collaboration among stakeholders in the Industry 4.0 ecosystem, the IDTA ensures the widespread adoption and effective implementation of the AAS framework across industries. This comprehensive approach by the AAS, supported by the IDTA, ensures that systems, devices, and platforms from different manufacturers can work together seamlessly, facilitating the creation of interconnected industrial systems

3.2 Asset Administration Shell reference architecture

The Asset Administration Shell (AAS), proposed by the German Institution Plattform Industrie 4.0, allows handling assets in the information world always in the same manner, reducing complexity and allowing scalability and interoperability

The Administration Shell is the standardized digital representation of an asset, enhancing the interoperability between the applications managing the manufacturing systems. The main goal is to spread a standardized format of representation as today's value chains are flexible, highly dynamic and globally connected networks. Therefore, it is crucial that machines and processes possess the capacity of sharing information between them, to cooperate in the most efficient way possible.

The AAS consists of several submodels in which all the information and functionalities of a given asset can be included. The information included in the virtual model includes features, characteristics, properties, statuses, parameters, measurement data and capabilities. Each submodel contains a structured quantity of properties that can refer to data and functions

From the perspective of interoperability, the aim is to standardize only a single submodel for each aspect / technical domain.

3.2.1 Structure of the information model

The main strength of the information model presented by AAS is the versatility of information that can be included.

As stated in Figure 3.1, the strict, coherent format enables the uniformity of the assets represented. The essential building blocks that ensure the information is managed efficiently and with sufficient detail are the following:

i. *AssetAdministrationShell* is the top-level element corresponding to an AAS. It must correspond to an actual asset and have an identifier. This element can contain multiple *submodels*. *Submodel* is the element that provides digital representations and technical functionalities.
ii. *Asset* is the element that matches an actual asset.
iii. *AssetInformation* is the element that includes the metadata of an asset. This denotes whether the asset is a type or instance. The difference between asset "type" and "instance comes from RAMI 4.0, which is the reference architecture for Industry 4.0 designed by Plattform Industrie 4.0

A major advantage of AAS is that in can represent traditional manufacturing resources of the field-level (Machines, Conveyors, Transportation Units) as well as assets from higher levels, like MES (Manufacturing Execution Systems) and ERP (Enterprise Resource Planning) systems.

For a full explanation of the metamodel, the reader is redirected to the specification [22] and the IEC 63278, where the information model in UML can be consulted, with specific notes to better understand it.

In terms of data sovereign, the access rights to each submodel can be regulated individually. Furthermore, an AAS can also consist of several nested Asset Administration Shells and form a network of digital models. This aspect is crucial as it explicitly contemplates the feature of connecting digital twins between them.

To maintain and guarantee the nature of standard of AAS, submodels cannot be randomly created by users and need to complete a validation process supervised by the IDTA, the Industrial Digital Twin Association, which is an alliance between powerful agents of the digital twin industry. As of August 2024, 89 categories of submodel elements are available

A relevant feature of the technology is related with how the fragments of code hosted in the information models has attached semantic meaning. This is a pivotal aspect of interoperability, as it is the mechanism to unequivocally identify the magnitude and meaning of the data stored.

Different standardization organizations have produced semantic dictionaries depending on the field. Plattform Industrie highlights two mechanisms, IRDIs or strategies based on ontologies. In the former and recommended by Plattform Industrie relevant examples might be ECLASS and IEC CDD whereas in the latter, initiatives like SAREF and MARCO are gaining relevance in the specialized literature [14].

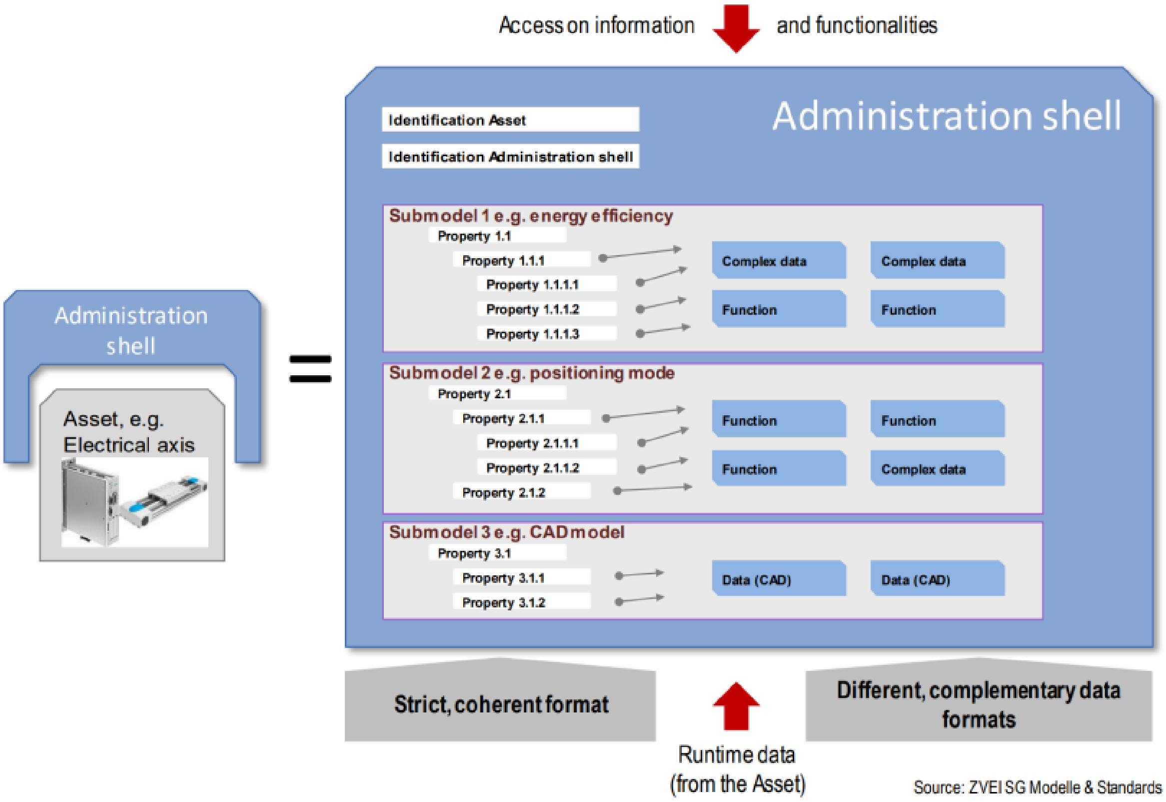

Figure 3.1: Asset Administration Shell morphology [16]

3.2.2 Data formats

Asset Administration Shell's information model is presented in a technology neutral specification to ensure interoperability between different systems. The specification is already under production by Plattform Industrie 4.0 and IDTA, presenting AAS information model in UML (Unified Modelling Language), a technology neutral format.

Its creators are aware that different data formats are used or recommended to be use depending on the life cycle phases/product features that want to be considered. It is important to highlight that by "data formats" the following is implied: information models, schemes, transmission protocols, etc.

As stated by the latest specification published by IDTA, in the moment of writing the report that being the one of June 2024 [17], AAS can be serialized and mapped in different data formats, depending on the field.

Data Format	Purpose/Motivation
OPC UA Information Model	Access to all information of the administration data and sharing live of data within production operations. Access for higher-level factory systems to this information
AutomationML	Sharing of type and instance information about assets, particularly during engineering. Transfer of this information into the operational phase
XML, JSON	Serialization of this information for the purpose of technical communication between phases
RDF	Mapping of this information to enable full use of advantages of semantic technologies

Table 3.1: Supported data formats in the AAS

3.2.3 Data Exchange

A crucial part of the Administration Shell is that it contemplates communication with any other I4.0 Component, that being, other softwares, or even other Administration Shell files. This last capability answers to the need of connecting digital twins between them.

