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Towards a Digital Twin Lifecycle Management Framework

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Declaration of Authorship

I, Luis Felipe Villegas Torres, declare that this thesis titled: "Towards a Digital Twin Lifecycle Management Framework", and the work presented in it are my own.

I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all of the main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Luis Felipe Villegas Torres
Tlalpan, Ciudad de México, December 3rd, 2021

Dedication

I dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents, Manolo and Cristina whose words of encouragement and push for tenacity ring in my ears. My brother Manolo, who helped me when I was drowned with work and has supported me throughout the process.

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Abstract

Smart Manufacturing has become one of the most important strategic priorities for manufacturing industries since it plays an important role in Industry 4.0 and Industrial Internet. Sensors and data transmission technologies are starting to be used most commonly to collect data at different stages of the product lifecycle, including product design, manufacturing, distribution, maintenance, and recycling. Big data analysis can enable the use of data to discover the causes of failures, simplify the supply chain, optimize product performance, improve production efficiency, etc. But to achieve these goals, they should first be able to overcome the challenge of connecting the physical product with its virtual product. The rapid development of advanced emerging technologies such as simulation, data acquisition, and data communication has helped to hold data synchronization between the physical product and the virtual product. In this way, is how Digital Twins (DT) came up to state the interactions between physical product and virtual product through a main channel called "Digital Thread" and generate the desired value from the captured data. Digital Twins, as an evolution of a cyber-physical system, has been paid more and more attention by academia and industry. DT can integrate physical and virtual data throughout the product lifecycle, thereby generating massive amounts of data that can be processed through advanced analysis. The results of the analysis can then be used to improve the performance of the product/process in the physical space. Being a relatively new concept, it lacks standards that homogenize the definition, maturity model, lifecycle, etc. among academic and industrial researchers. In this thesis, after conducting an exploration of the state-of-the-art, it was found that there is a need to make a first effort to establish a framework that guides DT designers throughout the entire lifecycle of a Digital Twin. This thesis presents a first approach towards a Digital Twin Lifecycle Management Framework that is sufficiently robust and comprehensive for its application in different use cases within the industry.

Keywords: Digital Twin, Lifecycle Management, Framework.

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Chapter 1: Introduction

Nowadays, with the constant evolution of Information Technologies (ITs) as well as Operational Technologies (OTs), and the emergence of new ones such as the Internet of Things (IoT), cloud computing, big data analysis, and Artificial Intelligence (AI), the digitization process of the physical world has been exponentially accelerated (Qi et al., 2021). At the same time, the use of sensors for data collection and transmission, at different stages of a product lifecycle, including product design, manufacturing, distribution, maintenance, and recycling has been increasingly used. By combining these two trends, both the use of newly developed IT and data collection technologies, industries are able to discover the cause of failures, simplify the supply chain, optimize product performance, and improve production efficiency (Kusiak, 2017). Moreover, the collaboration between these trends has triggered an unprecedented interaction between "physical space" and "virtual space", bringing with it the concept of "*Digital Twin (DT)".*

Digital Twins (DTs), as cyber-physical systems integration, contemplate both the physical assets (or physical entities) and their digital representations as a whole. With the use of *digitalization technologies,* entities, outputs, constraints, and relationships in the physical world are "digitized" to create high-fidelity virtual models (Glaessgen & Stargel, 2012). These *virtual models* gather up real data from the physical world to formulate their real-time parameters, boundary conditions and dynamics, in order to reflect the corresponding physical entities more representatively (M. Grieves, 2014). They communicate with each other through bidirectional interactions that allow them to co-evolve, leading to the production of a large volume of data (i.e. big data) that later on will be processed by advanced analytics. The result of this analysis is then used for decision-making of a certain aspect of the product or process in the physical space (Qi & Tao, 2018).

Thanks to the different applications of DTs that have been presented in the industry, it can be said that this type of technology provides many strategic advantages. Generally, in the first place, DTs are able to mimic the shape, position, gesture, state, and movement of physical entities in the digital world (Söderberg et al., 2017). In the second place, after the combination of sensed data, big data analysis, Artificial Intelligence (AI), and Machine Learning (ML), *Digital Twins* can be used to monitor, report, diagnose, predict, integrate, prescribe or make autonomous decisions upon the product design or process (Zaccaria et al., 2018). In third place, due to the constant evaluation of the ongoing status, the analysis of historical problems and data, and the prediction of future trends, DTs are able to provide stakeholders support for the wide range of operational decisions. In fourth place, once the system has evolved towards a usable digital representation of the functionalities and environment, DTs might have users, operators, maintenance personnel, and service providers training application (Goossens, 2017). In fifth place, the expert experience can also be "digitized", and when it has been recorded, transmitted, and modified throughout the enterprise it can narrow the knowledge gap. As a final application advantage, when the DT's simulation tools levels up to the point of implementing Virtual Reality (VR) tools, the level of understanding that an operator can have upon complex physical entries increases considerably (Qi et al., 2021).

Digital Twins have been increasingly implemented within different areas of the industry, not only because of the benefits mentioned above but also because they can help increase productivity and efficiency levels while reducing costs and times. Thanks to this infinity of advantages provided by DTs, Gartner has ranked *DTs* as one of the top 10 technological trends with strategic values for 3 years from 2017 to 2019 (Qi, Tao, et al., 2018). Despite the increasing popularity of the *DTs research,* development and deployment, Small and Medium-sized Enterprises (SMEs) lack knowledge of the key technologies and tools needed to set up a DT in their daily businesses. *Digital Twins* as a highly complex system that requires a long-term process to orientate, operate, and optimize has conducted researchers to propose frameworks, models, and methodologies that facilitate DT designers to correctly design, implement, and manage DTs.

Therefore, the goal of this thesis is to realize a first effort to develop *a Digital Twin Lifecycle Management Framework,* by digging into the scientific and grey literature to get a general idea of what has been generated so far and to identify a starting point. Once this starting point is established, the framework will be populated among some members of the scientific and industrial communities, experts in Digital Twins, to enrich and validate the proposed lifecycle management framework. This framework will seek to establish a guide in the flow of the lifecycle of a Digital Twin, taking into account its main faces: (i) Beginning-of-Life (in charge of planning and designing the DT), (ii) Middle-of-Life (in charge of maintaining the DT once it is put into operation or ready for its evolution), and (iii) End-of-Life (where the DT is decommissioned from its principal tasks).

1.1 Digital Twin Background

As mentioned above, *Digital Twins* are born from the desire to be able to model products, assets or processes that interact in different ways with their environment, and for which it is difficult to get to an accurate prediction of the outcome within a whole product lifecycle (Grieves, 2016). Because its operation is mainly based on the massive collection and accumulation of data in real-time through sensors, *DTs* are capable of creating both historical and current behaviour profiles, of the process or product, to improve the performance of an industrial plant. The benefits that this brings with it are that companies are able to have a "digital footprint" of their product, where the step of each of its components through the entire product lifecycle can be observed and registered. In addition, when a *Digital Twin* is deployed in a company, they can increase their value in terms of cost and lead-time reduction, serialization, traceability, quality improvement, operational costs reduction, shortened time-to-market, and incur into new business models according to their needs and the specific installed capacity for the DT.

1.1.1 Origin

Since the beginning of the First Industrial Revolution, the most important working space within the industry has been the "physical space". During the previous three industrial revolutions, physical resources have been manipulated, programmed, and supervised by humans in order to carry out the design and manufacturing tasks of products and processes. However, as is well known, both human hand errors and geographic limitations reduced the ability of companies to obtain high efficiency in their processes. Thinking about this type of deficiency and how to innovate in this area, in 2003, Grieves (2005) introduced the concept of *Digital Twin* for the first time. With the technologies developed in the 20th century, such as computer simulation tools, the internet and wireless networks, Grieves (2005) presented a three-dimensional conceptual framework (see **Figure 1**). This was comprised by a physical system, the virtual representation of it, and a connection between both systems, but there was not a further explanation nor description on how does the interaction between them was given, or what were the specific benefits of making that type of connections (Tao, Zhang, & Nee, 2019).

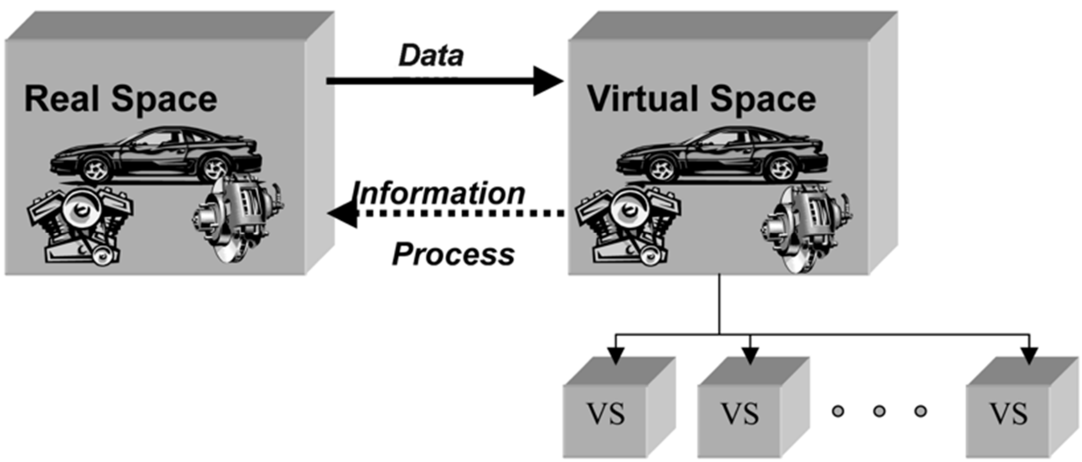

Figure 1. First Representation of a Digital Twin (Grieves, 2005)

Seven years later, in 2010, NASA retook the concept for a space vehicle project. In this work, they were able to provide a detailed definition for *DT* as *"an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin"* (Glaessgen & Stargel, 2012). This definition was approved by the research community in universities and institutes, which led them to not only to come up with new definitions but to put this concept into practice in various research areas, to develop new models based on this technology and to open different insights into the degree of sophistication of a *Digital Twin.*

1.1.2 Evolution

The concept of *Digital Twin* is somewhat recent according to what has been reviewed/published, however, it is a type of technology that has been constantly evolving according to the definitions that have been given to it over the years. According to Tao et al. (2019), this evolution of the concept or technology is segmented into three main stages, although a fourth one is proposed.

The *first stage of DTs evolution* has as set point the moment in which Grieves (2005) unveiled the concept of the *"twin"* in his PLM course. At this point, the conceptual framework that was being proposed was nothing more than a vague three-dimensional model where a certain type of connection linked the "real space" with its digital counterpart in the "virtual space". Later on, in 2005, Grieves takes up his concept and defines three different DT subtypes (Grieves, 2005). Within this classification, he mentioned that there can be *Digital Twins* for prototypes, instances, or aggregations. Despite this second contribution to the subject, few articles were written in relation to it. This is due to the fact that the technological and cognitive capabilities represented great limitations for the time. During the next 5 years, from the second publication of Grieves (2014), new technologies such as IT began to emerge and to be used in different areas. Thanks to this, the constraints that previously appeared in DTs began to break down and gave rise to the first evolution of this technology.

This first evolution brings with it the *second stage of DTs development* where, in 2010, NASA clarifies a roadmap for the operation of a space vehicle, detailing the modelling, simulation, and processing using ITs as a basis (Shafto et al., 2010). Shortly after, in 2011, the U.S. Air Force implements a DT in order to provide a prediction upon the life of the structure of an aircraft through the continuous structural FEM simulation analysis over a certain time interval (Tuegel et al., 2011). In 2012, both NASA and the U.S. Air Force came together to make known at a conference the importance that it would have in the future to base the operation and development of aircrafts on *DT systems* (Glaessgen & Stargel, 2012). This second period began with a focus on DTs in the field of aircraft and after the collaborative publication in 2012, numerous research studies in relation to DTs and aerospace began to be published. This was the beginning of the discovery of the net potential that *Digital Twins* have, both in the area of design, maintenance, and data-driven application systems.

After the increasing number of publications, in 2014, Grieves publishes with high exposure its whitepaper with the three-dimensional conceptual framework as well as the proposed subtypes (Grieves, 2014). This whitepaper becomes a breakpoint to reach the *third stage of DTs evolution* since with it the investigations began to open towards more fields of research such as the automotive industry, medicine, manufacturing, oil and gas, etc. Its popularity increased in such a way that even Gartner has ranked *DT technology* as one of the Top 10 Strategic Technological Trends with broad industry impact and significant potential for disruption from 2017 up to 2020 (Panetta, 2019). Additionally, the Smart Manufacturing Association of China Association for Science and

Technology placed "Digital Twins" as one of the Top 10 Scientific and Technological Advances for Smart Manufacturing in the world (He & Bai, 2021).

Taking into account the trend that the *DT concept* has had in recent years, and in the diverse applications, visions, and degrees of complexity that have been observed in scientific and grey publications, it can be said that a new evolution stage is about to come. This *fourth stage,* proposed in this thesis, needs to narrow down its scope accordingly to the needs of the user. This means that the installed capacity of a *Digital Twin* must be previously analysed in order to be able to efficiently satisfy its objective. However, the *DT system* has to be flexible enough either to improve the outcome, the value proposition of the outcome, the way in which it transmits or shows the outcome of a process or product where the DT was deployed. When the *DT system* is able to adapt to those needs, "Digital Twin Upgradability" turns up as the fourth evolution stage, where "upgradability" refers to the ability of the DT to continue running regardless of the increment of its workload, or its ability to scale its functionalities, capabilities, and degree of sophistication.

1.1.3 Relevant Definitions

Since the appearance of the *DT concept* in 2003, and the exponential exploration of it starting from the contribution of NASA and the U.S. Air Force, different definitions have been given to it by academics and practitioners. These definitions have evolved as *Digital Twins* have been applied to different use cases and in turn, new technologies have been introduced to the *DT systems.* The latest definitions and also those that have been most valued and cited among the scientific community, specialized in the research and application of *Digital Twins,* throughout these years are the following:

- "A *Digital Twin* is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin" (Glaessgen & Stargel, 2012).

- "A *Digital Twin* is a computerized model of a physical device or system that represents all functional features and links with the working elements" (Chen, 2017).

- "The *Digital Twin* can be considered as a virtual entity, relying on the sensed and transmitted data of the IoT infrastructure as well as on the capability to elaborate data by means of Big Data technologies, with the purpose to allow optimizations and decision-making" (Macchi et al., 2018).

- "The *Digital Twin* is a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data and information and can forecast the future of the corresponding physical counterpart" (Liu et al., 2018).

- "A *Digital Twin* is a digital representation of a physical item or assembly using integrated simulations and service data. The digital representation holds information from multiple sources across the product lifecycle. This information is continuously updated and is visualised in a variety of ways to predict current and future conditions, in both design and operational environments, to enhance decision making" (Erkoyuncu et al., 2018).

- "A *Digital Twin* is a set of virtual information that fully describes a potential or actual physical production from the micro atomic level to the macro geometrical level" (Zheng et al., 2019).

- "A *Digital Twin* is a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's lifecycle" (Madni et al., 2019).

- "A *Digital Twin* is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple lifecycle phases" (Stark & Damerau, 2019).

Of these definitions, the one that has become most popular among the *Digital Twin international research community* is the one established by Glaessgen & Stargel (2012). Despite being the first concrete definition, it has managed to transcend regardless of the technological improvements and fields of implementation of a *Digital Twin.* Notwithstanding this situation, the definition presented by Stark & Damarau in 2019 is considered of greater relevance in this thesis. It is a current version of what a *Digital Twin* represents and brings out the different degrees of granularity in which a DT can be implemented. In this definition, they make clear the permeability of a *Digital Twin* throughout a product or service lifecycle. However, this definition lacks certain points of relevance. A *Digital Twin* goes beyond the digital representation of a product, asset or service, it is a system that allows the real-time interaction and communication of these with their virtual instances, and that aims to satisfy the user's value proposition.

A *Digital Twin* is made up of not only a "physical product" and its "virtual counterpart", but also of a "digital connection" that guarantees the synchronization between both parts of it. This element is the third layer of a *Digital Twin,* known as "Digital Thread".

- "A *Digital Tread* is the layer capable of providing connectivity throughout the system's lifecycle. Depending on the ability to synchronize data, the Digital Thread collects data from the physical product to update the model of the virtual product, or even transmit the analysed data of the virtual product to make the necessary changes in the physical product" (Madni et al., 2019; Wärmefjord et al., 2020).

As an additional remark, the difference between a *Digital Twin* and a *Digital Shadow* relies on the "directionality" of the data captured from their physical counterpart and its usage, while a *Digital Shadow* has a "unidirectional" data flow from the physical to the cyber world aimed at creating a collection of all the data generated by a physical product during its lifecycle – e.g. for data analytics, a *Digital Twin* has a "bidirectional" exchange of data between the physical world (its physical counterpart) and the cyber world (its virtual counterpart) aimed at achieving an actuation loop.

- "*Digital Shadow* is a metaphor for all the digital information that a product, asset, process, or system creates during its entire lifecycle and it is traceable for data analytics" (Riesener et al., 2019)

1.2 Digital Twin R&D Motivation

Without a doubt, the automation of industries has brought a big change to the way things are manufactured today. However, the innovation curve for manufacturing has reached its limit in this new era where market requirements change constantly and geographically, where industrial systems must have the ability to respond effectively to unforeseen events despite their given conditions. In other words, it is necessary to start a new innovation process, a new curve to improve manufacturing performance, where the starting point is given by the ability of manufacturing systems to be flexible. At this point, a manufacturing system should be characterized by the rapid reconfiguration of production to such a degree that it can be reorganized when it is interrupted either by a consumer need or an unexpected change in the market. In this way, it is said that a company can remain competitive in the marketplace (Morgan & O'Donnell, 2017). In order to lead the market, industries are starting to research how to identify the appropriate management of industrial systems to increase their flexibility, appealing to the implementation of *Digital Twins* for the management of their production systems (Yangguang Lu et al., 2019). This is also how the Fourth Industrial Revolution was born, stipulating the idea that "smart" industrial systems should become *Cyber-Physical Production Systems (CPPSs)* that integrate and utilize cloud computing services through the Internet of Things (IoT) (Sajid et al., 2016). This reconfigurable feature of decentralized systems is essential to achieve manufacturing flexibility.

Today's manufacturing systems have several limitations that prevent them from performing centralized re-planning, shortening response times, and executing high-level tasks autonomously (Rosen et al., 2015). With the implementation of *Digital Twins,* these types of barriers are left behind for "smart" industrial systems, since the same complexity of the system, where the virtual copy of the real system reflects, analyses, and deduces the KPIs of interest in real-time, is agreed according to the customer need or purpose (Park et al., 2019). Moreover, in the process of planning and execution, *DTs* represent a strong solution to provide fast and advanced decision support for the elements that are involved within the same industrial system (Nikolakis et al., 2019). In addition, a robust *Digital Twin Framework* should provide the right way to overcome the limitations of using the latest technology in product lifecycle management such as the deficiency on the integration level between the "physical space" and the "virtual space". So, in this way, the synchronization and fidelity of representation provide a high potential application in product design, manufacturing, and service provisioning (Tao et al., 2018b).

1.2.1 Challenges

The implementation of *Digital Twins* can bring great benefits to an industry according to the needs or the objective with which the execution project of a *DT system* has been carried out. However, the class and amount of technology required for the development of this type of solution vary according to the complexity of the proposed *DT system.* The fact that a DT requires a large physical and virtual infrastructure brings with it a series of challenges that must be met in order to achieve the correct deployment of a DT project. In a generalized way, it has been found that the main challenges associated with the implementation of a *Digital Twin* are IT Infrastructure, Data Management, Interoperability, Privacy & Security, and Reliability. However, there is one last general challenge that has been limited discussed, and this is "DT System Upgradability".

1.2.1.1 IT Infrastructure

In order to run a *Digital Twin* effectively, a solid IT infrastructure needs to be implemented. A large amount of data is collected, processed, and perhaps stored, and may need to be analysed in a matter of seconds when deploying a DT, and for this, it is necessary to take into account the need to implement a platform that is capable of managing big data projects in terms of blending, integration, storage, centralized management, interactive analysis, visualization, accessibility, and security. With the use of external web services such as Amazon Web Services (AWS) and Azure IoT Suite, IoT platforms might be constructed in order to exchange data and execute tasks directly from the hosting place without copying to local memory in a convenient way (Rasheed et al., 2019).

The information that reaches a DT comes from different devices that are connected to the same network in a wired or wireless way, depending on their convenience. An *IIoT-based DT* requires a high-speed Wi-Fi internet connection for the data packets to reach their target on time. With the connection of so many sensors, actuators, and servers to the same DT, technologies such as "4G networks" will begin to present problems in their operation since the large number of elements connected to it will begin to exceed the limit of the radio-frequency spectrum. However, with emerging technologies such as "5G networks", which have a broader spectrum of frequencies, a greater number of devices will be able to connect to it without presenting disturbances in addition to being able to take advantage of its ultralow latency and unprecedented speed (Rasheed et al., 2019).

1.2.1.2 Data Management

The next challenge, once the correct arrival of the data to the DT has been achieved, is to be able to obtain useful information. With the aim to extract value from the received data, it must first be guaranteed that the values are being read in real-time. Subsequently, it must be verified that the information does not present any kind of noise, poor, or missing data (Fuller et al., 2020). In case this happens, the information has to be treated in the way that the received data is the same as the sent data. Commonly in order to eliminate distortions, these signals are pre-processed by filters or data transformers. Finally, to extract real value from the information it is necessary to pass it through specific analysis tools, such as Machine Learning (ML), as the case may be. According to the user's needs, the type of tool will be implemented, either to report, diagnose, predict, integrate, prescribe, or make automatic decisions about the process or product to be developed.

1.2.1.3 Interoperability

One of the most important challenges that exist within the development of a *Digital Twin,* and that is also part of the most important requirements according to the literature (Durão et al., 2018), is the ability of the DT to be "interoperable". This means that the system must be capable of converting, relating, and establishing the different equivalences between the models they represent. Going deeper, when a system or series of components are interoperable, they have the ability to work together, share information between them, and use it in order to provide specific services. A sufficiently interoperable system must provide and guarantee effective communication between the different components of the system, achieving the correct execution of complicated or critical processes (Gunes et al., 2014).

1.2.1.4 Privacy & Security

In terms of "privacy & security", it is a challenge to be able to control access to resources as well as to be able to protect sensitive information from those people or systems that do not have authorization. A highly secured system must be able to manage and track access controls for the modification of information and resources. This means that the system needs to be protected from sabotage where the quality of the product might be compromised, resources might be wasted, or even the entire system might collapse, failing to meet delivery times (Fuller et al., 2020). Similarly, when a security protocol against cyberattacks is not carried out in the *Digital Twins,* accidents can be generated by external actions (Sadeghi et al., 2015). These attacks can be directed at both the physical part (in order to damage the equipment in operation or steal sensitive information) and the virtual part (viz. corrupting communication, management layer, the decision-making mechanism, etc.) (Gunes et al., 2014). As a partial solution to this challenge, Fuller et al. (2020) recommend that all devices and technologies included in the *DT system,* strictly comply with the current practices, regulations, and standards in security and privacy.

1.2.1.5 Reliability

Like everything new on the market, *Digital Twins* generate mistrust or doubts about their safety, effectiveness, and potential. The first challenge, "security", is being worked on by establishing a solid base regarding the current policies of communication protocols and network protection, as mentioned in the previous point (Fuller et al., 2020). Second, in terms of "effectiveness", it is necessary to guarantee good accuracy in relation to the outcome and the current value or the calculated value as the case may be. This is achieved by validating the model where the current performance of the DT is compared with that of the physical system, seeking to tie both values (Mi et al., 2021). Finally, as far as "potential" is concerned, it is necessary to start up the DT system and evaluate the scope it is having together with the objectives proposed for it.

1.2.1.6 System Maintainability

Maintaining a DT system can become a difficult task due to its native System of Systems (SoS) configuration. This means that to provide maintenance to a DT it is necessary to decompose this system among its subsystems without losing the direct relationship that exists between them. In a Digital Twin, three layers make it up, the "physical product", the "digital thread", and the "virtual product". One of the biggest challenges is creating a maintenance strategy that not only guarantees good assistance to these layers that make up a DT but also must be able to handle the reflection effects suffered by the other layers when one of them is altered during the maintenance process.

1.2.1.7 System Upgradability

It is said that a *Digital Twin* must be capable of "scaling", which is to say, it must have the ability to continue running regardless of the increment on its workload. However, it has been stipulated as a challenge that a DT should be "upgradeable" in terms of its functionalities, capabilities, and degree of sophistication. Initially, the DT may be designed to provide certain information, with a certain value purpose, with a certain degree of *Human-DT interaction,* etc., but it must be able to change according to the evolving user's requirements in an efficient way. This means that if initially the DT was designed to improve quality through a predictive throughput if the end-user requires so, the DT must be able to mature to such a degree that it can improve quality but now keep track to reduce operational costs by making autonomous decisions. The *maturity level of the Digital Twin* must not exceed the basic requirements demanded in order to maintain the efficiency and the cost of the system.

1.2.1.8 Twinning (Mirroring)

The “exact mirror” concept of a DT is one of its biggest challenges. As in any real-world modelling and real-time simulation effort, the “virtual part” of a *Digital Twin* will require mapping out and mirroring (in real-time) the geometry, physics, behaviour, and rules of its “physical counterpart”, including sometimes its environment, with the highest fidelity possible (notion of the level of detail needed), in other words, “twinning” it. Therefore, any real-world virtual representation of a physical product/asset should offer a specific level of detail at a specific time, according to its application requirements, since reality is always changing as well as a real product/asset evolving, and in many cases, computational and connectivity resources may be limited for real-time synchronization of the virtual and the physical counterparts of a *Digital Twin.*

1.2.2 Trends

Figure 2 shows the temporal bar graph result of the analysis on the frequency of keywords used in publications related to *Digital Twins,* called Kleinberg’s burst detection (Kleinberg, 2003), realized by Ciano et al. (2020). This graph illustrates the popularity of the keywords in terms of duration and weight over time.

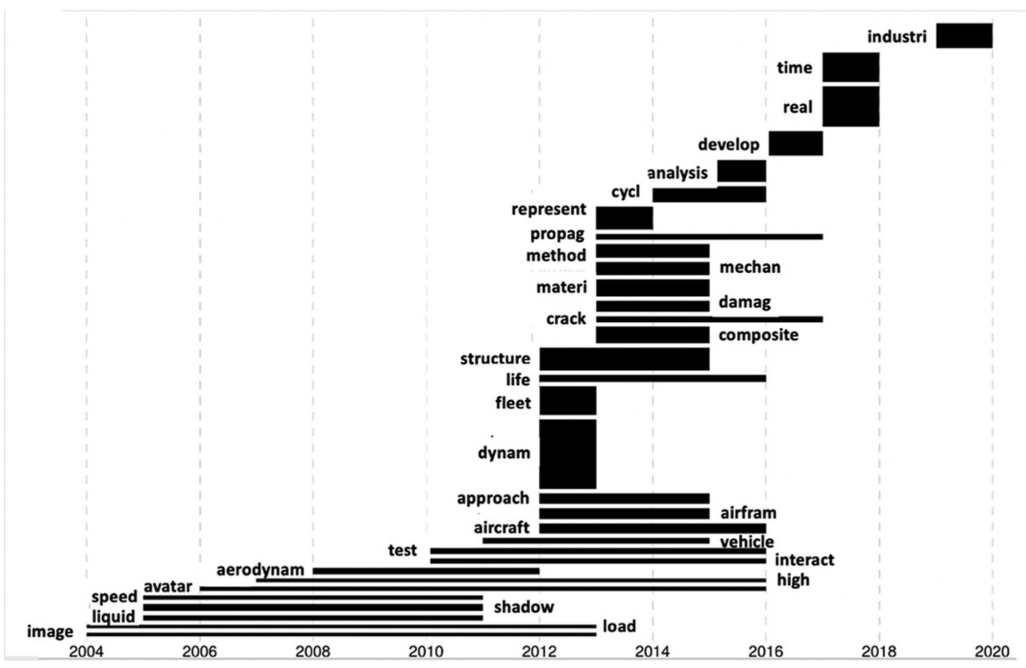

Figure 2. Keywords Bursts Temporal Graph (Ciano et al., 2020)

As can be seen, from the beginning of the *Digital Twin concept* a need has arisen along with the creation of *Digital Shadows* and *Digital Avatars* of physical systems. This timeline also shows the lack of research on the concept until 2012 when NASA and the U.S. Army pool their resources to put out a joint publication on the importance of DTs for future aircrafts’ design. This article brought the first burst into the themes of the *airframe*, *aircraft,* and *dynamics* that highlights the popularity of DTs in aviation. Words such as *composition*, *material,* and *structure* denote an interest in the type of materials to be used in an aircraft and its structural analysis. In the same way, the words *crack,* and *pop* can be translated into themes of stress factors and damage detection. Later, in 2012 and 2014, there was a particular interest in *life* and *cycle* keywords that allude to the study of the *DT concept* along with the *product lifecycle* (Tao et al., 2018a).

Finally, the second burst occurs in the sudden increase in publications with the topics of *real* and *time*, reflecting a new interest in *real-time systems* that go hand in hand with the appearance of the new emerging technologies such as big data and IoT. In turn, the keyword *industry* comes to light and matches with the emergence of the idea of Industry 4.0 and Smart Manufacturing. In this last burst, the paradigm that exists with the role played by *Digital Twins* as one of the pillars of Industry 4.0 is appreciated.

In conclusion, there are two major trends around *Digital Twins research.* The *first one* has a fresh and renewed approach to aviation issues in terms of design and real-time monitoring. While the *second one* has an approach towards more diverse and newer themes, specifically about the modelling and implementation of real-time systems (Ciano et al., 2020). With this latest boom, the deployment of these systems is limited towards the industrial area, i.e. "Smart Manufacturing" and "Industry 4.0" (Strozzi et al., 2017). *Smart Industrial Systems* that support *digital twins* represent the next research field for the future application of the DT concept. In order to compete in the future market, the adoption of flexible industrial systems designed to quickly respond to unexpected events are going to be needed (Morgan & O'Donnell, 2017). *Smart Industrial Systems* offer the possibility to do so, targeting the research upon the appropriate management of the flexible system. At this point, the interest to combine DT with Industry 4.0 technology has become crucial.

1.2.3 Issues

Thanks to the study carried out by Lu et al. (2020), at the University of Auckland, in order to analyse the connotation and recent applications of the *Digital Twins* within the manufacturing systems and processes, they were able to identify the main problems that companies face when implementing these types of DT technologies. After analysing the operation and deployment of DT in three of its variants (manufacturing asset, factory and people), working with different information models each (numerical models, finite element model, CAD model + OPC-UA, factory design and improvement (FDI) model, etc.) and based on different data communication standards (UART, OPC-UA, MTConnect, etc.) they land seven issues to be solved in future research (Lu et al., 2020).

1.2.3.1 Architecture Pattern for a Digital Twin

According to the literature and the different applications that have been reported, there are two options to set a system architecture model. On one hand, there is the "Server-based Architecture" where the data obtained from the physical system is redirected to a central server that performs data analysis and builds up the *Digital Twin*. This model provides economies of scale and ease of maintenance. On the other, by an "Edge-based Architecture", part of the data gets analysed at the "edge" of the system where data pre-processing is run locally on the raw data gathered from the physical system. Therefore, if it is properly designed despite its complexity to maintain, an "Edge-based Architecture" should be more effective in the low-latency data processing.

1.2.3.2 Communication Latency Requirement for a Digital Twin

The latency of communication between the physical system and its *Digital Twin* depends directly on the requirements of each application. It is necessary to bear in mind that the more deterministic the system is, that is, it requires a lower communication latency, the higher system development cost and difficulties for its implementation. Rauchhaupt et al. propose a nominal communication latency according to the hierarchy level of the communication layer for an Industry 4.0 (Rauchhaupt et al., 2016) that matches up with the Automation Pyramid (Schöning & Dorchain, 2014). They are useful as they might be used as a guideline for the design of the system architecture of a DT application.

1.2.3.3 Data Capture Mechanism

There are two methods used in order to extract data from the physical system. The first one focuses only on observing the changes and recording them regardless of the time of observation. On the other hand, the second one takes snapshots periodically no matter when the change of the data occurs. Something that these methods have in common is the requirement of large-scale computer systems that sometimes, depending on the complexity of the application, a mix of them can be required. In the same way, it is necessary to establish a prior validation of both methods for each of the applications where it is sought to implement.

1.2.3.4 Standards for Digital Twin

Although anyone is able to establish their own *Digital Twin solution* with the different technologies currently available, establishing development standards could not only help the easy development and implementation of DT projects but can also facilitate the longevity of the solution. The fact that all can be based on a standard and compatible model promotes the creation of flexible, interoperable, and scalable systems internally within the company or externally to establish new global standards. Currently, an ISO is being worked on in order to cover the need for standardization for *Digital Twin Manufacturing Systems* (ISO, 2021).

1.2.3.5 Functionalities of a Digital Twin

Current *Digital Twin applications* are used for monitoring and forecasting purposes and as human decision support applications. Although human participation in the Smart Manufacturing environment is required, autonomous feedback from the DT to the physical system should be established. In this way, *Digital Twin models,* at their higher maturity level, can give physical systems a certain degree of autonomy.

1.2.3.6 Digital Twin Model Version Management

A *Digital Twin* must be able to mature and evolve over time according to the changes presented by the physical model it represents. The historical changes that the physical model undergoes should not be discarded, rather they should be captured, stored, and integrated in order to be able to carry out a correct administration of versions of a *Digital Twin model.* In this way, when needed to go back to an older version of a *DT model* or review certain aspects of it, access will be much faster, and it will be easier for the system to mount on it again instead of creating a new one.

1.2.3.7 Humans in Digital Twin Applications

From the perspective of *Digital Twin-driven Smart Manufacturing,* the role of the human changes depending on the complexity of the tasks at hand. Some of these can be executed autonomously by the *Digital Twin* when they are low-level, and some others when they are crucial for decision-making, must be taken by humans. There is still a gap in the inclusion of the human within a smart manufacturing system despite the fact that technologies such as Augmented Reality (AR) have been used to reduce that gap between human-machine interactions. Future research analyses have to be carried out in order to include the human within these systems and to be able to carry out DT simulations, of the human and the machine as a whole and take compound decisions.

1.2.4 Future Application Opportunities

According to a joint investigation between the Center for Information Technology Research in the Interest of Society (CITRIS) and the Banatao Institute, in collaboration with the government, industries, and academies, they found that there are three high-level priorities, among the great leaders of the business such as Siemens, Komatsu, Kajima, etc., for the basis and development of future *Digital Twins.* These priorities are focused on (i) Sustainability, (ii) Smart Innovation, and (iii) Health and Safety, for their application within buildings, mines, vehicles, renewable energy assets, dams, forests, and human tissues and organs (Apte & Spanos, 2021).

1.2.4.1 Sustainability

Due to the increasing importance of “sustainability”, large corporations and organizations have begun to propose new strategies to reduce and eliminate their carbon emissions in a period of no more than 20 years. Thanks to the functionalities behind DTs, this type of technology could help companies achieve their goals. First, by drastically reducing the amount of energy consumed by establishing efficient processes, and second, helping the efficient development of green energy alternatives.

In terms of buildings, it is known that at least 40% of energy consumption is gathered by this sector as well as the emission of greenhouse gases. After the implementation of DTs in commercial buildings, energy consumption could be reduced by almost half. This is possible with the installation of sensor suites capable of providing the “current state” of the building that in combination with Artificial Intelligence (AI) and Machine Learning (ML) models, it is possible to adjust the light conditions and air quality of each room according to its occupancy and ventilation.

Finally, with a focus on industries, specifically in construction, mining, and quarrying, where their fundamental operations lead to increased greenhouse gas production, it has been found that DTs can help to develop more sustainable processes. In this aspect, DTs can improve the efficiency of machines and significantly reduce their emissions. Moreover, this type of innovation can even help sustainable solutions that are currently in operation, but ironically, although they are “green”, they may require more mining for their creation.

1.2.4.2 Smart Innovation

In the search for innovation in making everyday elements "smart", whether in cars, houses, energy, agriculture, infrastructure, or cities, it is necessary to implement a technology such as DTs to carry out the Digital Transformation to “smart systems”. For this case, DTs have been implemented in wind turbines, turning them into “smart systems” that, with the combination of Artificial Intelligence (AI) and Machine Learning (ML), are capable of measuring and modelling in real-time every detail of the turbine through fibre-optic sensing techniques. It is so complex that it is even able to predict when one of its bolts will come loose. In this way, it reduces maintenance costs, prevents catastrophic failure, and increases the reliability of renewable energy. Taking into account this *DT integration level,* it can be implemented in turn on roads, to regulate the traffic flow, and in dams, to warn of a possible breach. In agriculture, a set of aerial drones and terrestrial robots are implemented. They work in collaboration to provide the land, plant, or tree with the necessary amount of water, fertilizer and pesticide in an efficient way. This type of *DT-driven innovation* is concerned with the care of water in areas with regular droughts and with food security.

1.2.4.3 Health and Safety

The pandemic that has been faced since the end of 2019 has brought with it a series of changes, including how medical appointments are been carried out. From this moment on, interest in remote health care increased through telehealth visits. How this new way of providing care has evolved, increases the probability of continuing its course in the future, thanks to the level of safety and convenience that it offers both patients and doctors. However, if something has become very clear, is the fact that there are areas of opportunity to improve the quality of these telehealth visits, which go beyond the quality of audio and video. The implementation of a DT in this area expects to fulfil the totality of these deficiencies with real-time sensing to monitor patients, implementing Artificial Intelligence (AI) to analyse the information collected and provide a rapid diagnosis, and deploying Augmented Reality (AR)/Virtual Reality (VR) applications for better visualization.

1.3 Digital Twin Examples

Given the complexity of the development of a *Digital Twin,* due to the need to integrate different technologies that enable the real-time exchange of information between a physical product and its virtual counterpart, through a "digital thread", there are few applications in the real world. