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IoT-based digital twin framework for Industry 5.0

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To my mum
and dad.

Index

Abstract

The rapid evolution of Industry 4.0 has underscored the importance of digital technologies, particularly Digital Twins (DTs), in enhancing manufacturing processes through real-time monitoring, simulation, and data-driven decision-making. However, the existing frameworks for the development of IoT-based Digital Twins are incomplete and fail to address the new requirements introduced by the Industry 5.0, such as sustainability, human-centricity and resilience. To address these requirements, a new standard framework, adapted from the Internet of Things Architectural Reference Model (IoT-ARM) originally developed under a European Union-funded project between 2010 and 2013, has been realized. This thesis implements a monitoring Digital Twin case study to validate the newly proposed framework with the aim of proving its validity in the manufacturing sector. Through this detailed case study, the validity of the proposed framework is demonstrated, highlighting its potential to advance the objectives of Industry 5.0. The results confirm the framework's potential as a benchmark for future IoT architectures that incorporate Digital Twins and its possibilities to drive innovation in the manufacturing sector.

1. Introduction

In recent years, the fourth industrial revolution, commonly referred to as Industry 4.0, has emerged as a highly relevant topic in the manufacturing landscape. At its core is the concept of Smart Manufacturing, which is the result of the integration of digital technologies, data analytics and automation into conventional manufacturing processes, altering traditional work practices. Industry 4.0 is centered on the implementation of digital technologies that enable real-time data collection and analysis, offering valuable insights to enhance manufacturing systems, such as cyber-physical systems, cloud computing, data analytics and the Internet of Things (IoT) [1]. The latter provides connectivity within systems and devices to create a synergistic environment in industrial processes. This extensive network refers to the combination of sensors, actuators and computing technology in physical systems, realizing a real-time monitoring network.

Due to their high potential utilization in the manufacturing environment, Digital Twins (DTs) emerge as another essential component in this transformative movement. By generating a virtual representation of a physical object in a digital format, DTs facilitate the interaction and integration between physical and digital realms, allowing for simulation, real-time monitoring and efficient decision-making [2]. Differently from digital model, in which there is no exchange of data between the physical model and its digital representation, and from digital shadow, in which exists a unidirectional flow of information between the existing object and the virtual one, in the Digital Twin data flows are fully integrated in both directions, allowing a change made in physical world to trigger a change in the virtual one (and viceversa) [3].

Nowadays, industries must be more flexible in responding to unexpected real-time events and to the fast-paced changes in their markets (e.g. the increase in customer numbers and the growing need for personalized and unpredictable demands). To address these challenges, manufacturers are seeking innovative solutions to adjust their production plans when there are shifts in the production system. The reallocation problem is known as dynamic task allocation, and the development of DT can support this application in very complex environments through simulation and optimization techniques [4]. In this context, collaborative robots can aid operators to complete their tasks [5]. Specifically, in this thesis a DT of three UR3e robots is developed to perform dynamic tasks allocation between them to optimize the performances of the system.

Despite the new level of innovation and automation achieved by Industry 4.0 through the introduction of tailored and smart production technologies in manufacturing processes, Industry 4.0 falls in addressing the emerging societal, environmental and economical requirements of our contemporary world [6]. In response to these limitations, a new concept, named Industry 5.0, complements and broadens the key attributes and features of Industry 4.0, placing the fundamental needs and priorities of humans at the center of the process. The foundation of this new industry paradigm addresses both social and environmental needs and centers on three key development factors: human-centricity, sustainability, and resilience [7]. The term resilience means developing strong industrial production systems that can endure challenges and sustain essential infrastructure during emergencies. Instead to achieve sustainability, in an increasing recognition that companies that prioritize only profit are becoming less sustainable in today's uncertain global environment, industries must incorporate social, environmental, and societal considerations. Moreover, Industry 5.0 shifts attention towards workers and aims to align corporate objectives with social responsibilities. Driven by the lack of existing frameworks for digital twin systems and Industry 5.0, [126] developed a new scheme rooted in the IoT Architectural Reference Model (IoT-ARM) founded by the European Union between 2010 and 2013. This scheme aims to establish a standard set of architectural tools for designing an IoT framework that emphasizes digital twins while fostering sustainability, resilience and human-centricity. Standardizing architectural tools is crucial for ensuring compatibility and scalability within various IoT systems. Moreover, it simplifies data sharing, boosts the effectiveness of digital twin applications (also in different sectors) and establishes a unified framework that fosters collaboration and drives innovation.

This thesis aims to adapt the model to a system that focuses on digital twins without using an IoT interconnection and to discuss and prove the validity of the application in the manufacturing sector.

Chapter 2 provides a foundational understanding of Digital Twin technology, its evolution, characteristics, applications across different sectors, and its significant role in the progression towards Industry 4.0 and 5.0, further emphasizing the importance of the IoT ARM in creating a structured approach within the context of Industry 4.0.

Chapter 3 provides a detailed overview of the methodology used for conducting a literature review focused on the intersection of Digital Twin (DT) technology and Collaborative Robots (Cobots). It categorizes key findings and identifies future developments.

Chapter 4 presents a comprehensive overview of the IoT ARM, highlighting its crucial role in enhancing interoperability. It presents a new framework tailored for digital twins, addressing the evolving needs of Industry 5.0.

Chapter 5 presents the adaptation of the proposed framework to a detailed case study to prove its validity in the manufacturing sector.

Chapter 6 provides an overview of the work done, the results achieved, the challenges and possible avenues for future development.

2. Theoretical background

2.1 Digital Twin

2.1.1 History of Digital Twin technology

As shown in Figure 2.1, the concept of Digital Twin (DT) has experienced an evolution over the years due to the improvement of digital technology capabilities and has achieved a very high level of complexity and completeness. It has been defined as "a computerized model of a physical system that represents all function features and links with the working elements, and also as a living model of the physical system, which constantly adapts to operational changes, thanks to the information, and which can forecast the future of the corresponding physical counterpart" [8].

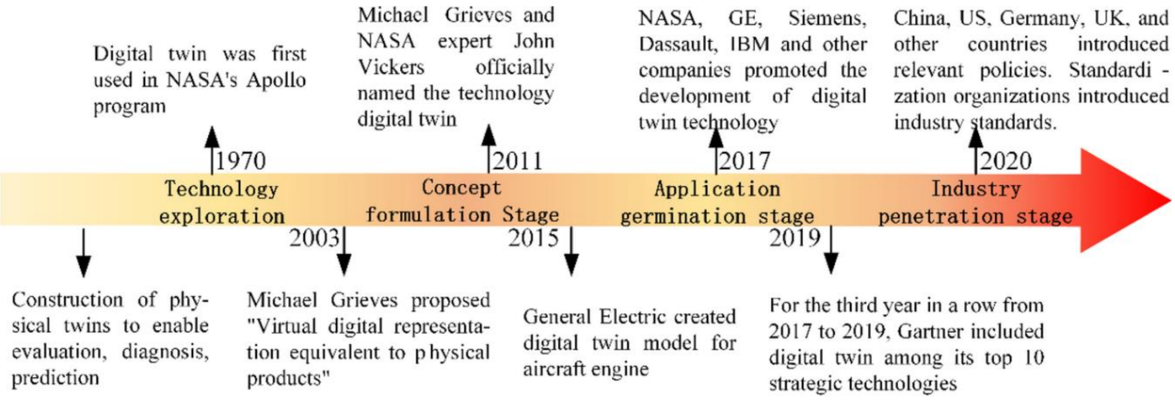


Figure 2.1 – Evolution of DT over years

Even though the term "Digital Twin" was not a familiar term back in 1970, the following example embodies many of its essential characteristics: during the unexpected explosion in Apollo 13's oxygen tanks in 1970, the NASA mission team responded by quickly adapting several high-fidelity simulators to replicate the conditions of the damaged spacecraft, enabling the astronauts to make the necessary maneuvers to return safely to Earth. In this way the simulators mirrored the actual conditions of the spacecraft, updating themselves in response to real-time data, and allowed the team to explore various future scenarios that had not been anticipated during the original design phase. Moreover, in 1993, the author David Gelernter wrote in his book *Mirror Worlds* about the existence of software able to represent the reality and in 2002, Michael Grieves, professor at the University of Michigan, gave a "Conceptual Ideal for PLM information mirroring", able to capture the relationship between real and virtual spaces and to highlight the need for the exchange of data between them in order to mirror each other [9]. It was the first time that the concept of Digital Twin appeared. Unlike the NASA definition, that described the digital twin as an aircraft or system oriented, Grieves expanded this definition at virtual level. He defined Digital Twin as a detailed virtual representation of a product, that includes every aspect, from the smallest atomic details to the overall structure and shape. He believed that four elements were necessary to constitute the system: the digital model, to represent the physical entity, the linked data, to create the interaction between the two, the identification and the real time capabilities to improve in a continuous manner its integrity and accuracy.

In 2011, professor Grieves was introduced into NASA thanks to the colleague Jhon Vickers and coined the actual "Digital Twin" name [10]. Although they were actively involved in the DTs and related technologies exploration, not many researchers focused on these areas, due to the constraints of Internet of Things and to data processing technologies, which hindered broader adaptation and practical use [11].

Figure 2.2 shows the main components of the Digital Twin at conceptual and simplest level. As mentioned above, it can be described as a realistic virtual representation of a physical entity, that can be anything, from a manufacturing unit or a simple object like an automotive to a very complex entity, as an entire city such as Singapore. Then, the interaction within the two spaces happens in the interface zone, where a flow of data from the physical space to the virtual one and a flow of information in the opposite direction take place to synchronize the two systems in real time.

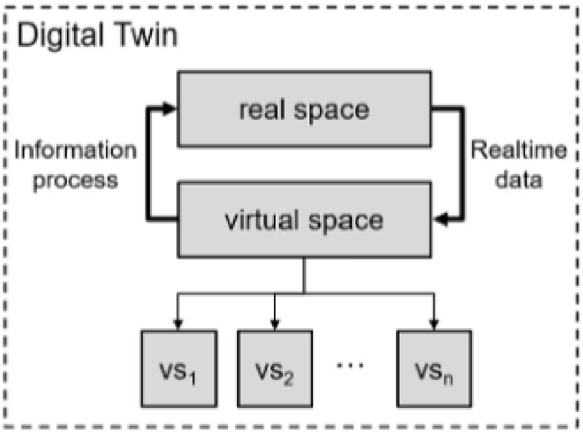


Figure 2.2 – Basic conceptual model of a DT

In 2010, the United States military materialized the first DT in the field of operational control aviation systems. With the aim of reducing maintenance and utilization costs, this technology was first used to realize the digital companion flights for F35. The following year, the United States Air Force Research Laboratory developed a model to allow health control, while in 2015 General Electric built a digital twin technology to monitor in real time the aircraft passenger engines.

In 2017, DT technology was used in a second field of application by both General Electric and Siemens AG. It was used to improve the management of physical and large installations, through virtual scheduling, simulation and inspection. In the same year, the third application field was developed: DT technology was used for the product interaction design to enable designers and customers to identify the effects of products and to optimize them during the design phase.

2.1.2 Characteristics of Digital Twin

As mentioned in the previous paragraph and shown in Figure 2.3, Digital model refers to a virtual model that represents in a consistent and complete manner the physical entities present in the reality and can simulate in real time their future behavior and performances [12]. It can be said that digital models are data, models and objects.

Digital Twin refers to the methods and processes used to represent through digital technology the characteristics, behavior, formation processes and performance of physical objects. It is important to notice how in the Digital Twin both entities communicate with each other: there is a bi-directional flow of data between the digital and virtual model. Data can flow from the physical object to the virtual one, enabling its changes, and the digital object can send data or information to the physical one to impose a perturbation or a change in the physical sphere [13]. Digital Shadow, instead, refers to a model in which the physical object is represented by the Shadow and the communication is a one-way communication: the physical object can send data or information to the virtual one, while the virtual one cannot send information to the reality.

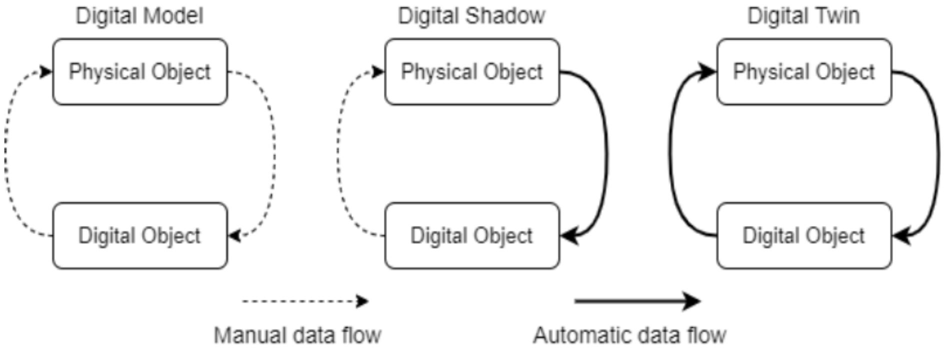


Figure 2.3 – Schematic visualization of Digital Model, Digital Shadow and Digital Twin

The basis of the characteristics of the Digital Twin consists in 12 themes in total, while the gaps in research and future directions are identified by 9 total themes [14].

By exploring the first 12 themes:

1. *Physical Entity*: different terminology has been used to describe this first characteristic, such as ‘system’, ‘models’ and ‘artefact’, but the commonality of all of them relies in the fact that they are physical and exist in the real world. Even if those terms refer to mainly man-made entities, also natural entities must be considered, such as Digital Twin of farms or children.
2. *Virtual Entity*: ‘model’, ‘cyber’ and ‘object’ are the main terms used to describe this second characteristic, which is a representation of the physical world.
3. *Physical Environment*: this third characteristic refers to the real space which hosts the physical entity. To ensure an accurate virtual representation of the real world, all the relevant parameters that may influence the physical entity are used to measure and capture aspects of the reality.
4. *Virtual Environment*: this fourth characteristic refers to the twinning representation of the physical environment, which is achieved through the measurement of key parameters that belong to the real world. Sensors are typically used as physical metrology to measure aspects of the physical entity.
5. *Fidelity*: this mainly refers to the performance of the Digital Twin and can be described as a full and accurate (from a micro to a macro level) mirror of the characteristics and functionalities of the physical twin. The metrics that are used to describe the level of fidelity are: the number of parameters exchanged between the two entities, their accuracy, and their level of abstraction.
6. *State*: this characteristic is useful to measure the current values of the environmental parameters or the condition of the digital and virtual entities. Some examples can include health and operation.

7. *Parameters*: this characteristic refers to the type of information, data and processes that are exchanged between the virtual and the physical reality. Some examples include the Form, used to measure the geometric shape and structure of an object, the Functionality, used to measure the movements of an object, the Process for the activities in which the object is engaged and the Performance, used to compare the actual operation of an object with the optimal one.

8. *Physical-to-Virtual Connection*: this theme refers to the connections used to transfer and to realize the state of the physical entity to the virtual one. The procedure consists of two phases: a Metrology phase, to capture the condition of the physical entity, and a Realization phase, to update the virtual entity based on the differences between the two. Internet of Things sensors, web services, 5G and customer requirements are used to capture the values of physical parameters and to update the virtual ones. This characteristic is useful to monitor state changes due to perturbation of the physical environment or of the Digital Twin itself.

9. *Virtual-to-Physical Connection*: this theme is the same as the Physical-to-Virtual Connection, with the only difference that the flow of information starts from the virtual to the physical entity. Changes in display terminals, process control, production management, PLC's and machine parameters are used to capture the values of virtual parameters and to update the physical ones.

As shown in Figure 2.4, when Virtual-to-Physical Connection is used with Physical-to-Virtual Connection, it is possible to close the loop between the two realities and to continuously adapt and improve the cycle of hypothesis, perform, test and adjust.

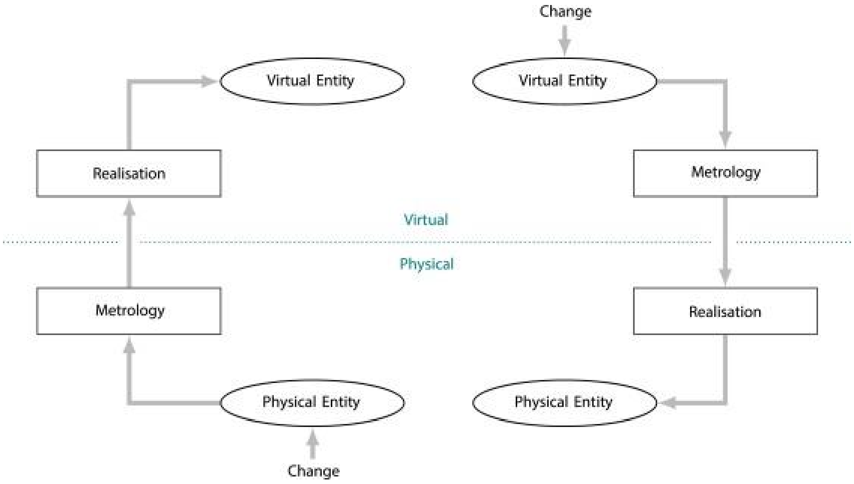


Figure 2.4 – Representation of the Physical-to-Virtual and Virtual-to-Physical Connection

10. *Twinning/twinning rate*: this theme refers to the synchronization between the physical and the virtual state. The process includes both the 8 and 9 connections and allows the equality of the values of the physical and virtual parameters.

The twinning rate measures the frequency of twinning. Real-time frequency is used to describe this rate in literature, and this means that the same change that happens in reality will be reproduced immediately in the virtual world (and vice versa).

11. *Physical processes*: this theme refers to all the activities (processes or purposes) that are carried out in the real environment by the physical entity and that enables a change in Physical Twin parameters. An example can be a manufacturing production line.

12. *Virtual processes*: this theme refers to all the activities that are carried out in the virtual environment by the virtual entity, such as simulation, optimization, modelling, prediction and diagnostic.

The themes for future directions and gaps in research are: *Perceived Benefits*, *Digital Twin across the Product Life-Cycle*, *Use-Cases*, *Technical Implementations*, *Levels of Fidelity*, *Data Ownership* and *Integration between Virtual Entities*.

Between them, an important concept is *Perceived Benefits*, related to the potential benefits that can be obtained with digital twin process, such as innovation, fostering, costs reduction, risks reduction, efficiency, safety, reliability and decision-making support.

Another important concept is *Integration between Virtual Entities*, that enables the communication between multiple virtual environments, each with its own use-case.

2.1.3 Applications of Digital Twin

The most explored context of applications of Digital Twin technologies are five: *Healthcare*, *Manufacturing*, *City Management*, *Maritime and Shipping* and *Aerospace* [15].

As shown in Figure 2.5, a lot of industries have expressed their interest in the application of Digital Twin such as, for example, GE Predix Platform, SIEMENS PLM, Microsoft Azure, IBM Watson, PTC Thing Worx, Aveva, SAP Leonardo Platform, Twin Thread, DNV-GL, Dassault 3D Experience, Sight Machine, Oracle Cloud. Also, Digital Twin patents have been filled for the efficiency of asset maintenance [16], for Siemens and for General Electric.

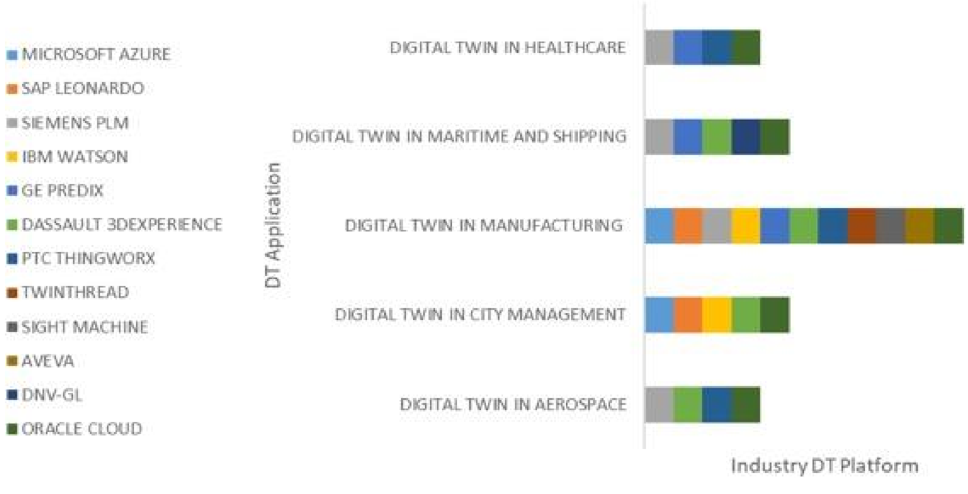


Figure 2.5 – Digital Twin applications in industrial platform

In the *healthcare sector*, Digital Twin technology can be used for various aspects. It can be used to create a safe environment by identifying the system and by testing in advance the consequences of potential changes. It can also be used as a prediction model, to predict patient health and to personalize the planning therapy, by identifying the best therapy option and drugs for a single patient [17]. Also, the use of a large quantity of data can be useful to make better decisions, to analyze the health and possible vulnerabilities of the population and to make experiments on large scale. An important role is played by Digital Twin in research: thanks to the simulation of physical assets, it is possible to use virtual reality to reduce damage, to make predictions in real time and to obtain information about results. In addition, it would be possible to store data in a decentralized and integrated way to ensure a higher level of efficiency and safety, and it would be possible for patients who are unable to physically go to the hospital to monitor their health.

In the *maritime and shipping sector*, Digital Twin is mainly used in the design phase. Without the use of the Digital Twin technology, the design phase is usually a time and cost consuming phase: it requires to perform a lot of simulations through the development of analytical models. By using the Digital Twin technology, it would be possible to visualize in real time all the key components without making them in practice, to make simulations and to analyze the performance. This helps to improve efficiency through the reduction of changes and reworks [18]. In the maritime sector Digital Twin technology can be used to perform risk maneuvers, to save costs by predicting maintenance using sensors, control systems and actuators, to increase the interoperability and maintenance of dockyards and ports and to increase the defense of a single naval force or of multinational task forces [19]. Instead, in the aviation sector the Digital Twin technology can be used to detect crack tip deformation, to identify damaged aircraft structures and to monitor the health of the structure [20].

In *manufacturing* sector, Digital Twin technology is used to monitor real time data and compare it with ideal ones to identify anomalies along the total life cycle of the product, from the design phase till the maintenance phase [21]. By using a higher number of sensors, it is now possible to increase the quality of measurements of machine's operations, also for what concerns the quality of materials used. Another important point is the possibility to store huge quantity of data, used to facilitate the overview of the evolution over time of the activity or process that is carried out by the industry. As shown in Figure 2.6, by using Digital Twin in manufacturing, it is also possible to develop a 3D graphical representation of the factory or of the process to better understand its characteristics, to keep track of all the business processes and interdependencies (including human interaction) and to create "what-if" scenario, used to simulate the behavior of the process or the productive line and to support decisions in a proactive way.

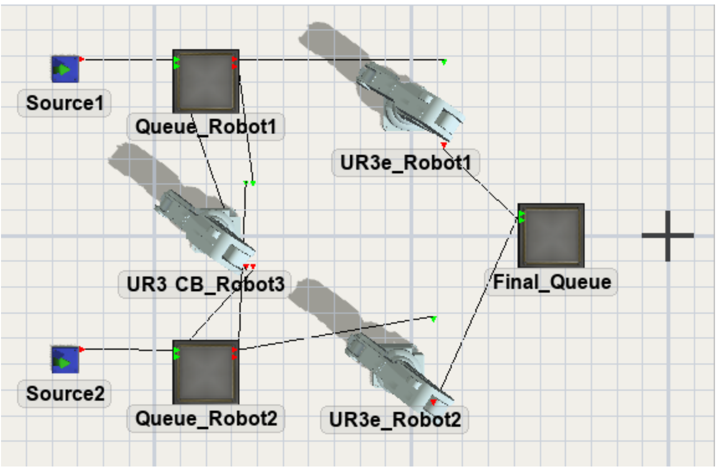


Figure 2.6 – Screenshot of 3D Digital Twin Representation of a production line

In *city management*, Digital Twin is used to create a virtual urban environment to improve the quality life of citizens, with the use of sensors and actuators to give the system interactive capabilities [22]. It has been observed four main sectors for the application of Digital Twin: mobility sector, to simulate people movements, to manage private and public transport and pollution, water sector, to manage water supply, energy sector, to manage the generation and the transmission of electricity in the network and finally the atmospheric sector, to model the climate and air quality [23].

In *the aerospace* sector, Digital Twin technology can be used in the design phase to predict the structure of the spacecraft and to optimize the specific parameters in the earlier stage [24]. Also, spacecraft digital twin can be used in orbit to predict failures and health management and based on the results can be used to make decisions in an autonomous manner and to effectively control the real spacecraft remotely. Digital twin technology can also be used to create "what-if" scenarios to simulate different atmospheric and parameters conditions and to limit damages by activating a self-reparation.

2.2 Digital Twin in industry 4.0

As shown in Figure 2.7, Industry 4.0 is the result of an industrial revolution, which started with Industry 1.0, characterized by the use of steam power, water power and mechanization, then Industry 2.0 with mass production, production on assembly line and the discovery of electricity, followed by Industry 3.0 with automation and the use of computers and finally the fourth revolution, characterized by the digital transformation of the machine manufacturing.

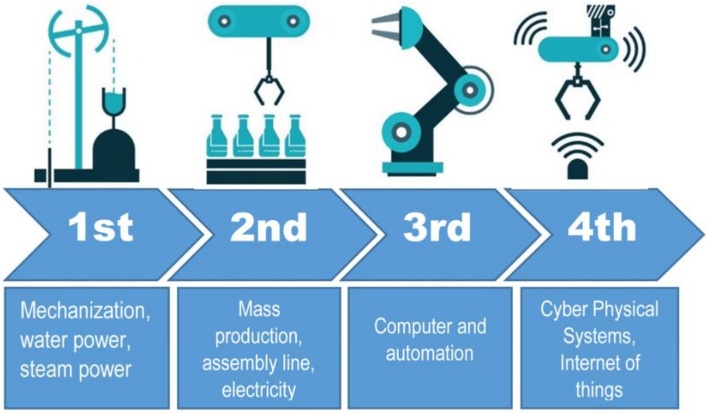


Figure 2.7 – Evolution of the industrial revolution

Industry 4.0 has been driven by ten new technologies [25], which are:

1. Cyber Physical Systems: systems in which cyber and physical components are effectively integrated through sensors and network technologies [26].
2. The Internet of Things: a network created through sensors and smart objects to allow real time communication between devices and objects [27].
3. Big Data Analytics: advanced analytical techniques to transform raw data, extracted from huge quantities of information, into useful ones to support decision-making [28].
4. Cloud Computing: delivery of services over the Internet.
5. Fog and Edge Computing: decentralized computer services to store and process data, used to decrease the travel distance of data in the network.
6. Augmented Reality and Virtual Reality: technologies used to make people interact with computer-generated world (VR) or to visualize digital images in the real world.
7. Robotics: robots and/or robotic devices are used to perform production tasks with high efficiency and reliability.
8. Cyber Security: tools used to protect the organization environment and the cyber system from attack, unauthorized access or destruction [29].
9. Semantic Web Technologies: standardized formalism to represent information for a better cooperation between people and computers.
10. Additive Manufacturing: on demand layer-by-layer fabrication of material, based on a 3D graphical representation of the product.

Industry 4.0 is characterized by six main pillars [30]: *interoperability*, that refers to the capacity of all programs to convey and work together, *virtualization*, which is the ability to create a virtual reality of the industrial facility, *decentralization*, that refers to the distribution of powers and functions, *real-time capability*, which is the potential to collect and analyze data instantaneously, *service orientation*, to better satisfy customer needs and *modularity*, that allows flexibility and responsiveness to changing conditions or prerequisites without inefficiencies or disruptions.

As introduced previously, one of the ten core components of Industry 4.0 is Cyber Physical Systems, used to integrate physical and cyber processes with the purpose of controlling and monitoring the real entity in real time. Digital Twin technology has played a pivotal role in the concretization and implementation of Cyber Physical Systems [31] and has been applied as a realistic tool for the fusion of the cyber and physical sphere [32]. With the contribution of IoT and robotics, Digital Twin technology allowed to extend the control over the entire product design and operation cycle, to ensure well-defined services (including control, monitoring, maintenance and optimization), to customize the production by supporting users' decisions, to identify and reduce possible harmful risks, to identify advantages and to define a security level [33].

2.3 Digital Twin in Industry 5.0

While Industry 4.0 was associated with a digital and technological transformation of industrial processes, characterized by robots, autonomous systems, machine orientation and coordinated processes and driven by the purpose of improving the effectiveness in the analysis and collection of data, the efficiency in the used models and the consistency between processes [34], Industry 5.0 was introduced as a response to solve an emerging challenge: the societal one. Industry 4.0, mainly focused on productivity, put societal needs and human values in background, while Industry 5.0 introduced three paradigms: *human centricity*, with the intent to place the interests of humans at the center of the production processes, *sustainability*, by promoting circular techniques such as repurpose, recycle or rejuvenation to reduce waste and the environmental impact and *resilience*, which is the capability to recover from failures or disruptions activities.

By considering a co-existence scenario, collaboration between humans and robots is performed instead of competition and the productivity can be increased without subtracting workers from the process. In this way, Industry 4.0 can be complemented and extended by Industry 5.0.

By considering a transition scenario, the transformation from Industry 4.0 to Industry 5.0 can be achieved through the implementation of critical thinking, communication, collaboration and creativity with respect to the three pillars mentioned above.

The use of Digital Twin in Industry 5.0 can be mainly associated with the collaboration between humans and robots [35]. With a Digital Twin, the interaction between the two can be modelled and simulated to maximize the efficiency and the safety: through simulation it could be possible to design collaborative robots able to work side by side with humans without compromising their safety. Collisions tests can be performed to prevent accidents before deploying robots in the real world. Also, thanks to the replica of the physical entity, real-time monitoring data can be collected during the process and can be used to reduce risks of accidents and injury. By applying Digital Twin technology, flexibility can be easily achieved, leaving the system to adapt to new human needs; real time feedback can be used to identify and correct ergonomic issues and to improve the performance of the robots, also under a sustainable point of view. Data can be used to predict maintenance and to guarantee a good level of resilience of the system.

2.4 IoT architectural reference model

2.4.1 History and benefits of IoT ARM

As mentioned above, one of the core components of Industry 4.0 is IoT, that refers to a network infrastructure by which physical and digital resources and users are connected. To guarantee interoperability, compatibility and integration, an Architectural Reference Model

(ARM) has been developed [36]. The main idea was to provide a common structure and guidelines to develop and analyze IoT systems at an abstract level.

The term *reference model* referred to "an abstract framework that comprises a minimal set of unifying concepts, axioms and relationships for understanding significant relationships between the entities of an environment". Specific architectures should be developed starting from the framework and should be used to describe at high level essential building blocks and design choices related to security, functionality and performance. Also, information usage needs to be provided, as well as interfaces need to be standardized.

The main benefits in using an IoT ARM listed according to their degree of abstraction are:

1. *Cognitive Aid*: the ARM can help to guide discussions by providing a standard language, can help people understand the IoT features by giving a rich view of the domain, can assist and support project planning and can be used to identify independent building blocks.
2. *Reference Model as a Common Ground*: by describing the IoT entities and their relationships, ARM provides a common ground for IoT systems.
3. *Generating architectures*: through guidelines IoT ARM can generate architectures for systems, enabling a degree of automation and a useful documented pattern to take decisions.
4. *Identifying Differences in Derived Architectures*: by looking at the architecture generated, a list of special features can be generated, as well as design choices to meet some targets.
5. *Achieving Interoperability*: IoT ARM allows the achieving of interoperability during the design-choice process or at posteriori, by including the system as a subsystem in another system, or by building a bridge between the functionalities of the two systems.
6. *System Roadmaps and Product Life Cycles*: design choices can be used to map the evolution of the system and the generation of the resulting product life cycles.
7. *Benchmarking*: through the standardization of system components and aspects it can be possible to identify in a very transparent manner the minimum features to be filled. By

increasing the number of functional components, a higher appreciation of the system can be achieved.

2.4.2 Architecture development process of IoT ARM

In contrast with concrete architecture, that helps in designing, building and testing the analyzed system and can be obtained using guidelines from the reference architectures, reference architectures describe the system in a more abstract manner. Then, as shown in Figure 2.8, from the concrete architecture it can be derived the model architecture, that establishes a foundation for a shared comprehension of the IoT field by illustrating its concepts and its interconnections.

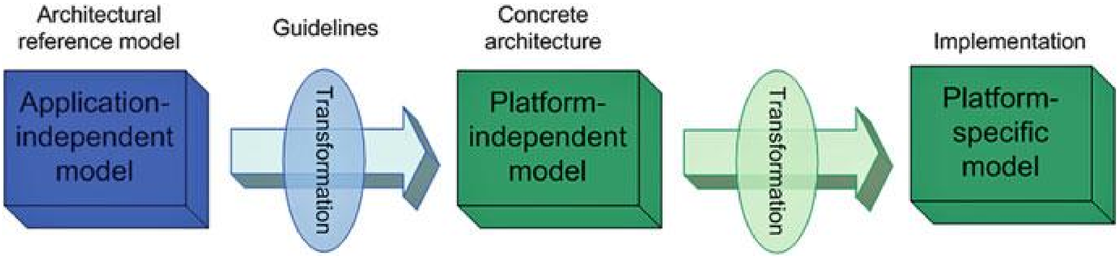


Figure 2.8 – Implementation of an IoT reference model

The first role of IoT ARM can be identified during the transformation of the architecture reference model into concrete architecture. It must provide guidelines and rules to transform the abstract model. It works in combination with design process practices that are influenced by the guidelines themselves and by the specific use case and requirements. Based on the strategies used, those steps can be performed in parallel or not.

Before proceeding with the transformation, a methodology for the ARM development and a methodology for the concrete architecture must be identified. The choice for the IoT model is not standardized and the IoT usage domain is wide and characterized by a high degree of abstraction. Instead, standardized methodologies such as Aspect-Oriented Programming

(AOP), Model-Driven Engineering (MDE), Pattern-Based design and SysML were designed for specific use cases and scenarios. Unfortunately, this level of specificity also influences how they function internally. In simpler terms, when these methodologies are used for broader applications, they do not produce generalized models applicable to the abstract concept of an IoT ARM; rather, they yield no results at all. Thus, the IoT ARM and the MDE methodology are similar via platform-independent models (architectures). Although the concept of model transformation advocated by MDE aligns with the IoT ARM approach, the methodology created for generating transformations between platform-independent and platform-specific models cannot be directly applied or modified to establish optimal transformation practices.

The following points provide an overview of what concepts it has been possible to incorporate from established architectural methodologies into the more abstract aspects of the IoT ARM:

1. Aspect-oriented programming: the specification of functions according to different aspects is reflected in the idea of functionality groups in IoT ARM.
2. Model-driven engineering: the fundamental idea involves transitioning from a broad model to a more detailed one. This concept is applied to outline and refine IoT ARM guidelines.
3. Views and perspectives: the idea of views and perspectives used to develop the IoT Reference Architecture, meaning the organization of all elements of the reference architecture based on these views and perspectives.

3. State of the art

3.1 Literature review methodology

The first step of the literature review method was a citation process performed on Scopus, conducted to find all the articles that cited as keywords *Digital Twin* AND *Collaborative Robot* (with synonyms and acronyms as DT and COBOT inserted in OR).

By using this criteria, 102 articles written in English language were found. Referring to the document type, 52 of them were conference papers, 45 articles, 3 book chapters and 2 documents were a review.

Figure 3.1 shows the review methodology, while the main components of the process carried are explained below:

1. Initially, 102 articles were found on Scopus from the intersection of the keywords *Digital Twin* and *Collaborative Robot* (with synonyms and acronyms as DT and COBOT inserted in OR). No duplication between the identified articles was found.
2. After that, based on title, abstract and keywords assessment, manual filtering was performed to include relevant articles and to exclude the ones far from the topic or not accessible by using the research means available. This process led to the removal of 16 articles.
3. The final step was a deep review of these documents, based on full text assessment. It was found that an article was more focused on the learning aspect of a network and 6 articles were more descriptive and focused on providing a theoretical and broader prospective of the topic, highlighting concepts, challenges, opportunities, potential applications and advantages in an abstract way.

At the end, 79 papers were analyzed.

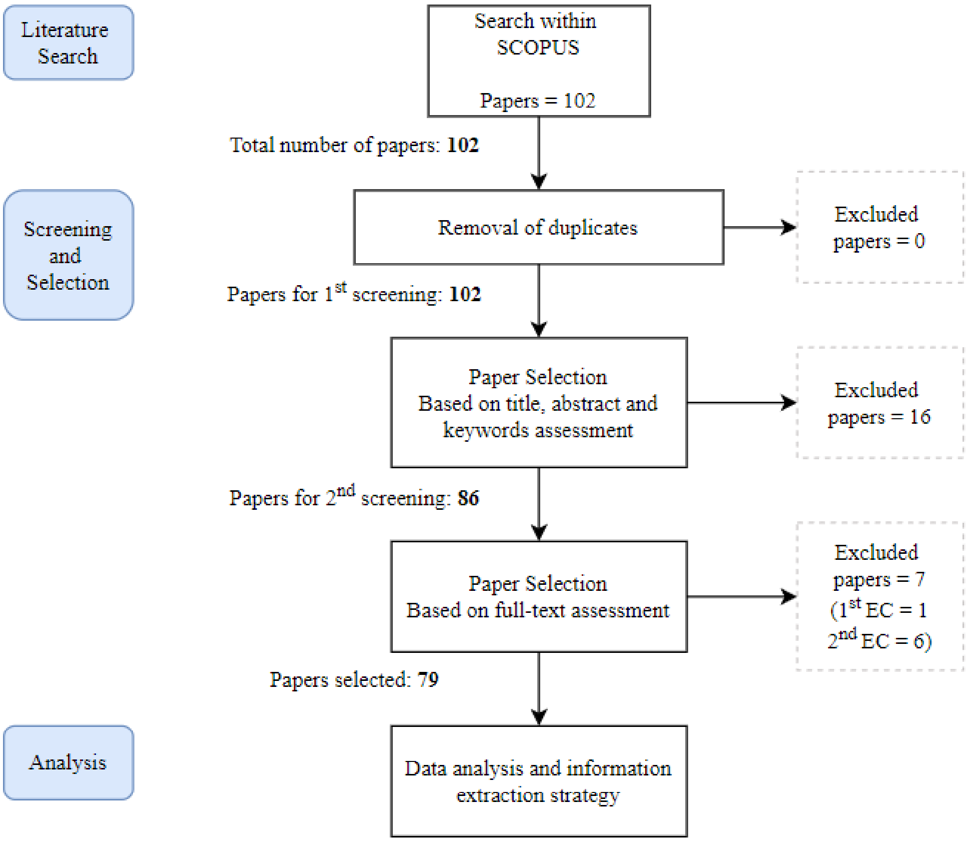


Figure 3.1 – Literature review methodology

3.2 Literature review analysis

A preliminary classification has been developed based on the application area. From this initial classification, it was found that all the reviewed articles analyzed the integration of digital twin technology and collaborative robot in the industrial sector.

Within this very broad category, most of them were related to manufacturing processes and smart factories, while few of them referred to more specific sectors, such as the painting industry [37] that uses the digital twin of the automated painting robots to simulate the painting robot's process. In this way, as shown in Figure 3.2, operators can change the parameters of the painting robot in the virtual environment and can choose the optimal ones before the execution of the tasks in the real world.

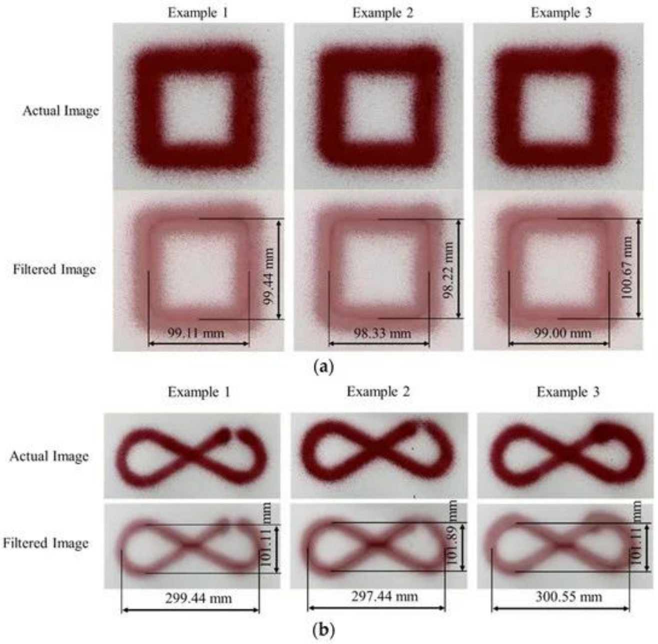


Figure 3.2 – Example of Square and Infinity shape patterns

Another specific sector was the construction industry, and three articles have been found about it. All items highlight the use of advanced technology and emphasize the collaborative efforts between humans and robots, aimed at improving the efficiency and safety in construction processes. They diverge in their specific applications. In fact, article [38] was more focused on the construction phase of projects, using simulations for real-time robot motion planning and task execution, article [39] specifically discussed tunnel construction and introduces the "Shimizu Smart Tunnel," which emphasized a system designed to enhance safety and productivity in that niche area and article [40] was more focused on a feedback system using location and force signals to control the assembly conditions in real time, focusing on material sustainability alongside technology.

After a detailed analysis of the remaining 75 articles, a second classification was carried out according to a new criteria, as well as the research outcomes:

1. 35 articles propose solutions to show how cobots and digital twins can improve production performance through flexibility and efficiency.

2. An article proposes a framework to show how digital twin technologies can be used to address resiliency concerns.

3. 29 papers develop applications to enhance worker safety in collaborative settings scenarios.

4. Nine articles recognize the necessity to place humans at the center of robotic systems.

5. An article provides a discussion about future research directions.

3.2.1 Applications for flexibility and productivity

After a detailed analysis of the 35 articles, a third classification was carried out according to the research methodology (simulations or real time monitoring), the techniques used (reinforcement learning) and the need to address modern manufacturing demands (mass customization, complex tasks and quality).

1. Nine papers have been identified to underscore the role of digital twins in simulating real-world conditions and troubleshooting. All the articles recognize the importance of human flexibility and adaptability alongside robotic efficiency, and they try to improve production efficiency through the adaptation of technologies, especially by varying parameters such as operational times, tasks allocation and assembly processes. Also, most of the articles highlight the lightweight and easy programming of collaborative robots as a solution to overcome obstacles and to improve adaptability. The main differences between article [41], [42] and [43] are related to the scope of application. While the first article investigates how process efficiency can change while changing collaborative robot motion parameters (motion, acoustic and visual) in a digital twin-based model (see Figure 3.3), the second tried to pre-validate and to test in advance a broader framework for implementing cobot systems in SMEs. Also the third article focuses more on a general level: it tries to develop a framework for object location without deepening into robot parameters. Based on the scope

of application, some articles focus more on specific production environments (like SMEs in [42]), while others are more general, addressing large-scale industrial applications, like [44]. This article emphasizes the need for real-time monitoring and operator training alongside flexibility in design. Some articles diverge for the focus area. Article [45] differs from all the other articles because it focuses on the logistics and the adaptation of AGVs in a digital twin framework. Articles [46] and [47] diverge in relation to the approach to flexibility. The first proposes a digital twin as a validation tool to create what-if scenario for managing the dynamic nature of cobots, while the second targets obstacle avoidance specifically using Unity 3D software. Finally, articles [48] and [49] are validated through industrial case studies. As for the previous articles, they both utilize virtual simulation for task planning and programming of cobots. They use Siemens software. They diverge in their specific methodology: the first article incorporates lean methods of manual assembly to foster collaboration, while the second article highlights online optimization techniques for real-time control based on the operational status of robots and humans.

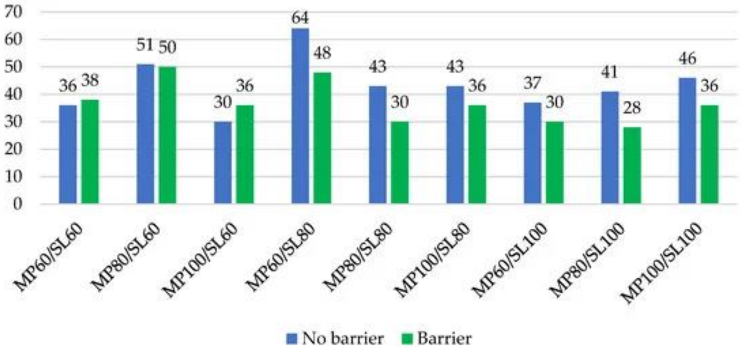


Figure 3.3 – Number of inefficiencies at different process parameters

2. Four articles have been identified with a common underlying theme: reinforcement learning, which is a dynamic area in which an agent gains knowledge by acting in an environment [50]. It has been used to improve robot learning and performance and to shift

to intelligent automation. All the articles showcase how cobots can be integrated with human operators to enhance efficiency and productivity. Also, all of them use the digital twin to represent and simulate the physical systems in advance. They diverge significantly in their scope of applications and technological approaches. Article [51] focuses on the integration of human, cobot and environment in a collaborative assembly scenario; article [52] integrates augmented reality (AR) elements and emphasizes coordination and motion planning; article [53] specifically addresses contactless delivery operations involving predictors for catch points and employs a neural network for predictive tasks related to package delivery. Finally, article [54] centers on training methods for collaborative robots using synthetic data and a point cloud framework. As shown in Figure 3.4, this last article focuses more on data generation processes rather than real time operations framework, reducing time and cost.

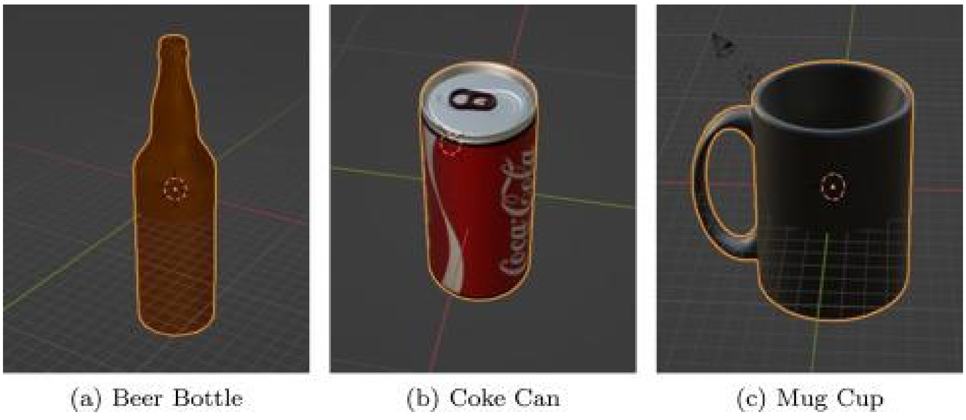

(a) Beer Bottle (b) Coke Can (c) Mug Cup

Figure 3.4 – Example of virtual objects created using 3D software

3. Twelve articles have been identified to underscore the role of digital twins in creating virtual replicas of physical systems for monitoring and optimizing real time operations. All the articles highlight the role of cobots in enhancing manufacturing and assembly processes and discuss the optimization of line tasks and productivity through real time monitoring. Also, all of them align with the principle of industry 4.0 and include advanced technologies

(like IoT, AI or data analytics) to facilitate smart manufacturing. The eight papers differ mainly in their specific applications and technologies.

Different application focuses have been identified. Using a bidirectional flow of information, article [55] focuses on customized medium-sized products and uses digital twin for real-time supervision to minimize downtime that could be due to operations interruption, while article [56] details the architecture of a digital twin for automated drone assembly. As shown in Figure 3.5, article [57] targets worker assignment and balancing challenges in assembly lines, utilizing employee data to enhance task allocation between the cobot and the worker. In doing so, it uses data analytics and learning algorithms for worker assessments and performance estimation. This article differs from article [58] in terms of data utilization. Indeed, it uses IoT for real-time data transfer in smart factories. Despite the same application focus, article [59] employs a different technological framework. It presents an assisted assembly case study and emphasizes the use of advanced technologies like mixed realities and CNN models for parts recognition. Also article [60] emphasizes the importance of innovative solutions to enhance efficiency. Article [61] differs in methodological approach: it aims to enhance operational efficiency through educational tools.

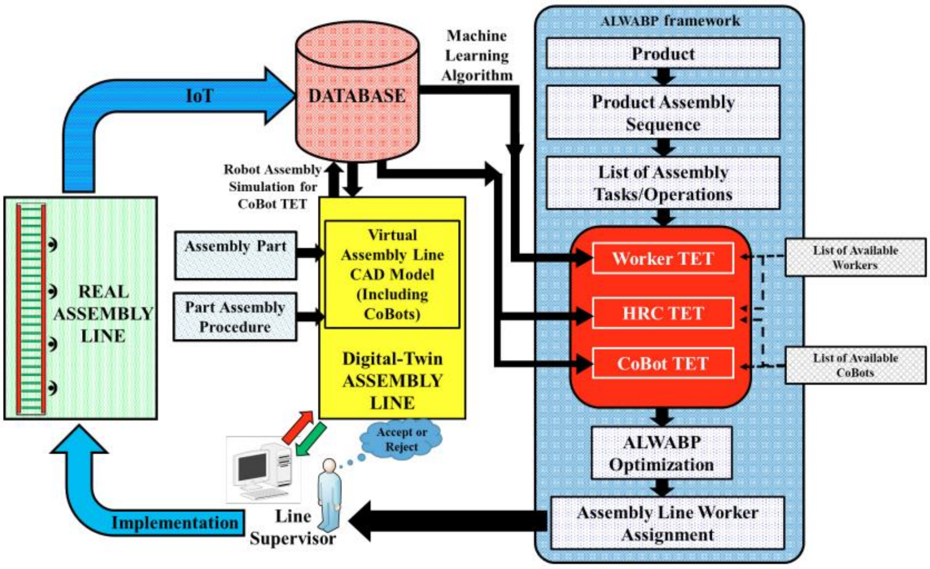


Figure 3.5 – Work allocation architecture

While all the articles were more focused on specific case studies, article [62] differs in scope of research. It uses an industrial case study (a digital twin to detect malfunctions or scheduled issues of cobot performance) to discuss systemic challenges posed by 6G in industry.

Finally, articles [63] and [64] emphasize the role of automation within the context of manufacturing processes. They both focus on full automation and real time synchronization leveraging on kinematic control methodologies, while articles [65] and [66] emphasize the role of communication, through workflow modeling architecture or block-based programming techniques.

4. Seven articles have been identified to share a common goal: the development of flexible, intelligent, and automated systems to address modern manufacturing demands, such as mass customization and complex assembly tasks. All the articles share a fundamental focus on digital twins and collaborative robots to handle dynamic conditions to improve flexibility and productivity. Also, all the papers work in the industry 4.0 context and few of them present case studies or real-world applications to demonstrate the impacts and the validity of the proposed frameworks. Articles [67], [68], [69] and [70] diverge in their specific contexts. Indeed, while articles [67] and [68] focus on an intelligent adaptative control of collaborative robot in general manufacturing, article [69] targets the assembly-commissioning process to optimize the sequence path of complex products (specifically automobiles) and article [70] addresses product-centric design for personalized products. From a technical point of view the last two articles introduce frameworks emphasizing cognitive abilities and planning algorithms, while [71] focuses more on real-time updates during the physical assembly process. In this case, digital twin of the physical complex-shaped architectures process is continuously adjusted, allowing the regeneration of commands. Always looking at the technicality aspect, article [72] proposes a service-oriented architecture for robotic resources applicable across various production

environments. Finally, the last article [73] differs from all the others for two reasons. Firstly, it focuses on a specific industrial application, the coal mine, and secondly it provides a broader technical analysis than the others.

5. Three articles have been identified to paint a comprehensive picture on how digital twins and cobots can influence quality and performance in manufacturing processes. All the three articles emphasize the importance of automation in enhancing systems and processes, address practical applications in the industrial sector and recognize the importance of quality and performance in innovation to improve productivity while reducing costs. The divergences between the three articles can be addressed to their specific applications and methodologies. Article [74] discusses a specific case study by focusing on the manufacturing processes of wind turbines and emphasizes the need for mobile robotic assistants to reduce costs and improve quality. Article [75] does not focus on a single application but provides a broader and theoretical overview for real time performance improvements, while article [76] differs also in technology, because it presents a framework with monitoring systems as sensors to extract more information from reality to activate commands.

3.2.2 Application for resilience

Article [77] has been identified to address resiliency concerns. It proposes a framework for medical assembly lines based on multiple parallel workstations with collaborative assembly robots. During the assembly process, parallel workstations can distribute assembly tasks among themselves if one workstation experiences a machine malfunction or an assembly error through real time monitoring and digital twin technology.

3.2.3 Applications for reliability and safety

After a detailed analysis of the 29 articles, a third classification was carried out according to the research methodology (empirical or theoretical studies), the techniques used (mathematical models) and the technology used (sensors).

1. Nine papers have been identified to underscore a recurring theme, which is the enhancement of worker safety using collaborative robots and digital twin technologies. All the articles implement Digital Twin systems as a sort of bridge between physical and virtual world to ensure safety. All the articles explore the interception of technology and automation. Also, all the articles are configured within smart industrial environments, often relating to industry 4.0 or 5.0 paradigms. Most of the articles include Artificial Intelligence and automation technologies to address challenges related to safety and reliability, present specific use cases to understand how theories can be applied to the real world and emphasize the importance of evaluating the performance to set the effectiveness of safety measures. Articles [78] and [79] differ from others because of their scope of application. The first article focuses on testbeds and presents a broader overview for manufacturing environments to simulate and model new potential hazards, while the second presents a broad review of collaborative technologies and implications. Article [80] presents a different level of integration: it focuses on a more detailed framework in medical device assembly. Other differences can be allocated based on the specific mechanism to achieve safety. Article [81] uses a condition monitoring system that integrates a prognostic and health management scheme to address uncertainties, while article [82] uses semi-supervised detectors to register the position of robots for ensuring a safe assembly environment. Regarding the technical approach, it focuses on AI technology, while article [83] on network technologies for telepresence. It uses virtual reality (VR) to enable a remote collaboration in the programming of the collaborative robot: the control can shift from a remote user (RU), who is immersed in a digital twin virtual representation of the robot, to the local one (LU), who operates on-

site and can be put in dangerous situations. Article [84] proposes to achieve sustainability objectives alongside safety. Finally, the last two articles differ for their collaboration approaches. Article [85] presents a novel simulation twin for control exchange strategy, while article [86] uses an exoskeleton to teach the human operator to perform its tasks. In this last example, the digital twin was used to guarantee interaction between the human operator and the exoskeleton, to provide visual feedback through VR and to drive movements of a collaborative robot.

2. Six papers of the analyzed ones emphasize enhancing safety through advanced mathematical model. Those models are used to improve interactions between humans and collaborative robots and incorporate techniques like key point mapping, deep learning, neural network and dynamic and kinematic modeling. All the articles adopt the digital twin approach to simulate and to evaluate performance of collaborative robots. To address safety concerns, most of the articles develop risk assessment protocols and collision avoidance models. Some differences can be identified between articles [87], [88] and [89] based on the modeling approaches. The first two articles focus more on physical hazard assessment through simulation and on the prediction of forces through the dynamic modeling of cobots and the associated joint dynamics, while the last one presents a more structured approach, characterized by qualitative risk analysis to safety controller design. For what concern modeling approaches, articles [90], [91] and [92] present some similarities. They all use digital twin technology for motion capture and human pose recognition and to virtually represent humans and cobots in a common environment. Technically speaking, they use different techniques. Article [90] centers on vison-based teleoperation and poses recognition to identify human skeleton models, while article [91] uses cameras and learning-based algorithms to extract human coordinates for collision avoidance. Article [92] includes uncertainty estimations.

3. As shown in Figure 3.7, article [93] worked more on a theoretical level and developed systematic guidelines for secure human-robot collaborative assembly as a response to the growing demand for safe integration of cobots in manufacturing. The guidelines are categorized. In this way, non-experts' users can implement in an easier way a safe environment too. Digital twin simulations can be used to evaluate the validity of those guidelines.

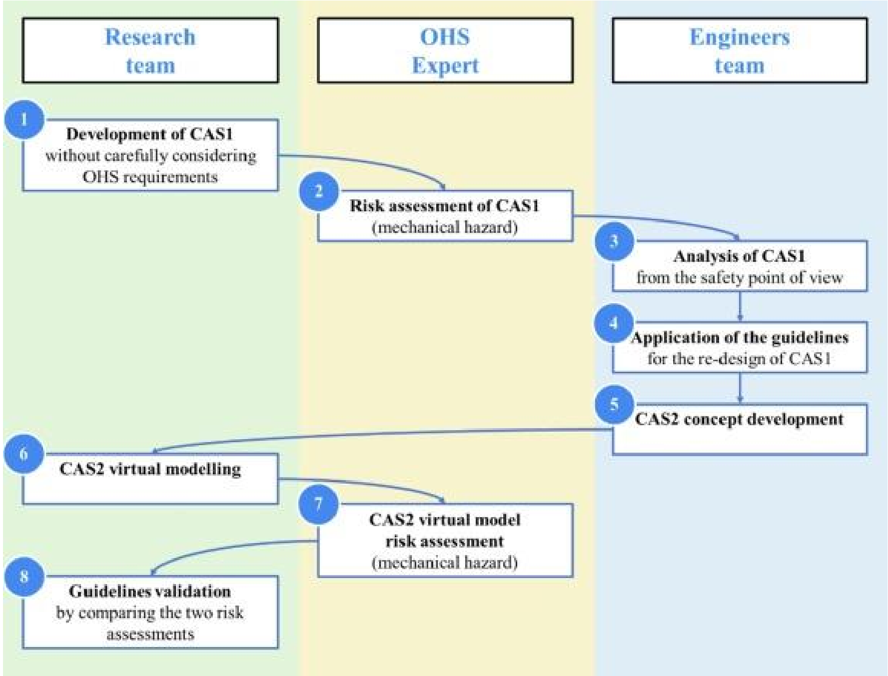


Figure 3.6 – Description of the validation guidelines process

4. Thirteen articles emphasize the role of sensors for human safety in collaborative industrial settings scenarios. Sensors are devices that detect or collect changes or signals from the environment and activate a reaction accordingly [94]. All the articles discuss the use of digital twins, which rely on real time data provided by sensors, to create virtual representation of physical systems. Those representations are designed to mitigate risks and enhance worker safety. Most of the articles explore the integration of one of the core components of Industry 4.0, Internet of Things, to enhance connectivity. Papers use sensors

also to improve system dynamism. Indeed, robots can adapt their actions based on sensory data. While articles [95] and [96] present similarities in their specific applications, because they both use modular sensors and digital twin to avoid collisions in robots' trajectories, article [97] focuses on collaborative assembly processes and uses augmented reality to drive the robot nodes' behavior through a graph model. A hybrid situation is provided by article [98]. Indeed, it presents broader operational aspects: it uses Kinect cameras and laser projectors to work both on the assembly sequences and the trajectory of robots.

Other differences may be due to the type of sensor technologies used. Article [99] emphasizes the use of laser scanners and body tracking cameras for monitoring human presence, while articles [100] and [101] use sensors for tracking machine dynamics. The first uses wrist-force sensors to identify the type of handled object based on its weight, while the second uses accelerometers sensors to improve tracking accuracy. Article [102] distinguishes itself by focusing on psychological sensors to monitor human responses during collaborative tasks. This article presents another difference in terms of scope of the analysis. Indeed, as shown in Figure 3.8, it presents a theoretical framework for assembly operations and human monitoring. It named three modules to show this process: awareness, to capture the environment with sensors, intelligence, to process data and action commands and compliance, responsible to modify robots' behavior.

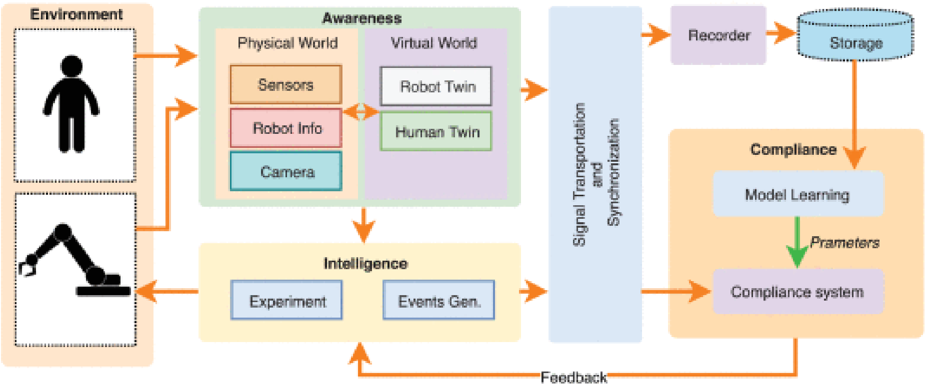


Figure 3.7 – Block diagram framework for monitoring the environment

Article [103] differs from others because it developed an easy-to-use program. In this way, operators with no experience can achieve an efficient human-robot interaction. Finally, articles [104] and [105] diverge in relation to the methodologies used to achieve a safety environment. They rely on real time data from sensors and virtual reality to facilitate remote assistance and control in contactless operations. The first article focuses more on a training scenario where a remote operator guides a local one during the learning process, while the second implements a scenario where the remote operator directly controls the cobot.

A practical example application in the disassembly of battery packs for e-cars is provided by article [106], where the combination of sensors camera and specialized kinematic model is used to continuously adjust the trajectory of the cobot to avoid task disruptions or safety movements violations.

In addition to sensors, article [107] employs ISO/TS 15066 as a basis for maintaining a safe distance during interactions.

3.2.4 Human-centricity applications

Nine papers have been analyzed and all of them emphasize the importance of placing humans at the center of robotic systems. They recognize the necessity to consider human capabilities, intentions and emotional states to improve collaboration effectiveness. All the articles provide human-robots collaboration systems and discuss the implementation of digital twin technologies to create virtual realities for the interaction between humans and cobots. Also, achieving safer interactions is a common theme analyzed by all of them. Articles [108], [109] and [110] diverge for the methodological approaches. The first article implements an emotional intelligence sensor to detect operator’s level of attention, capable of reducing safety and productivity, the second develops a fatigue sensor to adapt the workload of the operator accordingly, while the third proposes a new metric to establish the situation awareness to enhance mutual understanding between worker and cobot. Article [111] presents differences in technology: it uses Virtual Reality to measure human reactions to robot movements. Articles [112] and [113] diverge from the other articles because they propose a new architecture. Indeed, as shown in Figure 3.8, they discuss a Human-centered Digital Twin architecture. The main difference between a human-centered Digital Twin and the above-mentioned Digital Twin of technical components is that in the consideration of technical environments, a benefit can be achieved just if it is linked to a Digital Twin of a technical component. Also, human-centered Digital Twin contained more sensitive information, thus necessitating to comply with more legal requirements and authorization.

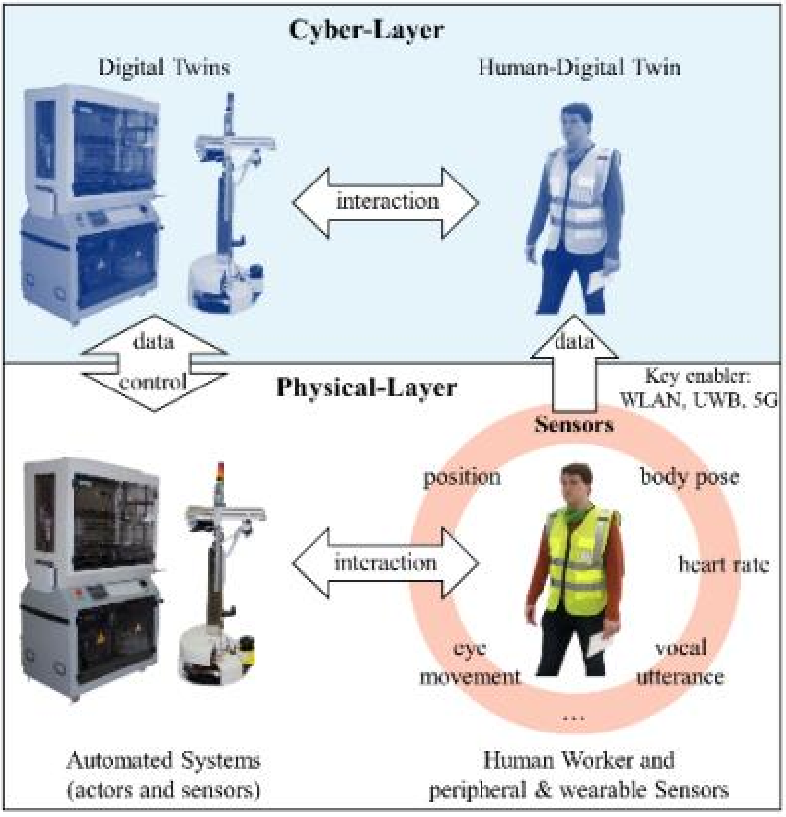


Figure 3.8 – Representation of a human-centered Digital Twin

Some articles vary from others due to their target audiences. Article [114] presents a very user-friendly interface to enable non-experts' users to set the weight of cost, time, fatigue and safety factors, while article [115] explores mixed reality to make the gesture control of the robot as user-friendly as possible. In this way, also non advanced operators can use the application. Finally, article [116] differs for interoperability reasons. It proposes a framework to enhance the integration between different platforms.

3.2.5 Future trends

The last analyzed article summed up the latest progress in Industry 5.0, specifically the three pillars' technologies of advanced manufacturing, that included digital twin and collaborative robots [117]. In addition, it provided future research directions.

Digital twin technology will be necessary to develop a metaverse of the whole industrial sector, from the design of the product to final services. A huge effort will be needed to integrate:

1. *Artificial Intelligence*, essential to predict machine maintenance and to alert workers when needed, to identify anomalies or defects, to help robots at responding to verbal commands or questions from humans, to recognize and manipulate objects and to use safeguards to protect individuals' rights deriving from possible misuse of data.
2. *Industrial Tactile Internet of Things*, to improve the interaction environment between humans and machines through the transmission of tactile sensation of the controlled object and changes feel in the robot environment from collaborative robots to remote operator.
3. *Prognostic*, to predict and to optimize resource allocation, risks, waste minimization and machine tasks distribution.

4. Adoption of Architecture Reference Model for DT

4.1 General overview of the IoT ARM

As introduced previously, one of the core components in Industry 4.0 is Internet of Things, that acts as a broad term for interconnected devices, items, services and technologies [36]. Although the potential for active and autonomous objects to communicate presents vast application scenarios and market opportunities that are continually evolving, the IoT covers a wide range of application areas with minimal similarities and different technologies. Therefore, the existing solutions often lack interoperability; although they may achieve success, they fail to establish a unified abstract framework that can drive substantial advancement across the entire domain.

The development of a shared "lingua franca", which serves as the focal point within the Internet protocol suite, is essential for the swift and widespread advancement of innovative solutions that can utilize various technologies created for diverse purposes across different application areas.

Following extensive discussions on the fundamental concepts of IoT over several years, a group of researchers from over 20 major industrial firms and research institutions collaborated in 2009 to create a foundational framework, known as the IoT-A project, to establish a much-needed common architecture for the Internet of Things. The IoT-A initiative has since become a flagship project for the European Commission within the EU's Seventh Framework Program for Research and Development, focusing on the creation of an IoT architecture. Focusing solely on the technical aspects, the project partners recognized that the current solutions failed to meet the scalability needs of future IoT applications. This was evident in both the communication among smart devices and the orchestration and management of intricate services. Additionally, the IoT landscape encompasses various governance models that are frequently not compatible with each other. At the end, it soon became clear that since no single design pattern can fulfill the needs of all application domains, it was essential to identify shared principles at a more abstract level.

This common ground can be provided by a reference model, that can be described as “an abstract framework that comprises a minimal set of unifying concepts, axioms and relationships for understanding significant relationships between the entities of an environment”. This framework is intended to facilitate the creation of targeted architectures, named reference architectures, that can operate at varying levels of abstraction and will outline both crucial components and design options for addressing competing needs related to performance, security and deployment. It was essential to standardize interfaces, and to establish best practices regarding functionality and the utilization of information.

The core choice made by the IoT-A project was to build upon existing technologies instead of starting from scratch. Consequently, shared characteristics have been identified to create the foundation of the IoT Architectural Reference Model (ARM), with the result of ensuring backward compatibility while also utilizing proven solutions across different aspects of the IoT.

4.2 Main components of the IoT ARM

The main components of an ARM are two: the Reference Model and the Reference Architecture [118].

The main entities, concepts and relationships in a domain are captured by the domain model, which is described using sub-models by the Reference Model. The information about entities and relationships is described in the information model, while the functional model of a working system describes the entities and concepts of its own. Lastly, the communication model contains the communication interaction of the communicating entities.

As shown in Figure 4.1, the second component of an ARM is the Reference Architecture, that serves as a communication tool for various stakeholders that are involved in the system. Each of them has a unique perspective of the same system, influenced by their interests and needs. Consequently, articulating an architecture requires showcasing the various aspects of the systems to address the differing interests of all stakeholders. Reference Architecture captures at a high level of abstraction the essential parts of a concrete architecture, such as the design, the different parts or the guidelines. Then, the concrete architecture can be further translated into real world components through designing and building. The real world can provide feedback to the concrete architecture about the design or the building choices, and the concrete architecture can use them as a contribution for the evolution of the Reference Architecture.

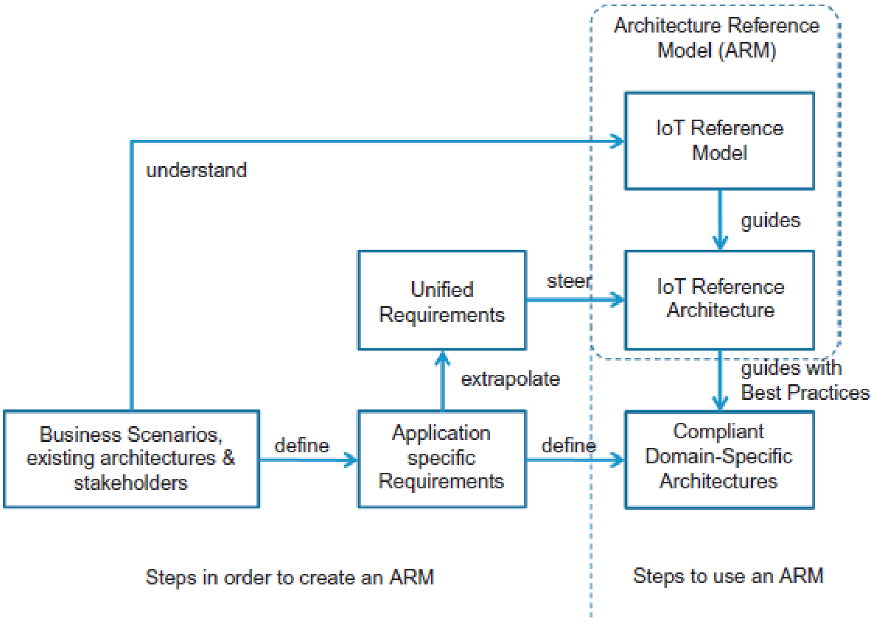


Figure 4.1 – IoT Reference Model and IoT Reference Architecture

4.3 IoT ARM Reference Model

The IoT Reference Model is composed of three sub-models: the Domain Model, which highlights key concepts, the Information Model, which outlines the conceptual organization of IoT-related information - its structure, relationships, and attributes - without detailing its representation and the IoT Functional Model, which categorizes various functionalities, many of which are based on the core concepts from the IoT Domain Model.

4.3.1 IoT-ARM Domain Model

A domain model captures the main concepts, attributes and relationships of a specific field of interest and is a tool to allow communication between humans.

The domain model of the Internet of Things (IoT) is described using Unified Modeling Language (UML) Class diagrams, which illustrate the relationships among key concepts. As shown in Figure 4.2, these diagrams consist of boxes representing different classes, connected by lines or arrows indicating their relationships. Each class defines a group of objects with similar structure, behavior, and relationships, containing a name and a set of attributes and operations. For the IoT domain model description, only the class names will be presented, with an emphasis on keeping the diagrams uncluttered by omitting attribute details. Instead, relevant attributes will be described in accompanying text.

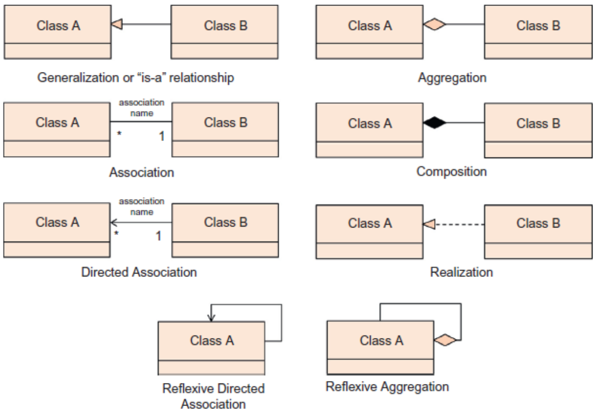


Figure 4.2 – UML class diagram

The main concepts of the IoT domain model are:

1. A *User*, which is a human person or a digital artefact and interacts with the physical world to achieve a certain goal.

2. A *Physical Entity*, which is part of the environment and is used by the user to achieve its objectives.

3. A *Virtual Entity*, which is the representation of the physical entity in the virtual environment. Each physical entity can be represented by multiple virtual entities and each of them has a unique identifier. The virtual entity has attributes that depict the state of the physical entity and need to be updated in real time.

4. *Devices*, to establish the relation between the physical and the virtual entity. Sensors are used to convert physical properties into electrical signals, actuators to convert an electrical signal into a change in the physical world and tags are attached to physical entities and identify them.

5. *Resources*, which are software elements that provide data or serve as control points for Physical Entities. They fall into two categories: on-Device resources and Network Resources. On-Device Resources operate directly on the device and manage information or controls for the attached Physical Entities. In contrast, Network Resources are hosted in the network or cloud. Resources can include various types, such as sensor resources that deliver data, actuator resources that enable actions or indicate their status (like "on" or "off"), processing resources that analyze sensor data, storage resources for data related to Physical Entities, and tag resources for identification purposes.

6. *Services*. The Resources make their functionalities available as Services with standardized interfaces, which simplify the underlying technical details.

Users interact with Physical Entities through the Virtual Entities associated with these Resources and their Services. The connections between Virtual Entities and Services can allow for monitoring or control via multiple Resources or Services, emphasizing the need to maintain these associations for easy access and discovery by Users. IoT Services can be categorized into three primary levels of abstraction:

Resource-Level Services: they focus on the functionality of devices by exposing their on-device resources. They also address quality aspects like security, availability, and performance. Additionally, they include network resources from powerful machines or cloud environments, which abstract the location of these resources, such as historical databases related to specific devices.

Virtual Entity-Level Services: they provide information or interaction features related to virtual entities, with their interfaces typically referencing the identity of these entities.

Integrated Services: are combinations of both Resource-Level and Virtual Entity-Level services.

4.3.2 IoT-ARM Information model

The information model provides additional information to data, answering the questions who, what, where and when.

The information model of the Internet of Things (IoT) is described using Unified Modeling Language (UML) Class diagrams and it provides at a high-level attributes and properties related to the Virtual Entities, such as the type of entity, the unique identifier and attributes. Also, it provides details about the association between the Virtual Entity and the Service. The attribute Service Type can take two values: “INFORMATION” if the associated service is a sensor, or “ACTUATION” if the service allows an action to be executed.

The IoT Information Model encapsulates all the elements of the Domain Model that need to be clearly defined and interacted with in the digital environment. It also outlines the connections between these elements. Essentially, the IoT Information Model serves as a meta-model, offering a framework for the information managed by IoT systems, which underpins every facet of the system and serves as a foundation for establishing the functional interfaces of the IoT system.

Of course, more details or models can be specified in real systems based on the specific use case.

4.3.3 IoT-ARM Functional Model

As shown in Figure 4.3, the IoT Functional Model focuses on outlining the Functional Groups (FG) and their relationship with the ARM. In contrast, the Functional View of a Reference Architecture details the functional elements of an FG, as well as the interfaces and interactions among those elements. The Functional View is generally derived from the Functional Model, considering high-level requirements.

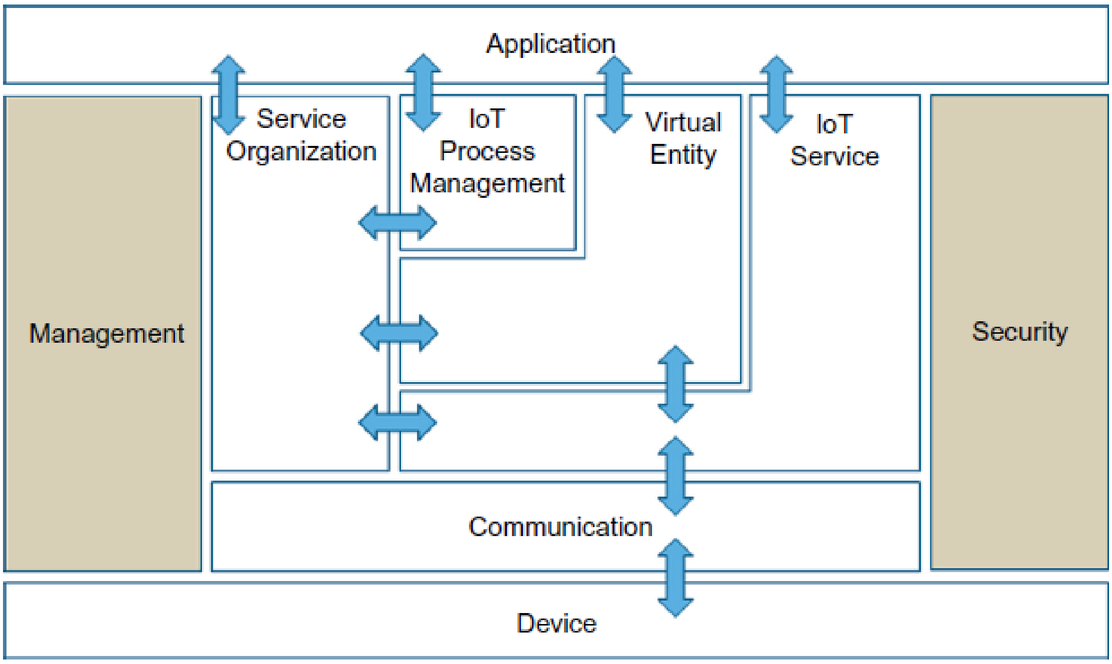


Figure 4.3 – IoT Functional Model

The most important functional groups are:

1. *Device Functional Group*: it encompasses all the functionalities provided by the physical devices employed to monitor the Physical Entities such as components for sensing, actuation, storage, and processing.
2. *Communication Functional Group*: The Communication Functional Group encompasses all potential communication methods utilized by relevant devices within a given system to convey information to digital components or other devices. These methods may include wired bus or wireless mesh technologies that enable sensor devices to connect to internet gateway devices.
3. *IoT Service Functional Group*: it encompasses individual IoT Services provided by Resources located on Devices or within the Network (for instance, processing or storage Resources). Additionally, support functions like directory services.
4. *Virtual Entity Functional Group*: it aligns with the Virtual Entity class in the IoT Domain Model and includes the required features to manage relationships among Virtual Entities as well as between Virtual Entities and associated IoT Services, specifically the Association objects in the IoT Information Model. These relationships can either be static or dynamic, depending on the movement of the related Physical Entities.
5. *IoT Service Organization Functional Group*: it is designed to bring together all the essential components that enable the integration and management of IoT and Virtual Entity services. Additionally, this FG serves as a central service hub, coordinating with various other functional groups, such as the IoT Process Management FG. Consequently, the Service Organization FG facilitates the linking of Virtual Entities to their associated IoT Services and includes functions for discovering, combining, and coordinating services.
6. *IoT Management Functional Group*: is a set of features designed to seamlessly connect IoT services (such as IoT Services, Virtual Entity Services, and Composed Services) with business processes within an organization.

7. *Management Functional Group*: it encompasses essential capabilities for monitoring system faults and performance, for configuring the system to adapt to evolving user requirements, for accounting and for managing ownership, administrative domains, rules and permissions for functional components, and data storage.

8. *Security Functional Group*: it encompasses the necessary elements that guarantee the system operates securely and manages privacy effectively. Additionally, it ensures the protection of sensitive information related to human users through various privacy mechanisms.

9. *Application Functional Group*: it encompasses the essential logic required to develop an IoT application and may function as a component of a larger Information and Communication Technology (ICT) system that utilizes IoT services.

4.4 IoT ARM in practice

As mentioned in the previous chapters, the IoT-ARM was introduced to create a common ground for the Internet of Things, to be applicable to a wide range of relevant domains, such as manufacturing, retails/logistics, healthcare and entertainment.

The IoT architecture reference model has been used to develop the following applications:

1. In seismic and volcanic studies to measure the level of CO_2 emissions from the soil, with the purpose of managing the risks of a possible eruption [119]. In this work, a LI-COR 830 sensor has been used to measure the CO_2 emissions, a technical infrastructure to allow communication and Internet of Things applications for monitoring purposes.
2. A framework for the development, design and generation of codes for the IoT systems [120]. In this application, the ARM has been integrated to obtain the domain model and the information model of the system.

3. A new architectural model for Smart Home environment [121]. The suggested architecture builds upon the IoT Architecture Reference Model (ARM) and includes reinforcement learning features aimed at managing the learning process, ensuring data governance, and overseeing general orchestration.

4. The SMARTIE platform architecture [122]. In this work, the IoT ARM has been used to provide guidelines for the development of the SMARTIE platform, designed to securely and efficiently share IoT data in smart city environments, while promoting security and interoperability.

5. The IoT Lab architecture [123], that utilized the IoT ARM (Architecture Reference Model) design framework to develop a preliminary architecture that incorporates the virtualization of crowdsourcing and testbed elements, along with the capability to connect and collaborate with other testbeds.

6. Semantic Interoperability Architecture [124]. In this architecture, the IoT ARM has been used to map the proposed semantic model, developed to allow devices to interact with each other by sharing semantic information.

7. Cyber physical architecture for the Social Internet of Vehicles [125]. In this work, vehicular networks components have been mapped into IoT architecture reference model to facilitate the share of information related to safety, comfort and efficiency between vehicles.

4.5 Framework for Digital Twin and Cobots in Industry 5.0

Motivated by the absence of frameworks for digital twin systems and Industry 5.0, [126] developed a new scheme based on the above mentioned IoT-ARM with the intent to implement a standard set of architectural tools for modeling an IoT architecture that prioritize digital twin while promoting the sustainability, resilience and human-centricity of the information system. Further, a digital twin for a vertical farming system has been developed to prove the validity of the proposed framework.

This work aims to adapt the model to a system that focuses on digital twins without using an IoT interconnection and to discuss and prove the validity of the application in the manufacturing sector.

4.5.1 General Overview

Consistent with the IoT Architecture Reference Model, the typical scenario provides a generic User that interacts with a Physical Entity (PE), as shown in Figure 4.4. The User can be a Human User, an application, a service or a software agent. The interaction between the two can be physical, when for example the human relocates an item from one place to another with the intent to achieve a certain objective, or can be mediated by a third-party intermediary, as a service or an application. In this last situation, the user uses a software entity with a user interface to invocate a service capable of performing an action upon the physical entity or capturing information. This is denoted as a service-oriented framework. The main limitations of using software interfaces to interact through services are related to technological, practical and ethical challenges. The key constraints include the necessity of compatible hardware components, connectivity problems such as communication delays or breakdowns, latency in response time and finally energy, security, privacy and resource constraints. These challenges can be mitigated through advancements in technology, strong security practices and careful design.

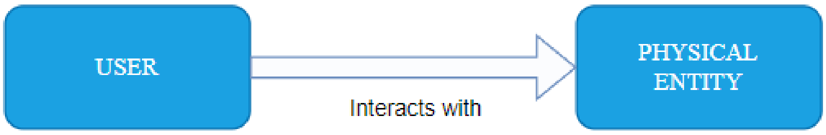


Figure 4.4 – Representation of the IoT interaction

The third main component of the model is the Virtual Entity, which is the virtual representation of the Physical Entity in the information system. This definition is closely linked to the digital twin concept, that consists of a set of adaptive models that replicate the behavior of a physical system in a virtual setting, with real-time updates allowing for the prediction of possible failures and the identification of potential opportunities for improvement. In this way, this emulation can suggest immediate actions, optimizing responses to unexpected events by closely monitoring and analyzing the system's performance. The key is the synchronized, bidirectional flow between the physical and virtual entities, which promotes proactive decision-making and enhances overall system efficiency.

Differently from the IoT-ARM, in the following framework the concept of Digital Twin has been used to represent the augmented entity, as well as the combination of the virtual entity and its physical counterpart.

To capture the complexity of the system, three models are required, as for the IoT-ARM. The domain model, that captures the main concepts of the system, the information model, that contains the conceptual information and the functional model, which identifies group of functionalities built on the core concepts of the Domain model.

Contrary to the IoT ARM, this framework does not present a security, trust and privacy model. This model defines a trust mechanism at application level for data confidentiality and identity validation, a security reference framework for service and communication security and a privacy sub-models to provide guidelines to prevent data misuse.

4.5.2 Domain model

The primary objective of the domain model is to document the critical components and relationships of a certain area to establish a common understanding for participants. Thus, the domain model describes the main concepts of a system. In addition, it describes the fundamental attributes of these elements, such as the name, the identifier and the relationships among them.

The main elements that serve as its foundational components to describe its characteristics are:

1. *Physical entity*. This type of entity refers to tangible and visible elements in the real world, such as animals, people and objects that are connected to the user's goals.

2. *Virtual entities*. Those entities are representation of the physical entity in the virtual environment. Those representations can have different forms, such as 3D models and can be classified in Active Digital Artifacts (ADA) or Passive Digital Artifacts (PDA). ADAs include software programs, agents, or services that interact with other resources, while PDAs refer to static software components that act as digital representations of physical entities.

To be classified as a virtual entity, it must satisfy two key criteria. Firstly, each virtual entity corresponds to a specific physical entity, while each physical entity can have multiple virtual entities. Secondly, any change in the physical environment must be mirrored in the virtual one and vice versa. Synchronization is a fundamental requirement.

3. *Devices*. They act as bridges between the digital world and the physical one, connecting virtual objects with real ones. Therefore, these devices need to work properly in both realms. In line with the IoT ARM mentioned above, devices can be classified in three main categories: sensors, actuators and tags.

4. *Resources*. They refer to software components that provide information from tangible objects or are pivotal to their functioning. In line with the IoT ARM, there are two different types of resources: On-Device Resources, that are installed locally and directly connected to physical entities and Network Resources, that can be assed via network.

5. *Services*. They act as the link between requirements and capabilities. They connect IoT services with non-IoT services. They offer a standardized interface that include all the necessary functions to manage resources and devices linked to Physical Entities. Services are classified in a tiered structure hierarchy, and they have a layered nature. The lower-level services are crucial because they interact with resources and are very close to the hardware part of the devices. They can be called by other services to perform more complex tasks.

When it comes to details, the domain model should differentiate between stable components and those who may change. It must remain stable, so it must focus on abstract representations without specifying technologies that may change.

Additionally, its abstract quality enhances its versatility across different sectors, such as the manufacturing one as shown in this work, and the fundamental components of the system are common across various industries, enabling the technology to be applied within different sectors.

This model is represented in Figure 4.5.

In the model a physical entity is connected to a smart device which is an electronic component that can connect, share and interact with both the user and other devices. It can contain sub-device classes such as sensors or actuators to monitor or influence the real environment and can leverage Network Resources or can host internal ones. The physical entity is represented in the virtual environment through a virtual entity which can evolve into a digital twin. The user can access the resources (including those associated with the virtual entity) through services.

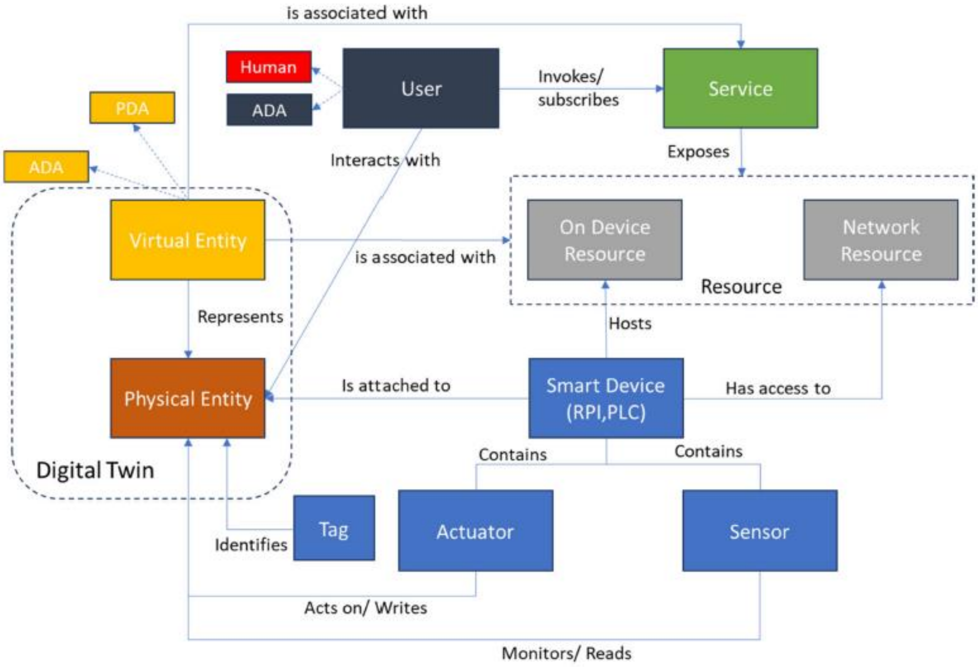


Figure 4.5 – Representation of the domain model

4.5.3 Information model

The information model contextualizes data, provides answers to key questions like who, what and when and describes the structure of the data handled by the system. The information model offers insights into how a virtual entity is structured.

As shown in Figure 4.6, the information model defines the attributes of the virtual entity, as well as the name, type and metadata values (e.g. the quality, the unit of measurement or the location and time at which it has been digitized). In addition, the information model provides the description of the service which is used by the virtual entity to access information. A service description outlines details about the service and its interface. It can also contain the resource descriptions related to a resource that the service exposes, while the resource description may offer information about the device that hosts the resource.

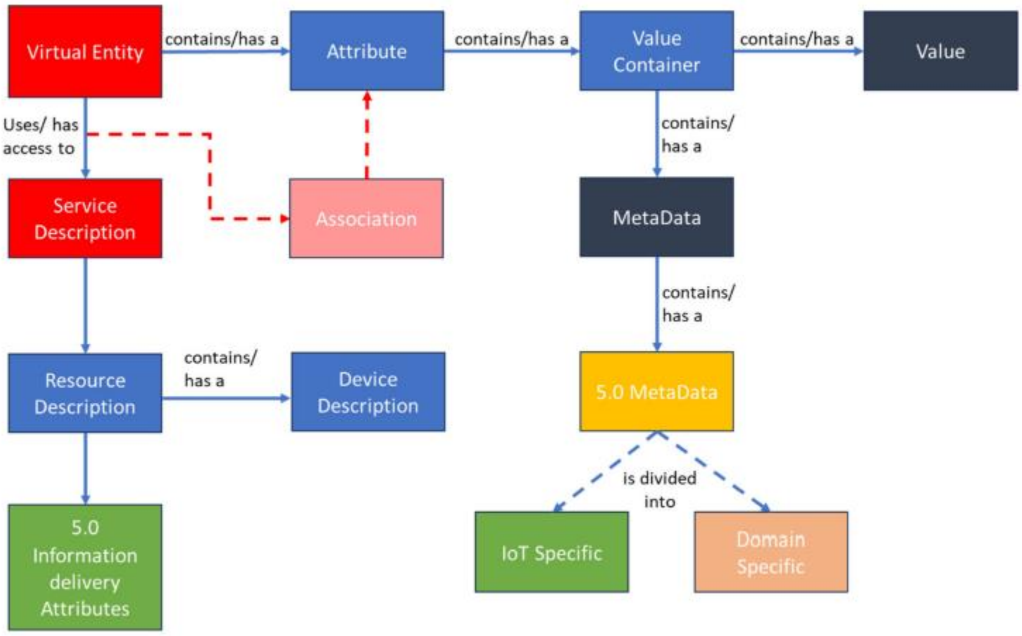


Figure 4.6 – Representation of the information model

To align the IoT-ARM with the industry 5.0 standards, this model proposed a framework for the Metadata component, which will house the metadata associated with the industry 5.0 requirements. It's important to mention that they will be categorized as Metadata rather than attributes because once industry 5.0 information is integrated into the virtual entity, they align with the concept of metadata, defined as "information about the value of a piece of information".

The industry 5.0 requirements are mainly non-functional ones, related to aspects that users cannot directly see. Those requirements must incorporate the three pillars of Industry 5.0, as well as sustainability, resilience and human-centricity. The proposed model is designed not only to enable the evaluation of system's adherence to these requirements, but also as a base to develop metrics or indicators to measure compliance with industry 5.0 standards.

1. Human centricity. This first pillar emphasizes the importance of considering human needs, motivations and beliefs during the implementation phase of these processes. This approach must be applied in all the systems that involve the presence of humans. The principles are

two, indeed fostering human potential and prioritizing human welfare and are based on key aspects, such as:

- Highlight the collaborative role of both designers and human users in shaping the overall experience, fostering active participation that combines human creativity with technological innovation.
- Recognize that human users are part of a societal context, where their experiences and collective knowledge inform the operational processes of a system.
- Cultivate an environment that encourages individuals to harness their self-direction and creativity.
- Appreciate individuals beyond their mere function as "users," acknowledging their diverse needs and contributions, and moving beyond standard labels.

2. Sustainability. The principle of sustainability relies on three pillars, as well as:

- The environmental component, measured through environmental key performance indicators (KPIs) like carbon footprint and energy usage per message sent.
- The economic sustainability aspect, which looks at the cost of transmitting information, such as the expense related to sending a message.
- The social impact, particularly regarding users beyond the immediate system limits.

3. Resilience. This requirement refers to the capability of a system to endure and recover its functionalities from failures, interruptions or harmful actions. Despite implementing resilience features in systems can be difficult, as they can create limitations for developers, this notion plays a vital role in both the design and the functioning of a system, especially when it has a very intricate and changing nature and is embedded in essential infrastructures. Resilience, or the capacity to remain robust and adaptable to disturbances, can be characterized by the following attributes:

- The ability to adjust to disruptions,

- An adequate level of scalability,
- The expected quality of the transmitted data.

4.5.4 Functional model

According to the IoT-A project, the Functional model serves as "an abstract framework for understanding the main Functionality Groups (FG) and their interactions". The main goals of Functional Decomposition are two: to simplify the IoT ARM systems into smaller and more manageable parts, and secondly to illustrate how these parts are interconnected the one with the others.

The presented functional model is based on the functional model proposed by [126]. It differs from the IoT ARM functional model because it replaced the "virtual entity management" with "digital twin management". Also, in this model the "IoT Process Management" and "the IoT service" are replaced with "Smart Process Management" and "Smart service", because the functionalities provided by the IoT interconnection are provided by the software used.

As shown in Figure 4.7, the functional model addresses nine layers, defined as Functional Groups.

The first layer is the device layer. It is connected to the physical entity and supplies the hardware elements that interact with physical objects, like sensors and actuators. The last layer is the application layer, that facilitates the user interactions.

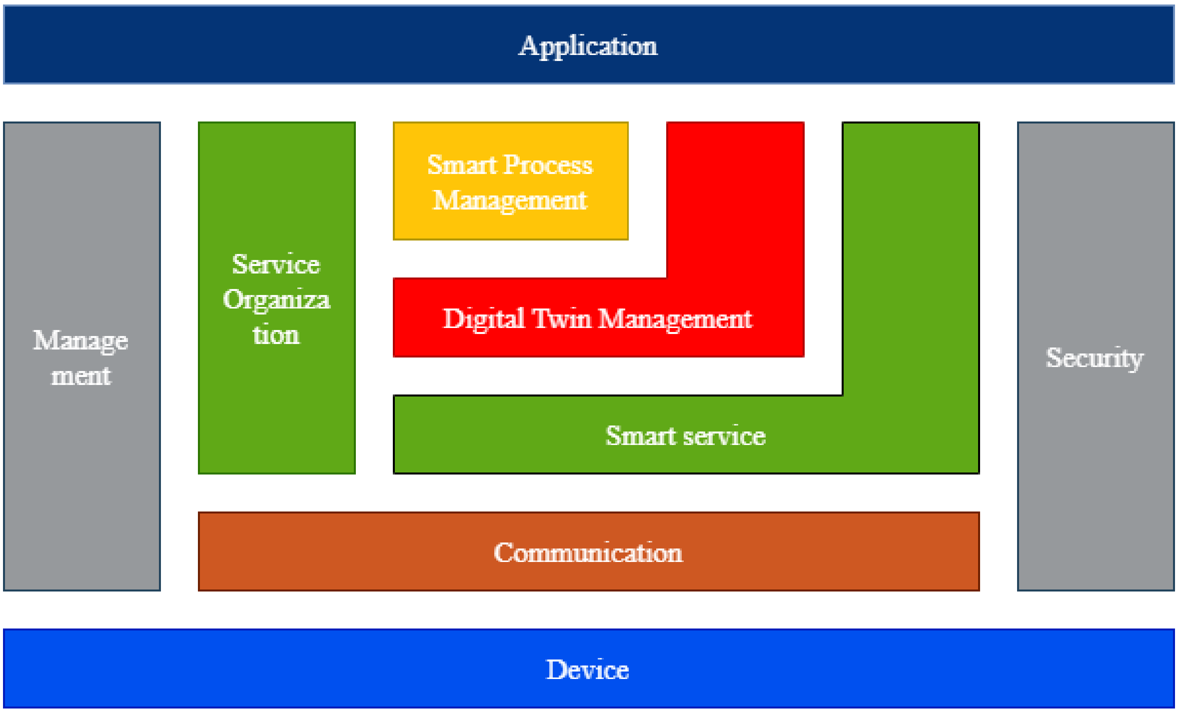


Figure 4.7 – Representation of the functional model

The communication layer governs the interactions of the different components and enables the transfer of information between the devices and the resources, allowing the communication to take place. It provides an abstract scheme to generalize the interaction within the device functional group and creates an interface for the service functional group. It covers various elements of the ISO/OSI communication model, addressing issues related to data representation, end-to-end routing, and network management. In this way, abstraction simplifies the management of the information flow and governs the interactions among different components.

The smart service layer enables the retrieval of data from sensors or the transmission of commands to control actuators devices. The service layer serves to make accessible the capabilities related to these sensors and actuators, such as the monitoring and control of specific elements in the physical environment.

The Digital Twin management layer provides all the information about the digital twin acquired from databases, sensors or applications. It also provides the capabilities to oversee the synchronization aspect with physical objects.

The smart process management group provides the functional concepts to integrate process management activities within the system. This layer creates the modeling of business processes that are specific to the business environment and to the software functionalities used to manage the system. Services are used to execute process models into the environment.

The security level guarantees the safety and privacy of both users and system. It protects users' personal information, facilitates its registration, guarantees authorized interactions between users and overseas secure communication between them.

The service organization layer serves as a central point of connection between the various functional groups. It is used by the Software Management FG to align the general and abstract process definitions to more concrete service invocations. In a few words, it facilitates the conversion of high-level requests to specific services, therapy connecting the management of the digital twin to the software service layer.

The last layer is the Management layer. It is important for the management and supervision of the aspects related to Industry 5.0 principles. This includes the setup and configuration of the system (such as communication protocols and devices integration), the management of strategic support decisions and of functionalities execution (such as the implementation of strategies that are aligned with the objectives of Industry 5.0 regarding human-centricity, sustainability, and resilience) and finally the monitoring of errors and system health, e.g. through real-time sustainability evaluations and tracking activities to guarantee system performance.

To support the management group, the following functions should be made sustainable: it’s important to promote adaptable work conditions for flexibility concerns, to facilitate an open dialogue between the team members, to motivate employees and to offer educational conditions. Also, it’s important to improve a reward system, to create an inclusive environment for individuals from different backgrounds, to provide all the necessary tools for individuals and to support a culture that values learning from mistakes.

5. Case Study

5.1 Case Study presentation

This chapter will present and discuss the case study that has been used to finalize this work. As mentioned previously, one of the core components of Industry 4.0 elements is the Digital Twin, which is the virtual representation of a physical system. It represents all the functional characteristics of the physical environment. Also, it's constantly synchronized with its changes and can predict future outcomes through machine learning models.

The use of simulation models in manufacturing areas has become more and more popular during the past years. This popularity is expected to growth in the future. Indeed, a 2020 study by Research and Markets indicates that digital twins will be included by 89% of all the IoT platforms by 2025. It will be a standard IoT feature by 2027 and around 36% of all the industries understand its benefits, with half of them plan to implement it in their future business by 2028 [127].

In manufacturing applications, the use of DT can serve as an important tool to support decision-making to solve industrial problems. Some examples of DT applications in this field are provided by [128]. It can be used to develop innovative products and to monitor them during their total lifecycle. In this way, designers can better understand product's feasibility and features and companies can spot abnormalizes and deviations to improve product's performance. Digital Twin can also be used to predict maintenance to improve product's durability. In this way, the time-to-service can be reduced, as well as the costs of assets breakdowns.

Finally, DT can be used to solve a crucial optimization problem in production [129]: dynamic tasks allocation and scheduling. As the production environment becomes more and more dynamic, it has become very difficult to obtain the production status in real time to make reasonable plans. The application of DT has made it possible the transition from static to dynamic scheduling. A digital twin enables rapid reactions to disruption events, such as order cancellations or machine breakdowns, to adapt the actual production plan to new situations as they arise. The dynamic scheduling can be of three different types: reactive, when decisions are based on the real time state of the production, robust, when an initial schedule is elaborated considering future disruptions' predictions and finally predictive-reactive scheduling, which is the result of the combination of the reactive and robust scheduling. It combines forecasting methods to foresee possible disruptions and real time features to quickly adjust the schedule to unforeseen events.

The situation that will be proposed in this case study has been practically implemented in the Mind4lab laboratory of the Politecnico di Torino and is as follows: it is about a production line, made of two parallel UR3e robots which are supposed to perform in loop for several time the same simple task with the same speed. They pick an item from a starting point and place it in the finishing point. All parameters relevant to the production plan are artificially provided, including units to be produced and the processing time. In the best-case scenario, tasks are allocated equally between the two robots, and they process the same number of items within the same period, without making any changes in the initial production plan. A third UR3e robot is used to mitigate the effect in case of delay of one robot and reallocate items in an optimal way to increase the performance of the system.

The manufacturing system in which they operate is characterized by a high degree of technology, that allows to solve industrial problems that can arise during production. The production chamber is characterized by a few sensors and an actuator which are connected to a programmable logic controller.

A digital twin for monitoring purposes is created at the production line level and acts as a decision-making tool when changes are detected in the physical system to minimize their consequences. In this case study, the simulation model mirrors the real environment and is composed of two sources, three queues and three robots. It is used to detect the robot's delay and to send a signal to the third robot, which performs scheduling changes and reallocates the items in an optimal way.

Also, in this case study DTs can help the operator of the production line get information of the behavior of the system and compare it with different scenarios to state that various benefits can be achieved through its application.

5.2 Manufacturing system domain model

As discussed in the previous chapter, the domain model provides a base for the other two sub-models (respectively information and functional models) by defining a common classification system for the key concepts and their relationships. It distinguishes between *physical entities*, which are tangible objects in the real world, and *virtual entities*, which digitally represent these objects. The model incorporates *devices* that bridge the gap between the digital and physical worlds, focusing on their functional capabilities in observing and modifying physical environments. Additionally, it differentiates between on-device *resources*, found locally on devices, and network resources, accessible online, highlighting their roles. Resources refer to software elements that either supply data from physical objects or play a crucial role in their functioning. *Services* in this framework connect components with broader information systems, establishing a layered structure where low-level services interact directly with hardware, enabling higher-level functionalities and business processes. Utilizing the modeling tools outlined earlier, a domain model is developed for the production line system.

1. The starting point, which is the *physical entity*, consists of the production line, made of three machines. Those machines are three collaborative robotic arms capable of performing

the pick and place action. Collaborative robotics, also known as Cobots (from mechanically COmpliant roBOT), are robots designed for direct interaction with humans [130]. Specifically, UR3e robot is a versatile, lightweight and easy to deploy collaborative robot designed to enhance automation processes while maintaining safety in a collaborative environment by Universal Robots. Its total weight is around 11.2 kg, and its form factor makes it easily portable, allowing the deployment in multiple environments. It can handle loads of up to 3 kg and its reach is 500 millimeters.

As shown in Figure 5.1, the UR3e robot's tubes and joints are central for its design, allowing for fluid motion and versatility. It has a six-axis articulated arm that enables the execution of a wide range of delicate and accurate movements. Each joint operates smoothly, and the design allows to perform both linear and rotational movements. Each robot has its own teach pensant, which is a pivotal component with an intuitive interface for user interaction to program and control the robot with minimal training. It has a touchscreen display that allows the user to set up tasks and adjust parameters.

Press and hold the Three Position Enabling device in order to proceed

Figure 5.1 – UR3e collaborative robot and its Teach Pendant

Two of them (UR3e_Robot1 and UR3e_Robot2) were programmed to work in parallel, while the third one (UR3 CB_Robot3) was programmed to intervene only if one robot is causing a delay and to reorganize the production in an optimal way.

Their behaviors are monitored by a few sensors that transmit data to a programmable logic controller, which is also responsible for managing an actuator that interacts with the physical entity to create optimal production conditions.

2. The physical entity is mirrored by a *virtual counterpart*, and together they form what is known as a digital twin. The virtual entity is represented graphically by FlexSim, a powerful software for material handling simulation modeling. As shown in Figure 5.2, the virtual system mirrors the organization of the physical production line. The components that are not present in the real system are added in the simulation model to guarantee the right functionality of the process.

Starting from the bottom, two sources (respectively Source1 and Source2) are used to generate the batch of seven items at an arrival time set equal to zero.

Moving to the upper part, three queues (respectively named Queue_Robot1, Queue_Robot2 and Final_Queue) are used to indicate the starting and ending positions where the robots in the physical system carry out their pick-and-place tasks. Queue_Robot1 and Queue_Robot2 receive the seven items from the two sources to be processed by the robots in the moment they are generated, while the Final_Queue is in common between them and receives the items processed by the UR3e_Robot1 and the UR3e_Robot2.

To represent UR3e_Robot1, UR3e_Robot2 and UR3 CB_Robot3 three processors' components have been used. Then, the shape and the appearance of the processors has been modified through a panel to make them as similar as possible in shape to the real components. The reason was because processors offer a wide range of functions, particularly when paired with the emulator tool, while the robot component is a task executor and as such it wouldn't yield valuable data if linked to the emulator.

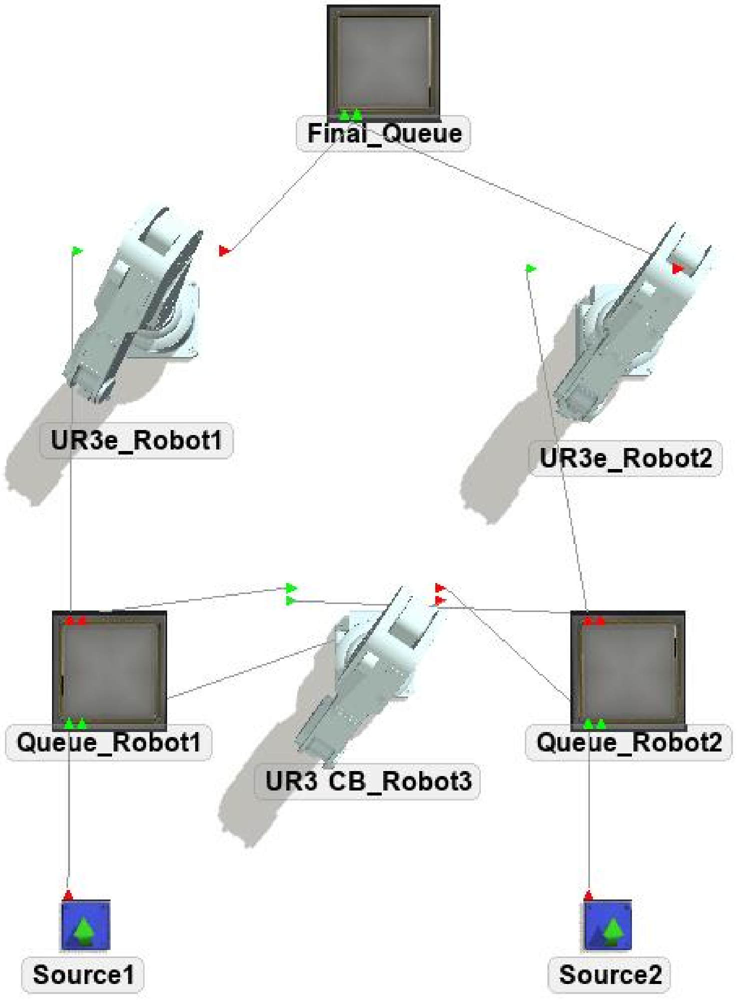
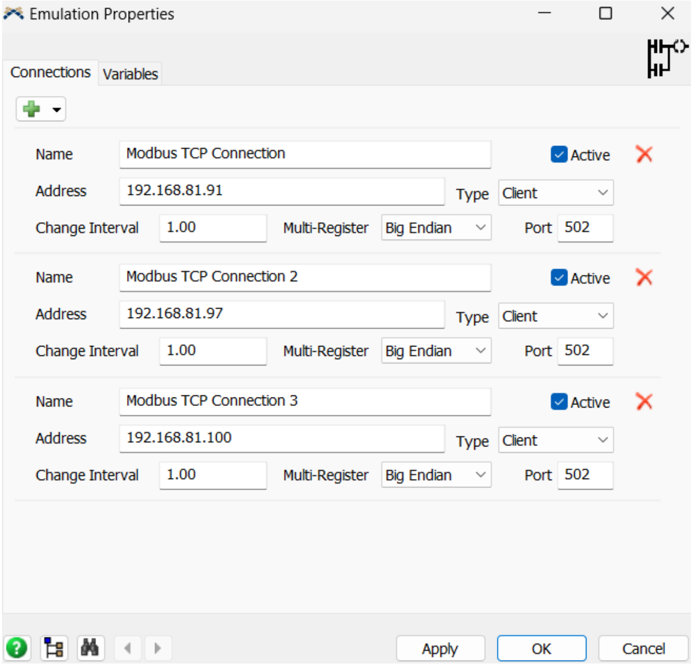


Figure 5.2 – Virtual representation of the production line

Virtual elements are connected to create a downstream product flow using the tool Connect objects, A-Connects. In this way, each single object is equipped with an input and output ports, represented respectively by the small green and red triangles. The orientation of the triangles defines the direction of the flow of items.

3. As shown in Figure 5.3, the *connection* between the physical and the virtual entity is established by the emulation tool of FlexSim, used for simulating programmable logic controller (PLC) within the software. The Emulation tool, accessible from the Toolbox, establishes a bridge between FlexSim and the robots' PLCs. In the chart below the generic name PLC has been used to indicate the control system used, without reference to whether it was emulated or not.



Name Modbus TCP Connection ☑ Active
Address 192.168.81.91 Type Client
Change Interval 1.00 Multi-Register Big Endian Port 502

Name Modbus TCP Connection 2 ☑ Active
Address 192.168.81.97 Type Client
Change Interval 1.00 Multi-Register Big Endian Port 502

Name Modbus TCP Connection 3 ☑ Active
Address 192.168.81.100 Type Client
Change Interval 1.00 Multi-Register Big Endian Port 502

Figure 5.3 – FlexSim emulation tool

FlexSim supports the Modbus TCP protocol to establish the connection, which is indicated in the name file. An IP address is used to send data packages and in the address field is indicated the IP address of the three robots in the form of 190.123.10.1, which is respectively 192.168.81.91, 192.168.81.97 and 192.168.81.100.

The performance of the robots is monitored by *sensors*. Sensors are devices that detect and measure physical properties and convert this information into signals for monitoring or control. Based on this definition, in this the case study the robot's PLCs connected with the robot's grips have been identified as sensors. They are used to synchronize the pick and place of the containers in the physical environment with the simulation one. They control in real time the production system. Specifically, they send a signal of 1 when a container is grabbed in the real environment and a value of 0 when the container is placed in its destination. In this way, when the simulator receives a 1, the virtual robot associated with the physical grips starts to work the item till the moment in which it receives a 0. In that moment, it realizes the item and stops working until the signal is received again, ensuring synchronization between the virtual and the physical sphere.

For the sake of simplicity, the name Robot's PLCs grips will be used to identify the PLCs connected to the grips of the robots, which are used as sensors.

The emulation tool also controls an *effector*, which is a component of a system that implements physical actions as a response to commands. Based on this definition, because the robot's PLC connected with the robot UR3 CB_Robot3 receives a signal to act on the physical environment when one robot is causing delay, it has been chosen as the effector of the domain model.

Specifically, it reorganizes the production in an optimal way. A code has been written in the FlexSim process flow to recognize whether a robot is in delay or not. If the number of items in queue is greater than the number of items that should be there based on the planned rate of production, a command is sent to activate the actuator in the real environment. It retrieves the remaining items from the robot that causes delay and hands them over to the faster one.

For the sake of simplicity, the name Robot's PLC UR3 CB_Robot3 will be used to identify the PLC connected to the third robot, which is used as an actuator.

4. The virtual entity is associated with *services* that either supply data to the virtual entity or receive data from it. In this case study, four types of services are available to the simulation model. The first is a monitoring service, that acquires sensor data from the physical entity to

synchronize the movements of the robots in the simulation accordingly. The second is the control service, that invokes a change by triggering the third robot in the physical environment to optimize production. An analysis service is used to acquire data from the virtual entity for visualizing a dashboard with data charts. Finally, the last service is the task allocation service, that invokes the three services mentioned above. It invokes the monitoring service to acquire information about the status of the production line, the analysis service to obtain specific metrics that allow to study the performance of the system in real time and finally the control service, to reorganize the production.

5. All those services expose a set of *on-device resources* hosted by PLC. Those resources are communication software, for providing communication functionalities, sensor drivers to acquire data, control logic to process them and evoke actuations to trigger actuators to optimize the process.

The *user* of the system is a human who can be an operator of the production line or a researcher that invokes the analysis service and compares data in the dashboard with different scenarios to state that various benefits can be achieved through the application of a Digital Twin in manufacturing systems.

Utilizing the modeling tools outlined in the earlier sections, the domain model developed for the manufacturing production line is presented in Figure 5.4.

The line ending in an empty diamond shape is also known as Aggregation and illustrates a relationship where one entity, in this case the entity On-device Resource, is a component or part of a larger entity, in this case Smart Device.

The simple line ending with a standard arrowhead is known as Directed Association relationship. This symbol indicates that the class from which the arrow starts (e.g. Human User) can navigate to the other (e.g. Service). This navigability signifies that objects of the entity Human User possess the necessary attributes to recognize their relationship with the objects of the entity Service, while the opposite is not the case; objects of class Service can exist independently without any references to objects of class Human User.

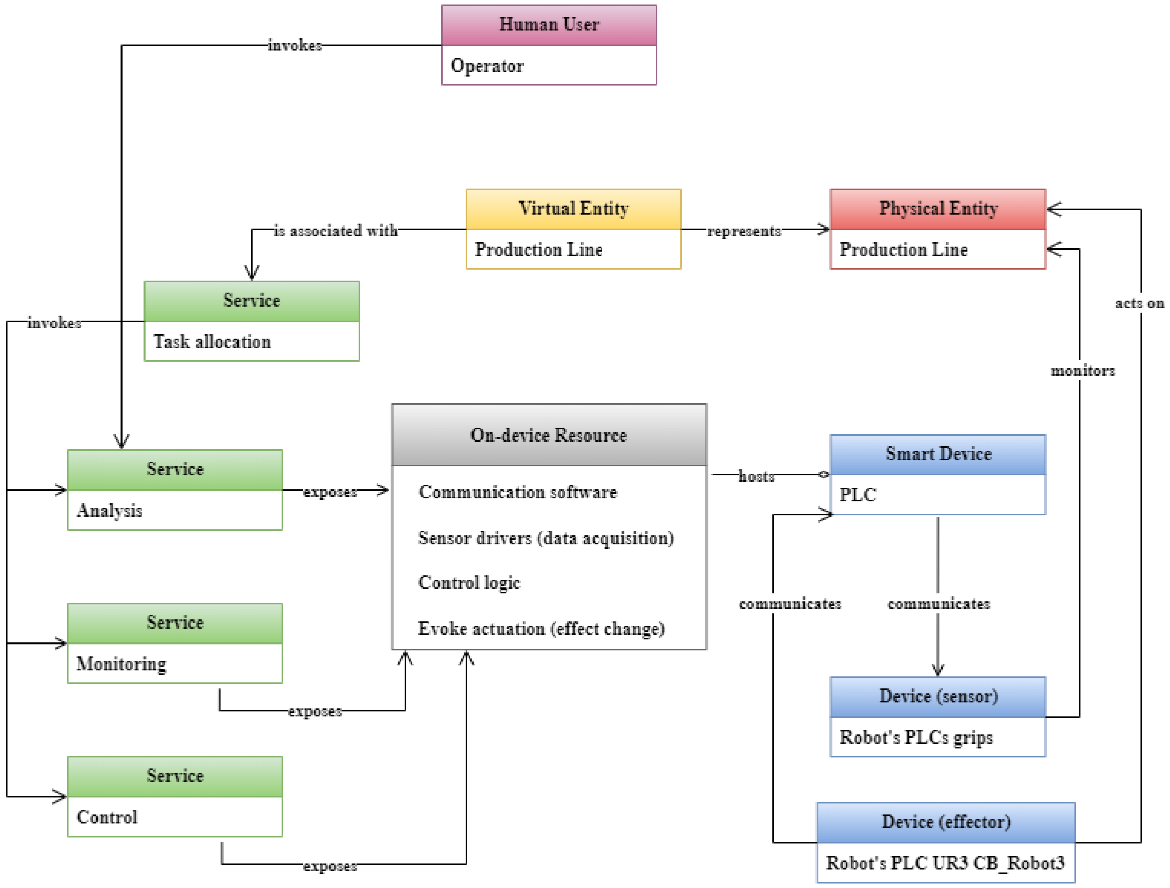


Figure 5.4 – Manufacturing System domain model

5.3 Manufacturing system information model

The information model provides additional information to data. It outlines the conceptual organization of the information handled by the virtual entity: its structure, relationships, and attributes, as well as the associated services. Using the established information model, an information view tailored to this use case has been developed.

The information structure of the digital twin is very simple. The starting point of the digital twin is the physical production line represented by a virtual entity, named "Production Line", made of two sources, respectively Source1 and Source2, two queues (one for each robot that processes items), Queue_Robot1 and Queue_Robot2, two robots that process items, UR3e_Robot1 and UR3e_Robot2, one robot that reorganizes the production in case of time failure, UR3 CB_Robot3, and one final queue which is common to both robots, Final_Queue.

As mentioned above, the two sources are used to mirror what happens in the physical sphere, as well as to generate in the virtual environment the batch of seven items to be processed.

The three queues are used to mirror in the virtual sphere the starting and ending positions where the robots in the physical system carry out their pick-and-place tasks.

The production line contains attributes with a name, a type and the relevant information pertaining to the specific twin. Information is taken or provided from the digital twin via services and an association is used to map the information of the service to a specific attribute.

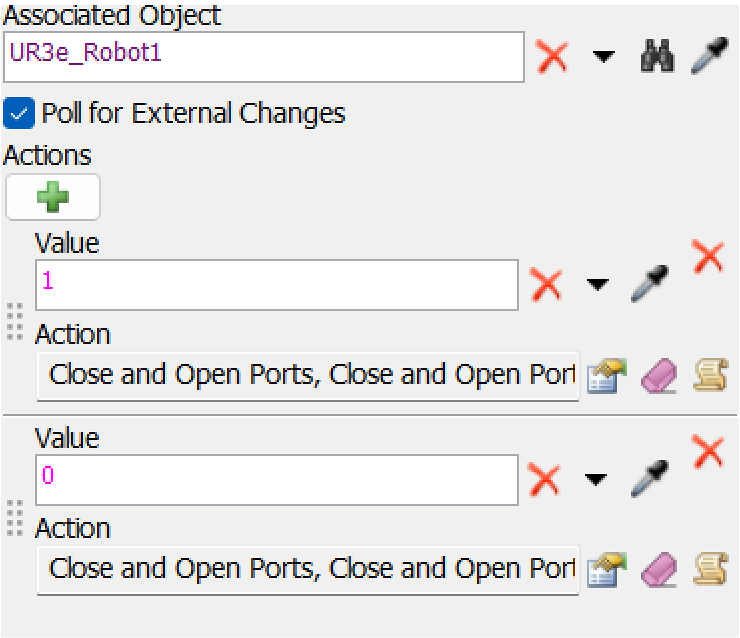
The type of information stored in the digital twins' attributes can either provide qualitative indicators about the physical entity (i.e. KPIs) or can refer to its specific conditions. To this end, they can be grouped as follows:

1. Status attributes that provide information about the real-time conditions of the physical entity, i.e. of the production line.

There are three identical status attributes, named Cycle 1, Cycle 2 and Cycle 3, one for each robot. For sake of simplicity, in the chart below is indicated the one related to robot UR3e_Robot1.

As shown in Figure 5.5, the value of the attributes is a Boolean value and can be 0 or 1, based on the signals sent by the robot grips. 1 when a container is grabbed and processed in the real sphere, and 0 when it is placed in its destination. This value controls the robot in the virtual sphere. Indeed, when a 1 is received, the process flow triggers the virtual robot associated with the physical one and an item is released till the moment in which a value equal to 0 is received.

Those attributes are acquired through the monitoring service invocated by the task allocation service with the intent to synchronize the movements of the robots in the simulation accordingly.



Associated Object
UR3e_Robot1

☑ Poll for External Changes

Actions

Value
1

Action
Close and Open Ports, Close and Open Port

Value
0

Action
Close and Open Ports, Close and Open Port

Figure 5.5 – Attributes associated with the UR3e_Robot1

2. Productivity attributes which are KPIs that provide an evaluation of the performance of the process over time.

For sake of simplicity, in the chart below are indicated the ones related to robot UR3e_Robot1, but the same exists for robot UR3e_Robot2.

The attributes identified to compare results and to evaluate the performance of the process are the following:

- Throughput rate (TH): it represents the number of completed items leaving the system per unit of time. The unit of measurement is item per second.

- Cycle time (CT): it represents the time required to complete a process. In this use case, it represents the time required to process all the seven items of the system. The unit of measurement is second.

- Work in process (WIP): it represents the number of items currently in progress within a system, that are either actively being processed or are in line waiting to be processed. The unit of measurement is items.

- Utilization: it represents the extend of time a machine is in use. This time includes the time required to process items, the setup time and any possible breakdown time. The unit of measurement is second.

As shown in Figure 5.6, after each simulations those parameters can be viewed through the analysis service invocated by the task allocation one on a dashboard. The visualization happens without interrupting the execution of the process thanks to the animation tool provided by FlexSim. Also, the application allows the user to change the graphs or their layout in the dashboard.

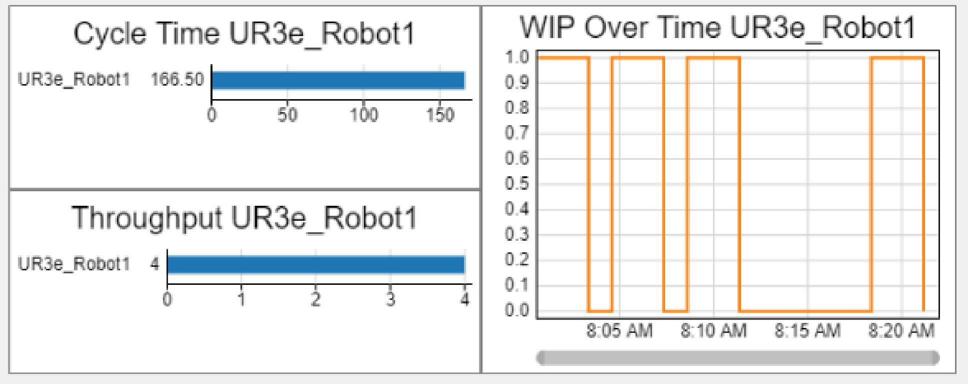
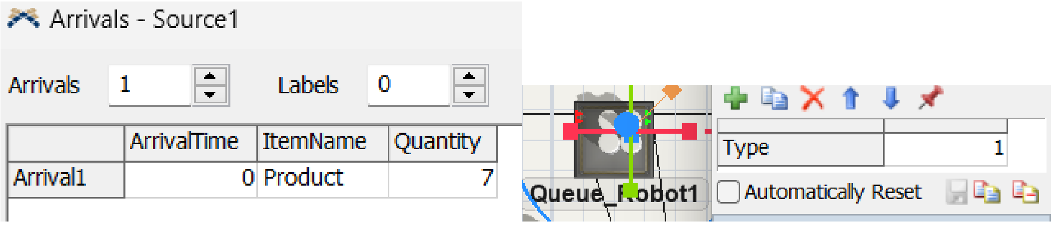


Figure 5.6 – Example of TH, CT and WIP dashboard

3. Configuration attributes, which refer to the setting of the manufacturing line.

As shown in Figure 5.7, the attribute Quantity contains the total number of items created at the beginning by each source, i.e. the number of items that should be theoretically processed by each robot if the system worked properly, without any time failure. In addition, an attribute Type is associated with each item on the entrance to the queue (before being processed by robots). If the item enters in Queue_Robot1, its Type value will be 1. Otherwise, if it enters in Queue_Robot2, its Type value will be 2.



Arrivals - Source1

Arrivals 1 Labels 0

	ArrivalTime	ItemName	Quantity
Arrival1	0	Product	7

Type	1

☐ Automatically Reset

Figure 5.7 – Quantity and Type attributes

The last two configuration attributes, Type1Content and Type2Content, are associated to the Final_Queue and contain the number of items processed respectively by UR3e_Robot1 (Type1Content) and by UR3e_Robot2 (Type2Content) at a certain moment. If the item processed belongs to Queue_Robot1 (i.e. Type==1) then Type1Content is automatically incremented, otherwise Type2Content.

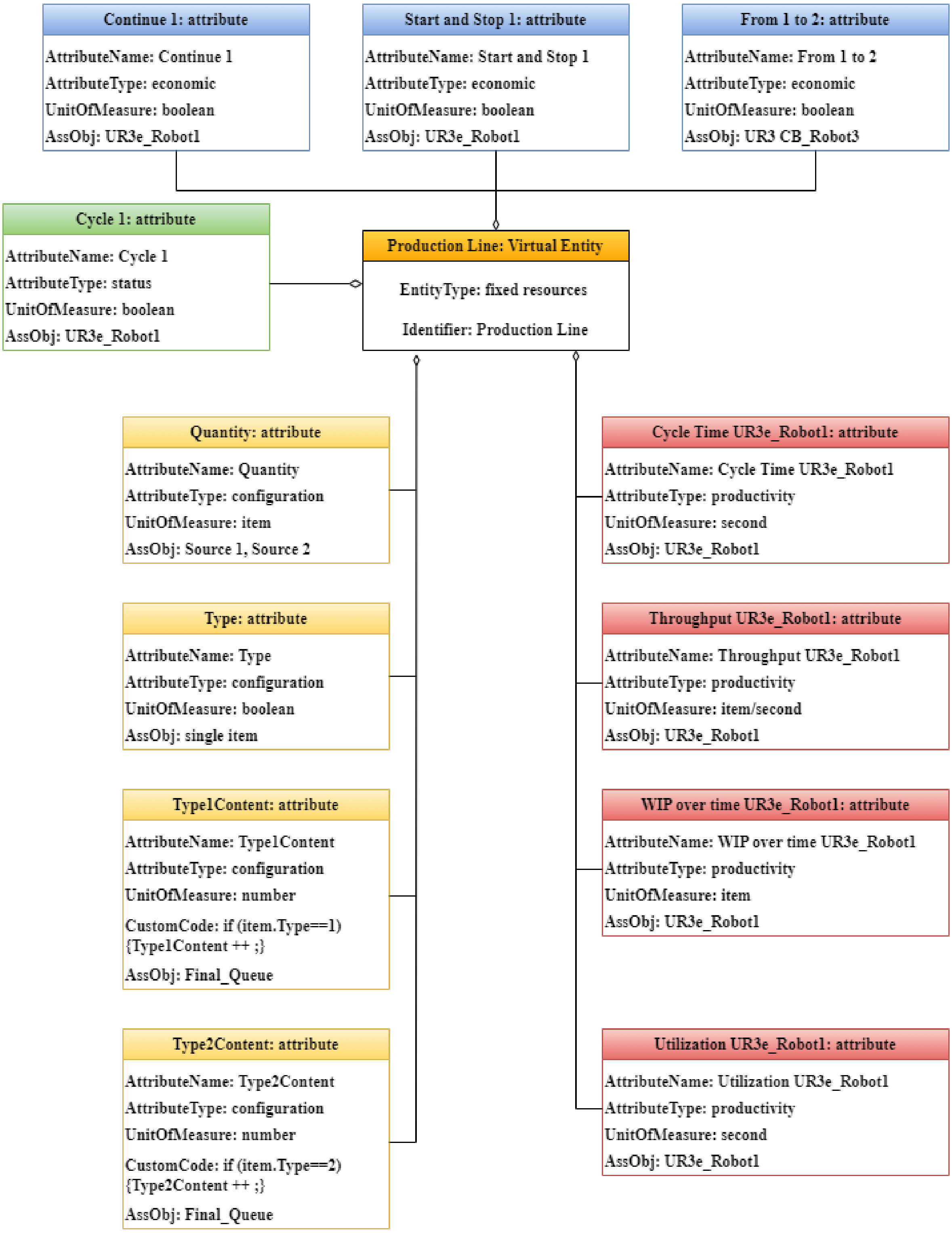
Those attributes will be used in the control logic through the controlling service for reorganizing the production.

4. Economic sustainability attributes, that take into consideration the optimization of the process.

The value of the attributes Continue 1 and Star and stop 1 can be 0 or 1. These values are caught by real robots and are used to change their behaviors though the control service to reorganize the production. For sake of simplicity, in the chart below are indicated the ones related to robot UR3e_Robot1.

The attributes From 1 to 2 and From 2 to 1 contain a value that can be 0 or 1. Based on these values, the UR3 CB_Robot3 will be triggered in the real system.

Utilizing the modeling tools outlined in the earlier sections, the information model developed for the manufacturing production line is presented in Figure 5.8.


Continue 1: attribute
AttributeName: Continue 1
AttributeType: economic
UnitOfMeasure: boolean
AssObj: UR3e_Robot1

Start and Stop 1: attribute
AttributeName: Start and Stop 1
AttributeType: economic
UnitOfMeasure: boolean
AssObj: UR3e_Robot1

From 1 to 2: attribute
AttributeName: From 1 to 2
AttributeType: economic
UnitOfMeasure: boolean
AssObj: UR3 CB_Robot3

Cycle 1: attribute
AttributeName: Cycle 1
AttributeType: status
UnitOfMeasure: boolean
AssObj: UR3e_Robot1

Production Line: Virtual Entity
EntityType: fixed resources
Identifier: Production Line

Quantity: attribute
AttributeName: Quantity
AttributeType: configuration
UnitOfMeasure: item
AssObj: Source 1, Source 2

Type: attribute
AttributeName: Type
AttributeType: configuration
UnitOfMeasure: boolean
AssObj: single item

Type1Content: attribute
AttributeName: Type1Content
AttributeType: configuration
UnitOfMeasure: number
CustomCode: if (item.Type==1) {Type1Content ++ ;}
AssObj: Final_Queue

Type2Content: attribute
AttributeName: Type2Content
AttributeType: configuration
UnitOfMeasure: number
CustomCode: if (item.Type==2) {Type2Content ++ ;}
AssObj: Final_Queue

Cycle Time UR3e_Robot1: attribute
AttributeName: Cycle Time UR3e_Robot1
AttributeType: productivity
UnitOfMeasure: second
AssObj: UR3e_Robot1

Throughput UR3e_Robot1: attribute
AttributeName: Throughput UR3e_Robot1
AttributeType: productivity
UnitOfMeasure: item/second
AssObj: UR3e_Robot1

WIP over time UR3e_Robot1: attribute
AttributeName: WIP over time UR3e_Robot1
AttributeType: productivity
UnitOfMeasure: item
AssObj: UR3e_Robot1

Utilization UR3e_Robot1: attribute
AttributeName: Utilization UR3e_Robot1
AttributeType: productivity
UnitOfMeasure: second
AssObj: UR3e_Robot1

Figure 5.8 – Manufacturing system information model

Each of the attributes presented in the manufacturing system information model contains the following fields: attributeName, attributeType, the unit of measurement and the associated object in the virtual model (AssObj).

The attributeName refers to the name of the attribute, while the attributeType refers to one of the four groups identified above, which are: status, productivity, configuration and economic sustainability. A different color has been selected for each category of attribute. The Productivity attributes Cycle Time, Throughput, WIP and Utilization are shown in red. Status attributes are in green, Configuration in orange and Economic Sustainability in blue. Every attribute is associated with a value container that holds both its value and the related metainformation. Metainformation includes, for instance, the time and place of digitization, the quality of the process and the unit of measurement.

For what concerns the description of the metainformation structure it will just be described the one for the attribute Cycle1.

As shown in Figure 5.9, the attribute Cycle1 has a value container, which has a value that can be 0 or 1 and has zero-to-many information that is related to the value by means of metadata. The metadata can be classified in two categories: general and industry 5.0-specific metadata.

The general one contains files such as the service and the device that delivered the information and the resource used to obtain it. Specifically, the monitoring service, invocated by the task allocation service, has been used to obtain those information. For what concerns the resources, the ones used are communication software, for providing communication functionalities and sensor drivers to acquire data, while the device used was the Robot's PLCs grips.

The industry 5.0 one contains information about the sustainability, human-centricity and resilience of the delivered information. In terms of human-centricity, two metrics have been adopted: the human factor for the cooperation and coordination between humans and robots, and the presence of sensors for supporting human needs. Sensors are used to monitor reality and to identify threats as quickly as possible to trigger actuators in critical scenarios. In this sense they act as human supporters: based on what should be the theoretical behavior of a system, they are able to catch possible differences and to trigger solutions to correct them. For sustainability three indicators are taken into consideration for two of the three pillars: for environmental sustainability the average carbon footprint and the energy consumed per bit and for the economic aspect the metric-average per bit delivery cost (APBDC). Finally, for resilience, two metrics are used: the quality level of data sent and the ability to identify faults and to adapt to disturbances (level of scalability). To assess the quality of data sent it has been considered the robustness and the reliability of the communication network, which is the Modbus TCP connection. In particular, the system relies on an error detection mechanism for detecting errors.

The second indicator is based on a scale from 0 to 5, which is used to rank the capabilities of the process: 0-standalone, 1-descriptive, 2-diagnostic, 3-predictive, 4-prescriptive, 5-autonomy.

A standalone system (0) represents reality without any connection with it, while a descriptive one (1) involves the connection and an exchange of data at any time. A diagnostic system (2) presents diagnostic information that allows to monitor the reality and to troubleshoot. A predictive system (3) can support prognostic capabilities and predict the system's future states, while a prescriptive one (4) can provide instructions and advice based on risk analysis and what if scenarios. Finally, an autonomy system (5) can make decisions and execute control actions in a completely autonomous way.

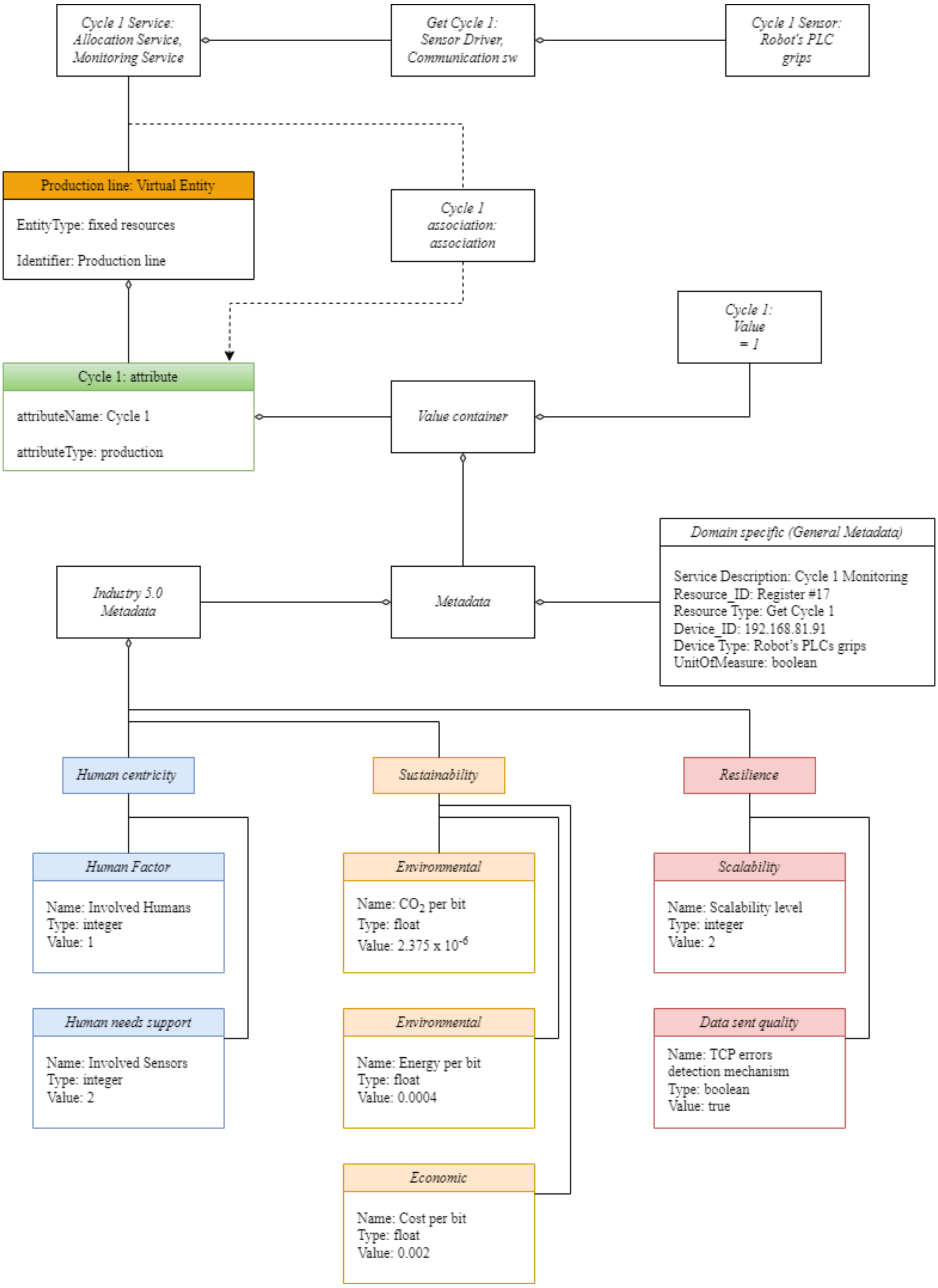


Figure 5.9 – Information model for attribute Cycle 1

The information flow is initiated by the Robot's PLCs grips. They send a signal of 1 when a container is grabbed from the starting position and a signal of 0 when it is released in its destination. The value is delivered to the attribute of the virtual entity associated with the measurement of the movements of the robots (i.e. Cycle 1) through an association. In this way, this signal replaces the value in the Cycle 1 attribute of the virtual entity.

5.4 Manufacturing system architecture

Based on previous considerations about the domain model and the information structure contained in the information view, the following figure shows the architecture of the mentioned above production line system.

The left side of Figure 5.10 shows the sensors, as well as the robots grips, that operate in the functioning area. They are connected to the PLCs of the robots. For the sake of simplicity, the name "Robot's PLCs grips" will be used to identify either the grips of the robots and the PLCs connected to the grips of the robots, as well as the sensors of this system.

Robot's PLCs grips sensors transmit their data to the PLC. PLC stands for Programmable Logic Controller and is an industrial computer control system used to interact with machinery. It receives signals from input devices or sensors, monitors them and based on custom program makes decisions to control the state of output devices. In this context, the PLC is simulated by FlexSim, a 3D simulation modeling software, within the application.

Data are transmitted through Modbus protocol, which is the most commonly available means of communication used to make possible the interaction between industrial electronic devices. It is an open protocol; this means that there is no need for manufacturers to pay royalties to build or modify it into their equipment. It is very simple to use and to be implemented and does not require huge investments. Specifically, in this system is used a variant of the Modbus family: the Modbus TCP/IP connection (Transmission Control Protocol and Internet Protocol), that enables to exchange data over a network.

The PLC is responsible for data acquisition of the signals send by the Robot's PLCs grips, for managing transmissions of data between the reality and the virtual system and for triggering actuators (UR3 CB_Robot3, in this case) to reorganize the production based on the outcome of the control logic.

The main software component is FlexSim, which is a powerful and easy-to-use computer software package to create and improve simulations of real systems. It is commonly used in manufacturing, material handling, healthcare, warehousing and supply chain industries and the main purpose is to develop, simulate and monitor dynamic flow process systems. FlexSim provides a graphical user interface to users for creating the 3D simulation system, for writing the control logic, for dashboard configuration and for graphic visualization of the process and historical information.

The actuator, which is the UR3 CB_Robot3, is shown in the right side of the graph and is connected to the PLC through Modbus TCP/IP connection. It receives a signal and acts on the physical environment to reorganize the production in an optimal way when one robot is causing delay.

FlexSim consists of four main modules. The first module is the communication module which is responsible for providing communication functionality through two different protocols: TCP/IP for real-time data exchange over a network and custom APIs, for integrating with specific external interfaces. The second module is the integration module, which enables continuous synchronization between the virtual system and the real one. This module includes components for receiving real-time sensors data from the robots to update and analyze performance of the simulation model, components for sending commands to the robots based on the sensors' outcome and components for synchronizing simulation time. The third module is the data processing and analysis module and involves on one side real-time data processing for transforming collected data into useful information and on the other visualization and reporting, for presenting thought a user-friendly interface the simulation results, performance and historical data. The last module is the control module, that implements control algorithms and decision-making logic to govern the behavior of the production line.

The communication within the software is not based on methods that rely on external protocols like HTTP or MQTT but is based on internal mechanism designed to facilitate interaction within the simulation environment.

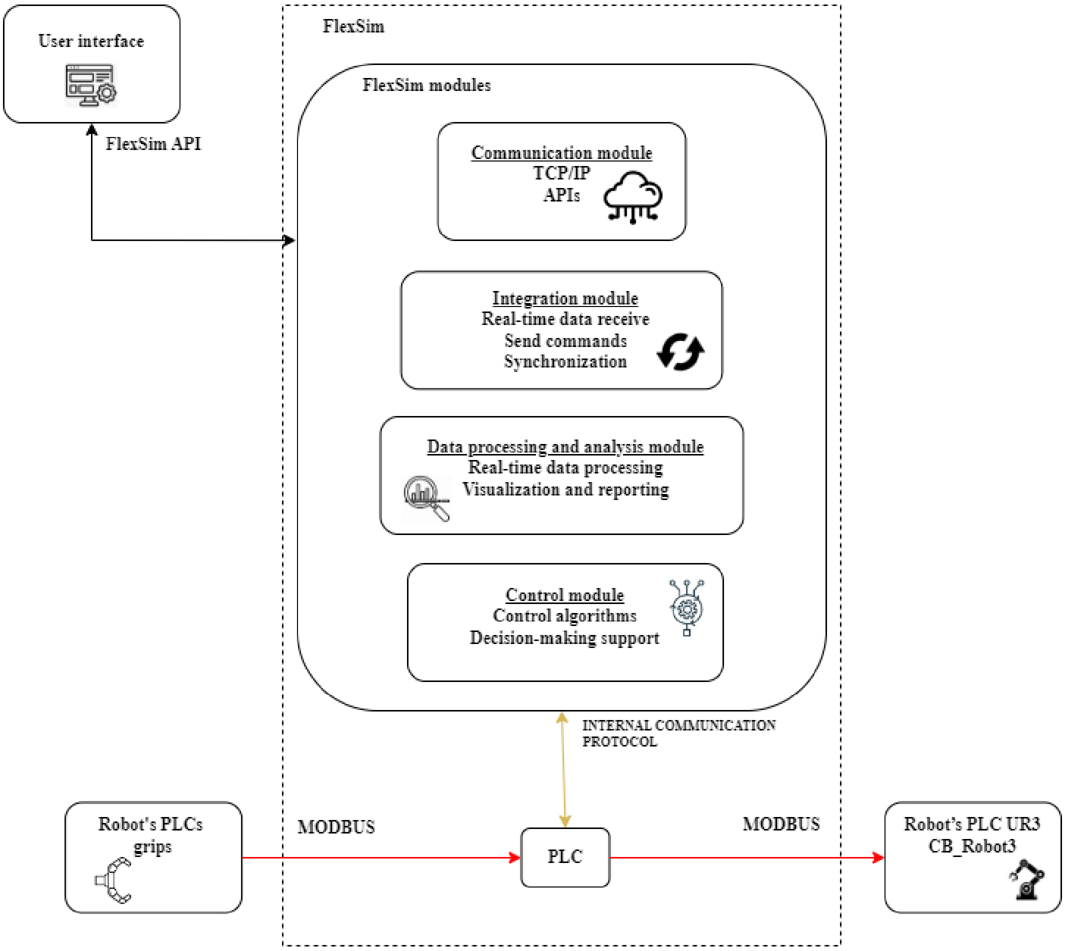


Figure 5.10 – System architecture of the manufacturing production line

Different measures have been taken to face requirements and to implement FlexSim system qualities. In terms of interoperability, different strategies can be applied to different devices, components and software to enable communication, interaction and exchange of data. Specifically, well-defined APIs, standard protocols and open-source software are used to face this issue. For what concerns scalability, as well as the ability of the software to simulate larger and more complex models without compromising the performance of the system, FlexSim should be able to handle models with a high degree of complexity, including connecting different kinds of resources and testing different kinds of failures.

5.5 Manufacturing system functional model

The application of functional decomposition, which is the methodology used to identify the various Functional Components (FCs) that comprise the IoT ARM and establish their interrelationships, is shown in Figure 5.11. The primary objectives pursued through the application of this methodology are twofold. Firstly, to simplify the complexity of the system into smaller and easy to handle parts and secondly, to illustrate the relationships within them. In brief, it consists of nine layers, including device layer, as well as the hardware parts, communication layer, which facilitates the interactions between components and application layer, which allows user interactions. The smart service layer enables sensor data retrieval and actuator control, and the digital twin management layer synchronizes digital twin with physical objects. Additionally, the smart process management functional group integrates business processes within the system, while the security layer ensures user privacy and secure communications. The service organization layer acts as a central hub for mapping processes to specific services, and the management layer oversees various operational aspects to align with Industry 5.0 principles, focusing on human-centricity, sustainability, and resilience.

The mentioned functional groups are outlined as follows:

1. Device: this layer includes the sensors and the actuator used in the manufacturing production line system, as well as the Robot’s PLCs grips and the Robot’s PLC UR3 CB_Robot3. It includes also the PLC used to control and retrieve data from them (with no

reference to the fact that it was emulated by FlexSim) and the haptic devices used to interact with the platform, such as the mouse and the keyboard.

2. Communication: this layer facilitates instant two-way communication between devices and various components of the system, including the virtual entity. It encompasses all communication protocols employed, such as the Modbus protocol for real-time data exchange between the PLC and the hardware components, the custom APIs for the integration of specific external interfaces and the internal communication protocol designed to facilitate the communication within the software.

3. Smart service: this layer consists of two elements. The first, which is FlexSim services, allows the transmission of data between platform, the sensors and the actuator. The second, which is FlexSim service resolution, acts as a connectivity hub that facilitates interactions between end users and the platform.

4. Service organization: this layer acts as a central hub and facilitates the connection of entities across these services with the use of virtual entities. It consists of two elements. The first, which is the service orchestration, coordinates and manages multiple services to achieve a particular outcome (e.g. use the value of grips to take actions and activate the third robot). The second component is service choreography, which manages the delivery of services to external entities that need them.

5. Digital Twin management: this layer contains all digital twin components, as it offers the necessary functions to deliver information about the digital twin. It includes the production line monitoring, which monitors the manufacturing system, the real-time data processing, which processes data for the decision-making support, used to take actions.

6. Smart process management: this layer contains the elements needed to create the process model. Also, it includes components associated with business process modeling and

execution, which are used to ensure that the predefined application requirements align with the service capabilities. It includes the FlexSim emulation tool startup and FlexSim startup.

7. Management: this layer integrates all the features necessary for comprehensive management and communication within the system. It includes components such as the performance monitoring to manage the production and visualize dashboards with real-time key performance indicators and the physical and virtual production line configuration, to manage devices in both the real and virtual spheres.

8. Security: this layer is responsible for maintaining the safety and confidentiality of the entire system. It includes computer user access credentials which is used as an authentication mechanism that requires the entry of an ID and a password to access.

9. Application: this final layer encompasses all the software tools utilized for managing and overseeing each stage of production. This layer features various dashboards that can be accessed locally on the platform, such as the process flow dashboard to set the virtual production line, the 3D simulation dashboard to visualize it, the charts dashboard to visualize the performance of the system and finally the emulation tool dashboard to set the connectivity between the physical and virtual spheres.

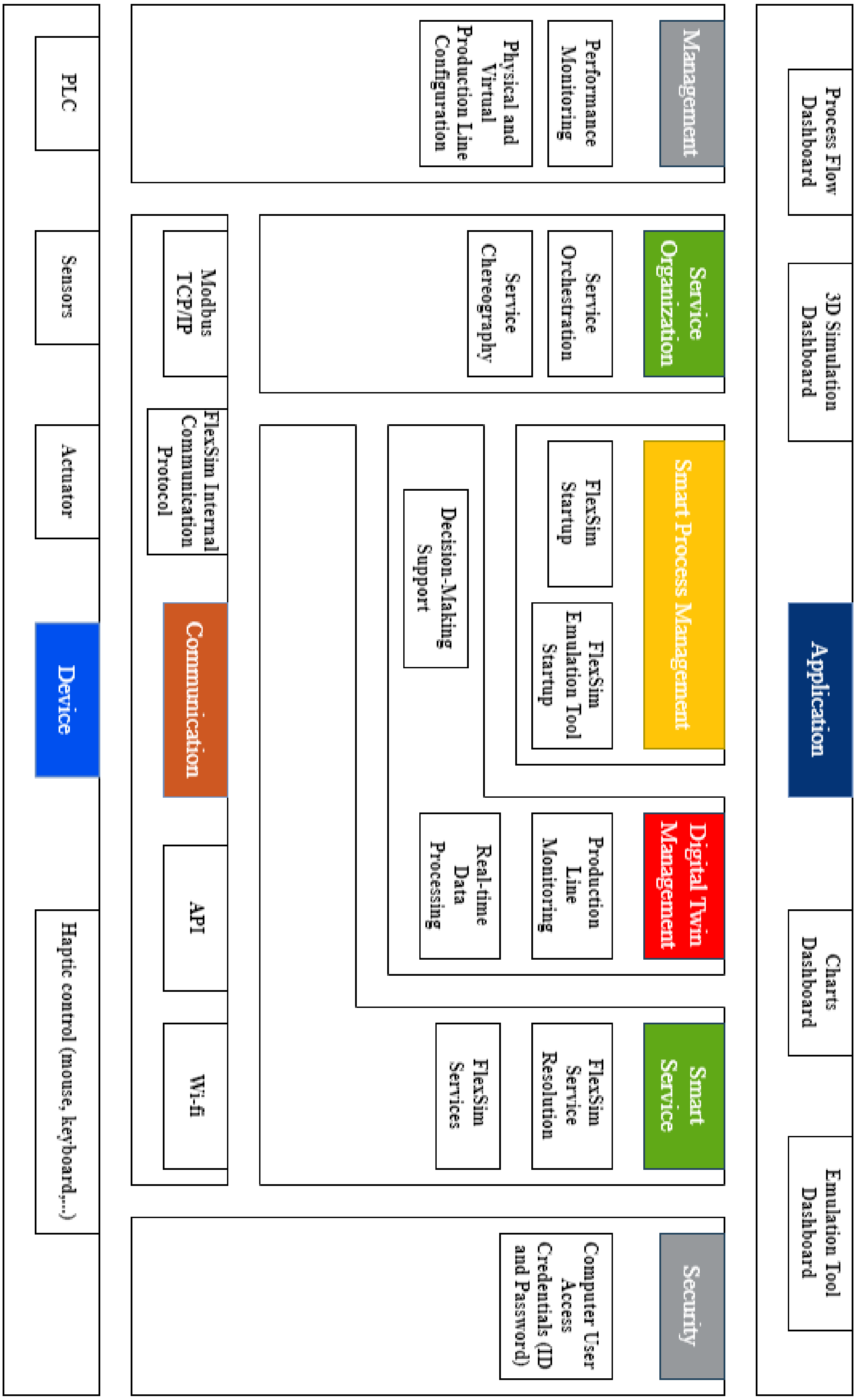


Figure 5.11 – Manufacturing system functional model

6. Conclusions

In conclusion, this thesis aims to develop and validate a novel framework for IoT-based Digital Twins, adapted from the IoT Architectural Reference Model (IoT-ARM) project funded by the European Union between 2010 and 2013, to address the requirements of Industry 5.0, namely sustainability, human-centricity, and resilience. Through the implementation of a Digital Twin case study involving collaborative robots, the proposed framework was successfully validated, demonstrating its applicability and potential for driving innovation in the manufacturing sector.

The work presented in this thesis involved a comprehensive exploration of Digital Twin technology, its historical context and its evolution over time, emphasizing the importance of IoT-based architectures in enhancing interoperability and scalability. Moreover, an extensive literature review has been conducted. The literature review section includes a systematic examination of the interrelationships of Digital Twins (DTs) technology and Collaborative Robots (Cobots) within various contexts, with the intent to classify the literature into categories, highlighting the common points and the differences between papers in each category. As the landscape continues to evolve, the same section identifies future directions for research.

The main difficulties encountered in the literature review section pertained to the identification of the criteria used to classify the articles, considering both a 4.0 and 5.0 perspective. Together, these findings pave the way for a more interconnected future, where cutting-edge technologies harmoniously improve efficiency, safety, and sustainability in dynamic manufacturing settings.

Following this theoretical foundation, this thesis presents a case study concerned the intervention of the digital twin technology to mitigate the effects of delay in a production system composed of two UR3e robots which perform in parallel simple processing tasks. This practical case study was implemented with the intent to evaluate and strength the applicability of the newly adapted IoT-DT framework [126] in a manufacturing environment. The results obtained prove the practicality and validity of the proposed framework in a different sector (i.e. the manufacturing one), with the general objective of optimizing production performances through monitoring and control services and to homogenize some quality aspects pertaining to industry 4.0 and 5.0 platforms. Moreover, as the manufacturing landscape continues to transform, adopting such frameworks will be essential for ensuring that technological advancements contribute to a more sustainable and human-centric industrial future.

However, the research faced certain limitations, including the absence of an interconnected IoT system like the one presented in the case study of vertical farming discussed in Article [126] and the need for further experimentation in diverse industrial contexts to assess the generalizability of the proposed framework. Although the case study demonstrated the framework's efficacy, real-world applications may present challenges related to varying operational environments and interoperability concerns.

As future work, it would therefore be good to prove the applicability of this framework across complex manufacturing systems, composed by a structured IoT environment and security aspects. Additionally, while the framework addresses core Industry 5.0 principles, future work could focus on incorporating more metrics related to human-robot collaboration (i.e. social sustainability) and resilience aspects under extreme conditions. In addition, a future attention can be given to security measures within the framework itself, ensuring a strong protection of user’s data. Finally, the practicality of the IoT-Based framework for Digital Twins can be further tested in diverse sectors, such as the service one.

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List of Figures

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