In the specification, three main mechanisms of information exchange are described.

i. File Exchange
ii. API
iii. Peer-to-peer interaction

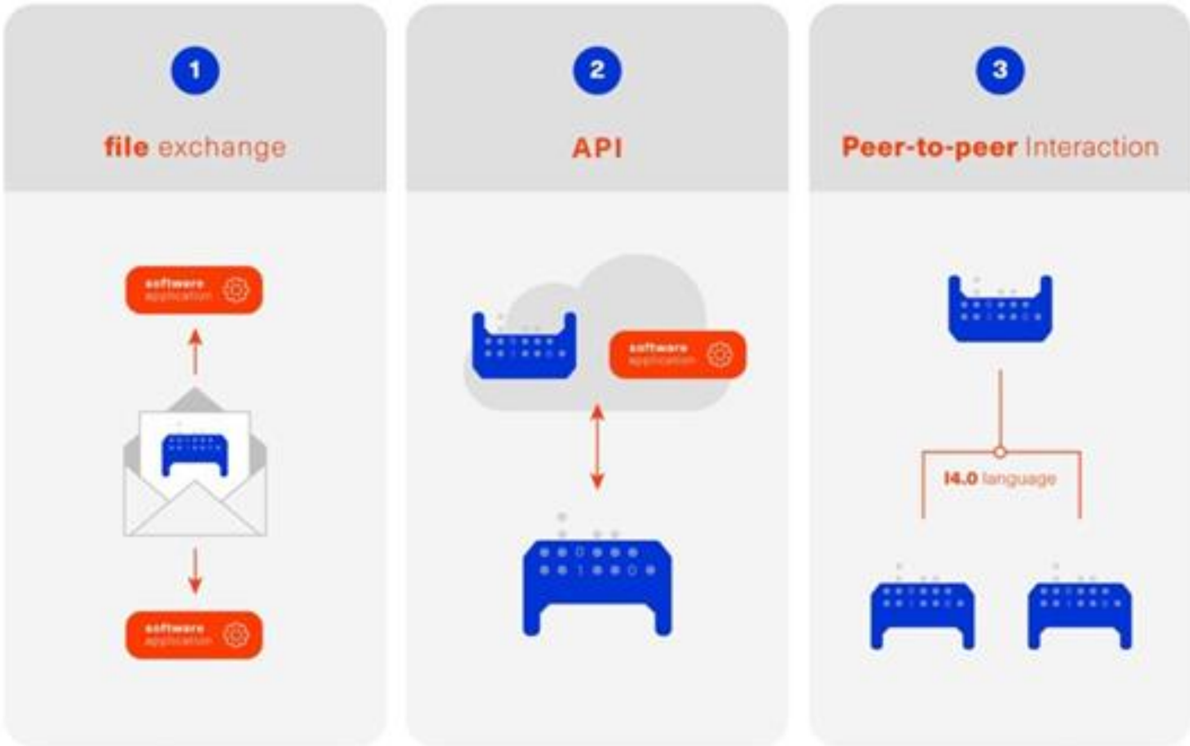

Figure 3.2: Type of information exchange via the Asset Administration Shell [22]

This mechanism contemplates the exchange of an Asset Administration Shell including all its auxiliary documents and artifacts from one value chain partner to another. However, it does contemplate connecting already deployed Asset Administration Shells running in a specific infrastructure. AAS counts with a specific platform to ensure this type of data sharing, named Package File Format for AAS (AASX).

The main challenges faced and solved by the platform includes the filtering of information, as not every content of the information model might want to be transferred, encryption capabilities and policies for authenticity.

The whole procedure to share this type of information has been compiled in a single document by IDTA, as part of a series of documents named "Details of the Asset Administration Shell". Part 5 is the document dedicated to this type of information exchange mechanism [18].

3.2.3.1 Application Programming Interface

This type of mechanisms deals with the task of enabling the access to the information stored in the Administration Shell. Similar to the information models, an API, or Application Programming Interface, the tool used to access the information, can be hosted in different technologies, like HTTP or MQTT, with recommendations for using one or another depending on the specific use case.

As a result, the solution conceived by IDTA offers a technology-neutral specification of the interfaces to make them compatible with already well-established API technologies.

Similarly, IDTA has compiled the procedure in a single document [19].

3.2.4 Peer-to-peer interaction

As shown in Table 3.2, this type of interaction is the one that specifically answers the challenge of connecting digital twin entities between them. That is the main reason why a new section has been created for this topic.

In fact, the original document that defined the strategy of what ended up being the Asset Administration Shell, published in 2015 [20], had as first requirement the following:

Identifier	Requirement	Tracking
STRAT#1	A network of Industry 4.0 components must be structured to ensure that connections between any endpoints (I4.0 Components) are possible. Components and contents must follow a common semantic mode	Network of components is possible but has not yet been included as the main scope of any document. Common semantic model is achieved by the use of domain-specific submodels (HasSemantics, ConceptDescription, Relationship Elements

Table 3.2: Requirement that reflects that connecting digital twins' entities is at the core of AAS [17]

As it can be seen in the right column of Table 3.2 corresponding to the Annex of document [17], network of entities is not the main scope of the document, so presumably, in the future, a specific document, issue of the series "Details of the Asset Administration Shell" lastly updated by IDTA on June 2024, will treat the specific mechanisms AAS use to ensure connectivity between Administration Shells.

3.2.4.1 Published documentation

In the meantime, the recommendation given to design and implement a solution consists in reviewing documents [22] and [20], as the enabler to connect digital twins relies on the information model itself.

3.3 Relevant topics discussed in literature

The Asset Administration Shell, as the standard architecture for interoperability of Industry 4.0 Components, is attracting the attention of scholars and researchers.

Filtering in the academic repository Scopus by **papers containing "Asset Administration Shell" in the title**, an interesting trend can be identified. From 2017 to 2019, eighteen papers were published, the same as in the entire 2020 year. Since then, the number of publications has yearly increased at more than a 50% rate annually. In 2023, fifty-two research papers were published. In total, since the 2017, the papers pool of papers with the Asset Administration Shell in their title is one hundred eighty-four.

In the previous chapter it was learnt that it is the enabler technology of the Digital Product Passport for Industry 4.0 Components (DPP4.0).

In that regard, the next research question wants to be addressed:

i. *Are there any other relevant sectors in which the Asset Administration Shell technology is the enabler technology?*

The user organization, The Industrial Digital Twin Association (IDTA) defines "The Industry 4.0 manufacturing and production plant" as a network of entities forming a Systems of Systems (SoS) environment. The environment is formed by AAS server applications that interact with each other [21].

3.3.1 Literature review on the Asset Administration Shell

To gain understanding of the research trends on the topic, two sources of information have been consulted: First, the "Publications" section of the Plattform Industrie website was consulted. In total, 31 documents under the category "Asset Administration Shell" are listed. Second, the following search string in Scopus was defined: Search within Article title, Abstract and Keywords "Asset Administration Shell" and "review". 11 documents were retrieved as of October 2024.

3.3.1.1 Scopus documents

[22] specifically focused on analyzing how the AAS can be utilized in the manufacturing field. By studying 29 papers, the relationship between the concepts of AAS and Digital Twin and the application purpose of the AAS deployed was studied.

Two main relevant conclusions are reached: Equally distributed, some researchers considered the AAS as the information model of the digital twin, others as the digital thread of the solution, and the remaining as the Digital Twin of the asset. This warning is directed to the reader, to guarantee that when reading other publications, checks how the author presents the concept. Regarding the application purposes of the papers analyzed, nearly 40% explored the capabilities of the AAS technology: data modelling, attaching meaning to the data and connecting AAS between them. The remaining explored concrete application fields as Predictive Maintenance, Human to Machine Interfaces and Production. Similar conclusions are reached in [23] where 50% of the 26 publications reviewed appointed the AAS as the essential technology for data modelling in the field level of production plants

With all this information, the following can be concluded:

i. The majority of the research about the Asset Administration Shell explores its data modelling capabilities.
ii. The production field is the main sector where research is being performed.

In that regard, relevant papers that address the different dimensions that need to be contemplated when deploying the digital twin solution are shared next.

[24] shares that typically the process of creation of a AAS requires of individuals with IT skills but highlights the capabilities in AAS creation offered by certain tools like AASX Package and Eclipse BaSys that made the process more user-friendly. In the context of manufacturing process components, [25] presents an automated method centered on forming AASs for individual assets in an environment when only one agent is present. The software proposed allows an AAS to be formed in a clearer and more user-friendly manner. For environments with multiple stakeholders, [26] proposed the OAASIS framework, tailored to enable access and modification capabilities of the AAS depending on the ownership and edit permission of the asset. [27] proposes a method for developing AAS models using AutomationML, as it provides a visual editing tool for modelling the AAS information. [30] proposes the modelling of the AASs of the processes, product and resources using an open-source platform called Papyrus4Manufacturing, in which data is identified using ontologies.

A relevant contribution is made in [28], where it is shared that as of 2022, most of the publications about the topic of AAS were conference papers rather than journal articles, which in the author’s opinion reflected a relevant degree of infancy of the technology. This aspect is supported with the fact that the international standard covering the AAS, and the specification of the technology have not yet been published completely. In [29] with the review of 18 publications, a gap within the data governance principles of the AAS is described. Two alternatives are presented regarding data management principals, access control and rights management. The official approach by IDTA, the user organization of AAS will be published soon, with the new specification of the AAS with a document assessing cybersecurity aspects of the Asset Administration Shell

3.3.1.2 Plattform Industrie 4.0

From the list of 30 documents uploaded in the publications section, only one was related to application fields of the technology. The remaining were part of the specification series described in 3.1.1.1 or white papers out of scope.

In [30], two projects are mentioned:

1. Product Carbon Footprint of a control cabinet assembly (ZVEI Showcase PCF@Control Cabinet)
2. Product Carbon Footprint during the manufacturing of a ball-pen (CESMI/LNI PCF Showcase)

Aligned with the previous conclusion, assessing the product carbon footprint of complete manufacturing/assembling processes is linked to the AAS Technology.

3.4 Research gaps

As has been checked with the research work published and compiled in the Scopus database, several fields are exploring the Asset Administration Shell technology. To list a few: developing systems to generate the information models, systems to enhance the semantics of the information included, or cybersecurity aspects.

With that in mind, and considering the conclusions shared in Chapter 2, it has been identified the following:

i. DTs are to be deployed by a user in a specific environment. The capabilities needed by each architecture will be dependent to the specific domain and the purpose of connecting the entities. For example, Industry 4.0 does not have the same requirements as Healthcare systems, or the Smart City [1]. This cannot be forgotten as most of the the available documentation deals with technological aspects of the AAS, rather than in its implementation. To counteract this trend [2] gathered a group of experts to conceive a list of requirements that characterized a platform for enabling the exchange of digital twin data across agents and [14] defined the list of requirements needed for a SoS structure of DTs.

ii. There are several publications proposing how the AAS architecture can be used to exchange data and use them in a concrete manner. Specific frameworks that contemplate connecting DT entities between them have been proposed to enable Flexible Manufacturing Systems [31] or Predictive Maintenance. However, the replicability of such architectures is very low as they are very specific to each use case and most of the times are just proposed in a theoretical and general manner.

All things considered; two lines of development have been identified.

1. [2] and [14] propose a list of requirements that digital twin architectures would need to enhance cross-exchange of digital twin data in an ecosystem of DT entities. Specific architectures available in the literature will be studied to **propose a list of requirements for connecting digital twins. The list of requirements proposed aim to work as a modelling guideline when designing a digital twin architecture.**
2. The Digital Product Passport is a concrete topic that will be spread to numerous industries as part of a EU Regulatory requirement. The nature of the data included in this "passport" will change from sector to sector, but it is expected that the **Product Carbon Footprint calculation** is a parameter that will be included. In particular, this parameter **needs the connectivity of plant assets to exchange** static (machine identification, batch number) and **dynamic digital twin data** (energy consumption). In that regard, **the flow of information between the different agents in a simple manufacturing scenario will be presented in the next chapter.**

3.5 Relevant future applications of the technology

Stefan Schork, Manager Automation at ZVEI, the foundation organization of the AAS, defines why the Asset Administration Shell will be a relevant technology.

"The AAS provides a framework format for describing the assets in a standardized and semantically unambiguous form, thereby acting as a digital twin of the asset".

3.5.1 Digital Product Passport

Unlike any other field in which digital twins was implemented, the Digital Product Passport, which is a concept described in the European Union regulation "Eco-design for Sustainable Products" builds on specific technologies for its deployment: The Asset Administration Shell (IEC 63278) and the Identification Link (IEC 61406).

The Digital Product Passport (DPP) is a requirement that will become mandatory for certain product groups starting in 2027. The objective of this regulation is to provide a unique digital identification to product groups (static information). The European

Parliament and Council defined in 2023 that batteries are the first product for which the implementation of a DPP will be mandatory. In addition, last June, the agenda for implementing the concept to the textile sector was published. Enhancing the traceability, circularity and transparency of the manufacturing stages of textile apparel is mentioned in [32].

In section four, it is further elaborated how a specific aspect of the digital product passport might be relevant in the field of digital twin interoperability.

3.5.1.1 Why is this relevant

The economic implications this regulatory change will have in the technological landscape of the Italian companies is relevant, as the automotive industry, which is under a complete transformation with the electrification of its powertrains, contributes 9.3% of Italy's manufacturing turnover and 5.2% of its GDP, while the fashion industry accounts for nearly 4% of the GDP.

As a consequence, defining the list of requirements for the implementation of Circular Economy concepts with the Asset Administration Shell could be beneficial for the upcoming important regulatory framework that will inevitably affect manufacturing and automotive companies.

4. Communication requirements in specific architectures

The Asset Administration Shell technology offers functionalities to create interoperability between all Industry 4.0 Components. It provides a framework in which assets are described in a standardized and semantically unambiguous form, acting as a digital twin of the asset. The technology is the enabler of the Digital Product Passport of Industry 4.0 Components (DPP4.0). **The sharing of static digital twin data and the capability of digital twin entities to interact are needed capabilities to successfully implement the technology.**

First, a **list of specific requirements relevant for enabling digital twin connectivity** will be proposed, based on specific literature and the analysis of existing architectures. **The list of requirements proposed aim to work as a modelling guideline when designing a digital twin architecture.** Lastly, and like in the approach taken in [2], **the communication requirements that are needed between field-level agents to estimate the Product Carbon Footprint** will be proposed. To specify them, a fictional manufacturing environment defined by the author will be presented.

It is worth noting that this chapter aims to breakdown the communication requirements that would be needed for implementing each architecture. The implementation itself is out of the scope of this master thesis, as it demands for extensive knowledge in the "science behind the digital twin", including topics like communication protocols, cloud computing, API programming and cybersecurity.

4.1 Analyzing existing architectures

To retrieve DT architectures that contemplate connecting different AAS entities, two strategies were followed. First, the papers mentioned covering the production field in relevant literature reviews were consulted [22] [23]. Secondly, the search string in the Scopus database was refined to only retrieve papers that focused on connecting Digital Twins. For that, the filter option "Search within Title" set to ("Asset Administration

Shell") and "Search within Title" containing link*, or connect*, or interact* or integrat* or active (* is used to include all the words with that root) was used.

The literature analyzed is compiled next in the next table. The column of "Item mentioned" refers to the specific requirement the paper focuses on. This does not mean that references to the remaining requirements are not performed in the work.

Reference	Architecture proposed	Item mentioned
Gölner et al. (2022) [14]	AAS are connected through an intermediate AAS that uses as input data from the other AAS. Proposes deploying the AAS using a Digital Twin Generator	(2), (5)
Chilwant et al. [25]	Creation of AAS in a single stakeholder environment and real-time interaction with assets	(6)
Mengmen et al. [26]	API to limit the access of AAS depending on the agent that included the information	(1), (7), (8)
Ye et al. (2022) [33]	Bidirectional data exchange between enterprise and control applications with AAS using AASX	(4), (5)
Arm et al. (2021) [34]	Deployment of AAS using an automated configuration wizard and specification of communication points between agents in a manufacturing environment	(2), (4)
Iñigo et al. (2022) [35]	Appoints International Data Space connectors to enable data exchange between agents in JSON format, with AAS in both ends.	(7)
Erik et al. (2023) [36]	Software applications to enable push and pull sequences of data exchanges between AAS Customer Applications	(3)

Table 4.1: Literature used to extract the interoperability requirements

Acknowledging the content of the literature reviewed, and with the list of requirements for DT connectivity available in [37] and [38], the following list of requirements for connecting digital twin entities is proposed:

(1) **Purpose**: Functionalities for data processing, storage and transmission are defined. Value gained from enabling DT interaction is specified.

(2) **Data acquisition**: Mechanism to generate the virtual representation of assets are specified. Automated and manual data inputs into the virtual representation model are allowed and specified.

(3) **Data Inputs** are acknowledged. Communication interfaces between assets and the different agents are specified. Ownership of data is assessed, and creation, access, modification, and generation of virtual models specified.

(4) **Interoperability**: data transactions can be done unambiguously, ensuring that the exchanged data assets are easily understood by both agents. Exchanged mechanism of the data is mentioned. Mechanisms to ensure that data files share a common format and can connect assets from field level to management (MES) and enterprise (ERP) level are specified.

(5) **Data link** mechanism between the physical asset and its virtual representation is specified, pointing out the level of integration. (Model, Shadow or Twin)

(6) **Synchronization** Data regarding the manufacturing equipment is fed into the virtual model in real time, including data logs generated on the manufacturing shopfloor. Data generated on the virtual model is fed into the manufacturing equipment.

(7) **Data Security** meaning data must be protected and secure when transmitted from the location of the manufacturing shopfloor to the service provider. Direct and trusted communication channels are used for data exchange.

(8) **Traceability** across the asset lifecycle where a clear image of the assets' data at all stages is provided.

4.2 Digital Product Passport

The Digital Product Passport provides a unique identification for each product serving as a transport container for relevant information and characteristics. The specific content this passport will include remains unclear and will be most likely sector dependent.

In that aspect, modularity of the data transport containers and semantic interoperability, to ensure information is stored consistently throughout assets is needed. In that regard, the Asset Administration Shell technology excels, with the standardized submodels approved by IDTA. Regarding how to attach semantic meaning, to provide a unique identification for each fragment of data included in the passport, the ECLASS data standard is considered by the IDTA as a relevant data format to consider.

In conclusion, the Digital Product Passport is an identification tool of an asset to organize relevant information about a product, where digital twin interoperability is limited to the semantics of the information included.

4.2.1 Product Carbon Footprint

A specific parameter that will most likely be included in the DPP is the Product Carbon Footprint. It is precisely in the calculation of this parameter where the need to connect digital twin entities comes into play.

Even though **the DPP can be considered as a static information set that becomes available once the product is in the customer's possession**, its nature up to that point has been dynamic, with continuous update of its values. A specific example is precisely the Product Carbon Footprint estimation, where real time data, like the energy consumption of the machines involved in the manufacturing process, is constantly being shared. In the vocabulary of the Asset Administration Shell technology, this would include updating the submodel that contained the Product Carbon Footprint by other AAS elements.

Stefan Schork, Manager Automation at ZVEI, shared in the last Hannover Fair 2024, that they recognize the Asset Administration Shell as a powerful tool to keep data formats consistent between manufacturing assets. However, he pointed out that the calculation and use of the product carbon footprint calculations is associated with large uncertainties.

With that in mind:

i. *Which are the communication points needed in the manufacturing plant to enable the Product Carbon Footprint calculation?*
ii. *How can this calculation help to optimise the manufacturing process?*

For that purpose and considering the list of requirements specified in the previous section, a diagram is presented next.

The diagram shows the communication points between the agents of a manufacturing operation. The agents are: Enterprise and manufacturing control applications, resources in the field level (Machinery, Transportation Units), and the product being manufactured.

The sequence of steps needed to exchange static and dynamic digital twin data are appointed, and the mechanisms to enable the data exchange are specified in the next diagram:

Apart from proposing the communication diagram between the different agents to calculate the product carbon footprint, a first approach to the technological solution will be given. Therefore, each of the types of communication needed will be analysed.

4.2.1.1 Solutions to reach interoperability

Interoperability between manufacturing machines and other assets

To calculate the product carbon footprint, most of the data needed comes from the manufacturing equipment that allows the transformation from the initial product to the final product (Drilling machines, CNC, etc.).

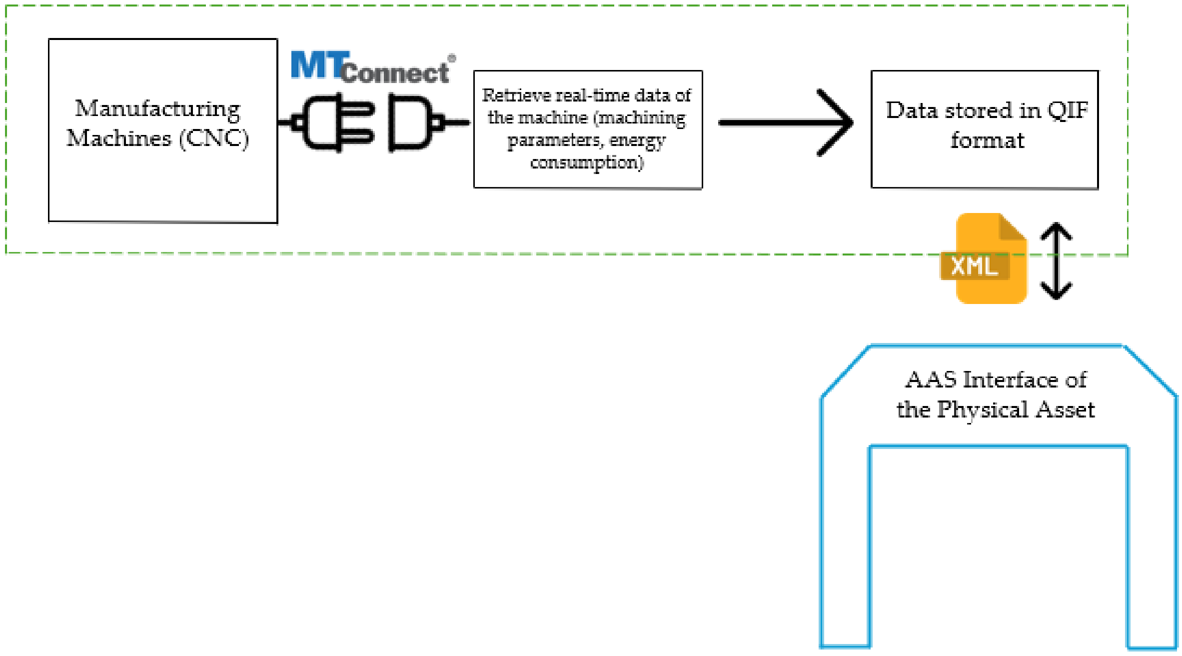

Figure 4.1: Communication technologies between manufacturing assets and the remaining assets of the plant

Most typically, the layout of the plant is formed by machinery from different manufacturers and brands. This lack of uniformity can be solved by the "MTConnect technology". This solution is a device that captures real-time data from machines and provides a translation of the magnitudes read into a normalized semantic vocabulary.

In addition, MTConnect is prepared to store data in the Quality Information Framework (QIF) information model, which is a standardized data carrier format for manufacturing information (ISO 23952)

The key aspect that enables interoperability in the case study presented is that the QIF information model stores the data in XML format, which is supported by the Asset Administration Shell. **To enable that the digital models of the manufacturing**

machines can communicate with the other assets of the plant, they are transformed into AAS elements. This is done because the assets of the plant layout that are not physical manufacturing machines (conveyors, transportation units, product being manufactured) cannot be represented in QIF Format. QIF format is the standard to represent data during the model definition of a product.

A missing piece to this puzzle and aligned with the work in [2],[4],[5] and [6] is a mapping between the information model of QIF (ISO 23952) and AAS (IEC 63278). In addition, semantics need to be considered as well.

Connectivity between digital twins (black arrow)

The data carrier chosen in the diagram presented is the Asset Administration Shell. Relevant papers contemplate different mechanisms to ensure that different assets represented with an AAS model can effectively communicate between them. In particular, [34] mention an automated approach for deploying the AAS on servers, [14] specifies the sequence to enable the communication between AAS, [35] refers to IDS (International Data Spaces) for connecting AAS applications between them. In particular, the solution named Eclipse Connector is proposed [36] proposes a software application to enable the pull/push of data from AAS elements, [35] explores concrete communication protocols for the orchestrator entity and explore how to connect enterprise/management level entities with AAS.

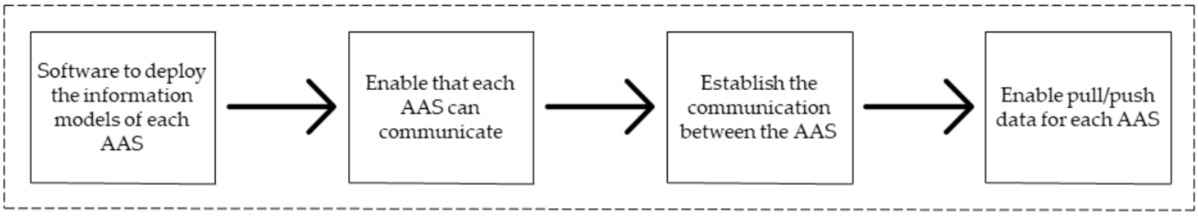

Figure 4.2: Communication sequence between AAS elements

4.2.1.2 List of requirements

The list of requirements proposed in the previous section aim to work as a modelling guideline when designing a digital twin architecture. In the next table, how the requirements shared in section 4.1 are present in the communication diagram is shared.

List	Requirement	Description
1	Purpose	Perform the calculation of the product carbon footprint to comply with the EU Regulatory Framework

2	Data acquisition	Manufacturing machines information model is QIF. Compatible with AAS due to XML Data Format. Rest of the assets of the plant (Product, Conveyors, Control Systems) in AAS. Bidirectional communication with MTConnect standard.
3	Data Inputs	AAS interaction as described in literature. View connection points from previous slide
4	Interoperability	MTConnect standard is compliant with the QIF data carrier structure. Manufacturing data meaning is set with the MTConnect vocabulary. AAS and QIF are theoretically mapped in XML, which would allow the creation of a transformation model as showed in literature.
5	Data link	The product information is used to train AI algorithms that affect the manufacturing process. Seeing the process as a sequence, the features of the physical product affect the machine parameters: Digital Twin level
6	Synchronization	Real-time synchronization brought by the MTConnect standard
7	Data Security	AAS will publish guidelines regarding data control and sovereignity
8	Traceability	Each contribution to the PCF throught the process is monitored by the machine that performed each task.

Table 4.2: Overview of requirements in the architecture

4.2.1.3 Value gained of the architecture presented

Regarding the second research question, it can be stated that enabling the product carbon footprint calculation would help to optimize the manufacturing process due to the following reasons:

Part of the production manufactured in the plant would have to undergone quality testing. The testing results would be included in the digital twin of each product (the AAS the product) and from there to the AAS of the machines.

Product carbon footprint calculations and as-manufactured data would be fed into submodels of specific AAS that contained predictive maintenance and machine parameters selection algorithms. Consequently, the decision of machine parameters in future production operations would be calculated considering previous testing results, closing the information loop between the digital twin of the product and the digital twin of the machines.

An example on how this would be useful is shared next: A “median energy usage” for the manufacturing of a product class could be identified. Each production process would be characterized by the average value and a dispersion interval considered as acceptable. Deviations from this value could be used to identify machine parameters that resulted in higher energy consumption than needed or to better schedule maintenance operations.

5. Conclusions

Connecting digital twin entities between them is a topic that has attracted the attention of industry and academia in the last five years. In 2019, just four papers with the words "Digital Twin" and "Interoperability" in their title were published. Five years later, just in half of 2024, plus forty papers have been already published.

Digital Threads are at the core of the strategic vision of multiple companies. Big players like Siemens and ABB have led the production of specific software in the Digital Twin Industry. Alongside academia, they have acknowledged that a lack of standardization in the process of storing data of physical assets and sharing it with other agents exists.

In a literature review in ScienceDirect and Scopus it was identified that there is consensus in appointing the Asset Administration Shell as a relevant technology in the field of digital twin interoperability. This technology is an information model that allows to represent assets in the digital world in a standardized manner. The characteristics, features and representations of an asset can be represented in specific "submodels", which are standard blocks of information.

In the development of this thesis, the main topic explored was on studying frameworks and cases studies on interoperability of digital twins. This being, enabling the capacity of digital twins to share data and use it efficiently through the Asset Administration Shell (AAS) framework. By addressing a critical research gap, this report provides an examination of the essential requirements for digital twin connectivity and demonstrates practical applications, such as calculating the Product Carbon Footprint (PCF), which is particularly relevant for industries in Italy. The architecture proposed highlights the importance of standardized architectures like AAS to bridge gaps in digital twin interoperability, facilitating seamless data exchange among diverse assets present in the field.

5.1 Interoperability challenges addressed

In November 2024, in Volume 42 of the *Journal of Industrial Information Integration* published that same month, a research team of the University of Oulu, in Finland, published a paper under the title of Interoperability levels and challenges of digital twins in cyber-physical systems [39]. By performing a literature review of 63 papers, they acknowledged two primary concerns: i) There is a need for discerning different interoperability levels and ii) Specific challenges should be identified and categorized within these levels.

77 challenges were identified and mapped across the following categories: Technical, Syntactic, Semantic, Pragmatic, Dynamic, and Organizational Interoperability.

The diagram produced by the authors is shown next as it can be useful tool to frame the work done in this master thesis.

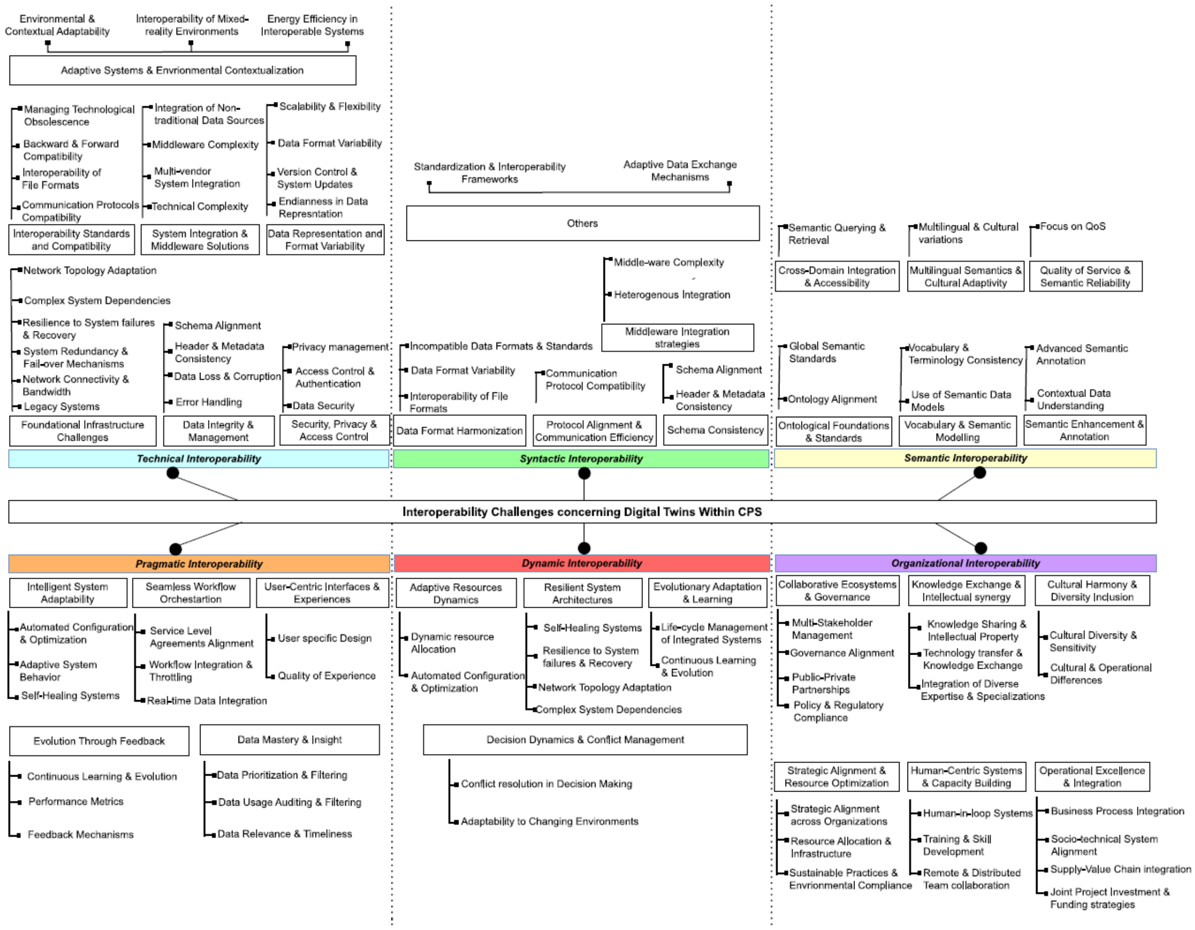

Figure 5.1: Challenges in cyber-physical systems and digital twin interoperability [39]

Out of the **33 topics** identified by S. Acharya et al., the following were mentioned in one way or another in the report. Somehow, **the following section can be contemplated as a summary of how industry and academia are tackling some of the challenges mentioned by the Finnish team.** To keep it organized, they are going to be commentated respecting the thematic blocks defined by the authors.

a) <u>Technical Interoperability</u>

Challenge management: The Asset Administration Shell is a standard which has as vision to enable the connectivity of every Industry 4.0 asset. By providing a common framework to represent physical and non-physical assets, it aims to standardize the technical facade of digital twins.

Literature reviewed: [8]-[10]

b) Syntactic Interoperability | Data format harmonization

Challenge management: Multiple efforts are being made in industry and academia to solve this problem. In the first literature review, it was learned that Siemens and ABB are working on transformation models between their own digital twin service technologies and the standardized information model Asset Administration Shell. In addition, enabling transformation models between data formats is a common approach in academia. DTDL, NGSI-LD, AAS and TD are mapped between each other. Standardization organizations are also taking part: IEC have recognized the AAS as a relevant technology in the field, and ETSI, under the STF 628 Program, is aiming to achieve interoperability based on ontologies, with the SAREF Framework. With the case study presented in section 4, a compatibility between the AAS and QIF technologies is appointed as relevant to enhance the product carbon footprint calculation in manufacturing environments.

Literature reviewed: [2][3][4][6][7]

c) Semantic interoperability | Global Semantic Standards

Challenge management: Several frameworks contemplate this problem. In the manufacturing field, the MaRCO ontology is gaining popularity. A well-established solution is the ECLASS data standard, which is backed by ISO and IEC to provide unique identifiers to data formats.

d) Pragmatic Interoperability | Evolution through feedback and Data Insight

Challenge management: The framework presented to perform the product carbon footprint estimation based on connecting digital twin entities between them is an example of defining the data insight and data feedback. The data exchanged by the digital twins provides relevant information (Product Carbon Footprint). The added value of performing the calculation using digital twins is that feedback capabilities are enabled, adjusting the manufacturing process depending on the product information. In addition, specific papers that contemplate this connectivity between digital twins was reviewed in section 4. They have been used to detail a list of requirements.

e) Organizational Interoperability

Challenge management: To cite a relevant agent in the industry, Siemens is tackling the problem in a multistakeholder approach. Two years ago, it launched a group project with industry experts to define a framework that contemplates the share of digital twin data. In addition, relevant organizations in the industry such as the Industrial Digital Twin Association (IDTA) is deploying several resources to enhance connectivity between digital twins. In section three of this thesis, an analysis of the documentation and projects available is performed. On the standards realm, ETSI, IEC and ISO are working towards technologies that aim to improve the interoperability situation.

f) Interoperability Levels

In a less detailed manner, the list of requirements proposed in section 4 encapsulates the different dimensions of interoperability proposed in [39].

List	Requirement	Interoperability Level
1	Purpose	Pragmatic interoperability
2	Data acquisition	Technical interoperability
3	Data Inputs	Syntactic interoperability
4	Interoperability	Semantic interoperability
5	Data link	Pragmatic interoperability
6	Synchronization	Pragmatic & Dynamic interoperability
7	Data Security	Organizational interoperability
8	Traceability	

Table 5.1: Mapping between list of requirements proposed in this report and the interoperability levels of [39]

5.2 Key Contributions

All in all, the main contributions of this report can be breakdown as it follows:

1. **Comprehensive Literature Review**: This work synthesizes the current state of Digital Twin interoperability, including a review of industry efforts and standardization initiatives from leaders like Siemens and ABB, as well as academic contributions. It highlights the need for standardized connectivity models to streamline DT integration across industries.
2. **AAS-Based Requirement Framework**: Building on AAS architectures, the thesis proposes a structured list of requirements to enable digital twins' communication and interoperability. These requirements serve as a foundation for designing systems that can manage and share data effectively. In particular, the data stream available in specific papers is reviewed.

3. **Case Study on Product Carbon Footprint (PCF)**: By applying the AAS model to calculate the PCF in a manufacturing context, the thesis addresses the EU's regulatory requirements and provides an actionable framework to follow. In addition, it proposes a mechanism to use this product carbon footprint calculation in favor of the design of the production system. A data loop framework is introduced to optimize manufacturing parameters and maintenance scheduling by integrating machine energy use and product quality data.

5.3 Future Lines

The insights gained from this research open multiple pathways for future work:

- **Field Implementation**: Deploying the proposed product carbon footprint estimation framework in a real-world manufacturing environment would offer practical validation and highlight potential refinement.
- **Expansion to Other Use Cases**: Future research could explore additional applications in which product data could be used to enhance the manufacturing process.
- **Analysis of other interoperability challenges**: The work published by S. Acharya et al. tracks the existing challenges in enabling that digital twins can interact between them. A future relevant work could be exploring how other challenges are being addressed.

Advancements in this research pathways presented would offer a significant contribution to the body of knowledge on digital twin interoperability, presenting a valuable resource for both academic research and industrial implementation. By fostering greater alignment between digital twin technologies and real-world applications, it would support the broader advancement of Industry 4.0 initiatives and sustainable manufacturing practices.

Annex I: Initial Literature Review

Title	SCOPUS ǀ Title: Digital AND Twin AND Interoperability (Sort By Newest as of 03/07/2024)			
	Result	**Year**	**Accepted**	**Reason**
Digital Twins' Maturity: The need for Interoperability	1	2024	**Yes**	Starting point. Good analysis on why Interoperability is needed in DTs. Definition of different levels
Generation of AASs with Large Language Model Agents: Towards Semantic Interoperability in DTs in the context of I4.0	2	2024	**Yes**	Analyzed to compare it with paper #12. Both claim interoperability flaws from the original architecture and propose alternative solutions
The Role of Interoperability for Digital Twins	3	2024	**Yes**	Good overview on the different fields where interoperability might be tackled from. The research agenda is based on a conceptual framework that combines theories and approaches from four computer (and information) science disciplines: architect ture of distributed systems, model-based system engineering, ontology-driven conceptual modeling, and linked data with semantic web technologies
Interoperability assessment model in Industrial maintenance according to DTs	4	2024	Yes	Specific example on how Industrial Maintenance is affected by multicriteria (multiple DTs)
Increasing Interoperability between DTs standards and Specifications: Transformation of DTDL to AASs	5	2023	**Yes**	The Article explores that a generic mapping between DTDL and AAS can be applied for transformation in use cases where DTDL models are provided while AAS is required
DTs: Enabling interoperability in Smart Manufacturing Networks	6	2023	**Yes**	Interoperability is between assets participating in a smart manufacturing environment
The conundrum in Smart City governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins	7	2024	No	Overview on how cities could benefit, but does not focus on how to perform the integration
Semantic DT for Interoperability and Comprehensive Management of Data Assets	8	2023	No	Interoperability is with the physical object
Design of an Educational-development platform for Digital Twins using the Interoperability of OPC UA Standard and Industry 4.0 Components	9	2023	**Yes**	**Example** on how a DT would gain interoperability with the combination of OPC UA and AASs. It treats different standards on information models generation
Improving Interoperability in the Exchange of DT Data within Engineering Processes	10	2023	**Yes**	Motivation and research problem of the interoperability problem, and how AASs could be relevant

Title	SCOPUS ǀ Title: Digital AND Twin AND Interoperability (Sort By Newest as of 03/07/2024)			
	Result	**Year**	**Accepted**	**Reason**
Analyzing Interoperability in Digital Twin software architectures for manufacturing	11	2023	**Yes**	Research Goal (RG) of this paper is to analyses interoperability in DT software architectures for manufacturing. Why manufacturing? Specific standard dedicated to DTs. The problem is that ISO 23247 does not tackle interoperability directly. To field this gap, the Level of Conceptual Interoperability Model is used. it precisely highlights the need to increment interoperability levels from Semantic to Dynamic (Kuruppuarachchi et tal). (Axelsson et al) presents an example in which dynamic interoperability was achieved using linked data and ontologies in the domain of System of Systems
Semantic Interoperability of DTs: Ontology-based Capability checking in AAS modelling framework	12	2023	**Yes**	Transforms **AASs into other form that enhances semantic interoperability**. It defines AASs as the standard that caters for syntactic interoperability and mentions that semantic interoperability needs to be considered.
Enhancing Interoperability of DTs based on Digital Twin Definition Language	13	2023	**Yes**	It refers to the idea of enabling communication between DTs developed following the **Digital Twin Definition Language (DTDL)** with applications compliant to the OPC Unified Architecture. Translating a OPC UA to DTDL is currently available using OPCUA2DTDL, but the opposite is not that clear. The paper contemplates that aspect.
DT-Driven Design: A Framework to enhance Interoperability in Industry 4.0	14	2023	No	Out os Scope: It contemplates feeding a single digital twin with data of different parts of the life cycle of the product to optimize the Product Development Process
Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life-cycle management	15	2022	No	Not familiar with the blockchain and smart contract technologies
Model-based engineering and semantic interoperability for trusted digital twins big data connection across the product lifecycle	16	2022	No	Not selected because it considers open-source technologies not developed in the rest of the literature review. Might be interesting because it mentions the task of exchange of data across digital twins through FIWARE NGSI Context Broker
Enhancing interoperability of Digital Twin with MB Ontology Reasoning	17	2022	**Yes**	Assumes lack of interoperability is because DTs are not equipped with semantic data models, that avoided communication with other software systems (DTs and not DTs). They Propose using a rule-based ontology reasoning model
Towards a Digital Twin for Simulation of Organizational and Semantic Interoperability in IDS Ecosystems	18	2022	No	Out of Scope: Aims to solve a problem in the Data Sharing field using a DT, but it is not focused on DT Interoperability
Digital Twin for Smart Cities: An Enabler for Large-Scale Enterprise Interoperability	19	2022	No	Descriptive: It assesses how Smart Cities would benefit from multiple DTs interconnected but does not assess anything of how the interaction would be performed
A simulation based approach to DTs Interoperability, Verification and Validation	20	2022	No	Interoperability is with the physical object
Software as a component of Industry 4.0: Cross-manufacturer interoperability using DT	21	2022	Would be	Not access and could not find the paper
Building a Digital Twin for IIoT with Interoperability	22	2022	No	Interoperability is with the physical object
Interoperability, Integration, and Digital Twins in the mining industry	23 24	2021	No	Not relevant: Overview of the mining industry

Title	SCOPUS | Title: Digital AND Twin AND Interoperability (Sort By Newest as of 03/07/2024)			
	Result	**Year**	**Accepted**	**Reason**
Production in the loop – the interoperability of digital twins of the product and the production system	25	2021	No	Theoretical application result of that interoperability but does not mention nothing on how they would communicate
Digital Twins: Universal Interoperability for the Digital Age	26	2021	No	Not relevant
File- and API-based interoperability of digital twins by model transformation: An IIoT case study using asset administration shell	27	2020	**Yes**	we present requirements as well as a solution to enable interoperable digital twins by flexibly transforming their information models. we applied our solution to a real-world application example in an industrial context by transforming ABB Ability™ digital twins to the AASs format

Table Annex I: First systematic literature review

Bibliography

[1] R. Klar., N. Arvidsson. and V. Angelakis, "Digital Twins' Maturity: The need for Interoperability," *IEEE Systems Journal,* vol. 18, no. 1, pp. 713-724, 2024.

[2] C. Liepert, "Improving Interoperability in the Exchange of Digital Twin Data Within Engineering Processes," in *Subject-Oriented Business Process Management. Models for Designing Digital Transformations*, Switzerland, 2023.

[3] M. Platenius-Mohr, S. Malakuti, S. Gruner and T. Goldschmidt, " Interoperable Digital Twins in IIoT Systems by Transformation of Information Models: A Case Study with Asset Administration Shell," *Association for Computing Machinery,* Vols. Proceedings of the 9th International Conference on the Internet of Things, IoT 2019, Bilbao, Spain,, p. 22–25 , October 2019.

[4] C. Schmidt, F. Volz, L. Stojanovic and G. Sutschet, "Increasing Interoperability between Digital Twin Standards and Specifications: Transformation of DTDL to AAS," *Sensors,* 2023.

[5] H. Pakala, H. Kumar, D. Christian, O. Kazeem and K. Sebastian, " Integration of Asset Administration Shell and Web of Things.," *Kommun. Der Autom.,* 2021.

[6] J. Mayrbäurl and Niedung, "Open Digital Twins Ontology for the Industrie. 4.0 Asset Administration Shell.".

[7] B. Oakes, A. Parsai, B. Meyers, I. David, S. Van Mierlo, S. Demeyer, J. Denil, P. De Meulenaere and H. Vangheluwe, "Digital Twin Description Framework and its Mapping to Asset Administration Shell.," in *International Conference on Model-Driven Engineering and Software Development*, Switzerland,, 2021.

[8] Enxhi Ferko, Alessio Bucaioni, Patrizio Pelliccione and M. Behman, “Analysing Interoperability in Digital Twin Software Architectures for Manufacturing,” *Software Architecture,* pp. 170-188, 2'23.

[9] Yining Huang, Saadia Dhouib, Luis Palacios Medinacelli and J. Malenfant, “Semantic Interoperability of Digital Twins: Ontology-based Capability Checking in AAS Modeling,” *6th International Conference on Industrial Cyber-Physical Systems (ICPS),* pp. pp.1-8, May 2023.

[10] Christoph Nölle and P. Kannisto, “Timeseries on IIoT Platforms: Requirements and Surveys for Digital Twins in Process Industry,” *Cornell University.*

[11] G. Shao., S. Frechette. and V. Srinivasan, “An analysis of the new ISO 23247 series of standards on digital twin framework for manufacturing,” in *Proceedings of the ASME 2023 Manufacturing Science and Engineering Conference*, New Brunswick, NJ, USA, 2023.

[12] International Organization for Standardization, “ISO 23247,” 2021.

[13] M. Neubauer, L. Steinle, C. Reiff, S. Ajdinovic, L. Klingel, Armin Lechler and A. Verl, “Architecture for Manufacturing-X: Bringing asset administration shell, eclipse dataspace connector and OPC UA together,” *Manufacturing Letters,* vol. 37, pp. 1-6, 2023.

[14] Denis Göllner, Rik Rasor, Harald Anacker and R. Dumitrescu, “Collaborative Modelling of Interoperable Digital Twins in a SoS Context,” in *55th CIRP Conference on Manufacturing Systems*, Lugano, 2022.

[15] Plattform Industrie 4.0, “Implementation strategy Industrie 4.0,” 2015.

[16] Plattform Industrie 4.0 & Kosmo, “Joint White Paper on common strategy for interoperability for Industry 4.0 based on AAS,” 2022.

[17] P. Industrie, “Specification of the Asset Administration Shell: Part 1 - Metamodel,” June 2024.

[18] P. Industre, “Specification of the Asset Administration Shell: Part 5 - Package File Format (AASX),” 2024.

[19] P. Industrie, "Specification of the Asset Administration Shell: Part 2 - Application Programming Interfaces," June 2024.

[20] P. Industrie, "Specification of the Asset Administration Shell: Part 3a - Data Specification compliant with IEC 61360," 2024.

[21] Plattform Industrie 4.0, "What is the Asset Administration Shell from a technical perspective?," 2021.

[22] Tasnim A. Abdel-Aty, Elisa Negri and S. Galparoli, "Asset Administration Shell in Manufacturing: Applications and Relationship with Digital Twin," in *10th IFAC Conference on Manufacturing Modelling*, Nantes, France, 2022.

[23] Alexandra Schlemitz and V. Mezhuyev, "Approaches for data collection and process standardization in smart manufacturing: Systematic literature review," *Journal of Industrial Information Integration,* 2024.

[24] Elisa Negri, Simone Galparoli and L. Fumagalli, "A Methodology for the Design and Creation of Asset Administration Shell for Manufacturing Systems," in *Summer School Francesco Turco*, 2022.

[25] Brno University of Technology, "Automated Design and Integration of Asset Administration Shells in Components of Industry 4.0," *Sensors,* vol. 21, pp. 1-20, 2021.

[26] Indian Institute of Technology Bombay, "Open Asset Administration Shell for Industrial Systems," *Manufacturing Letters,* vol. 20, pp. 15-21, 2019.

[27] Xun Ye, Mengmeng Yu and W. S. Song, "An Asset Administration Shell Method for Data Exchange Between Manufacturing Software Applications," *IEEE Access,* vol. 9, no. 144, pp. 171-178, 2021.

[28] Elisa Negri and T. A. Abdel-Aty, "Clarifying concepts of Metaverse, Digital Twin, Digital Thread and AAS forCPS-Based production systems," in *IFAC World Congress*, Yokohama, Japan, 2023.

[29] Mario Angos-Mediavilla, Michael Gorenzweig, Gerome Pahnke, André Pomp, Matthias Freund and T. Meisen, "Advancing Industry 4.0: Integrating Data

Governance into Asset Administration Shell for Enchanced Interoperability," in *ICEIS* , Angers, 2024.

[30] Plattform Industrie 4.0, "Asset Administration Shell Discovery in an Industrie 4.0 System Environment," 2024.

[31] H. Yining, S. Dhouib. and J. Malenfant., "AAS Capability Based Operation and Engineering of Flexible Production Lines," in *26th IEEE International Conference on Emerging Technologies and Factory Automation*, 2021.

[32] European Parliamentary Research Service, "Digital Product Passport for textile sector," *Scientific Foresight Unit,* pp. 1-80, June 2024.

[33] Xun Ye, Won Seok Song, ,. Y. C. K. Seung Ho Hong and N. H. Yoo, "Toward Data Interoperability of Enterprise and Control Applications via de Industry 4.0 Asset Administration Shell," IEEE Access, 2022.

[34] Jakub Arm, T. Benesl, Petr Marcon and Z. Bradac, "Automated Design and Integration of Asset Administration Shell in Components of Industry 4.0," *Sensors,* vol. 21, 2021.

[35] Miguel Iñigo, Jon Legaristi, Alain Perez, Blanca Kremer and E. Montejo, "Towards Standardized Manufacturing as a service through Asset Administration Shell and IDS Connectors," in *48th Annual Conference of Industrial Electronics*, 2022.

[36] Sven Erik Jeroschewski, Johannes Kristan and M. Jäntgen, "Integrating IoT Infrastructures in Industrie 4.0 Scenarios with the Asset Administration Shell," in *ECBS* , 2023.

[37] Hendrik Habe, Hendrik van der Valk, Frederik Möller and B. Otto, "Design Principles for Shared Digital Twins," *Springer,* 2022.

[38] Tomás Moreno, Antonio Almeida, Cesar Toscano, Filipe Ferreira and A. Azevedo, "Scalbale Digital Twins for industry 4.0 digital services: a dataspace approach," *Production & Manufacturing Research,* vol. 11, no. 1, 2023.

[39] S. Acharya, A. A. Khan and T. Päivärinta, “Interoperability levels and challenges of digital twins in cyber-physical systems,” *Journal of Industrial Information Integration,* vol. 42, no. 2024, 2024.

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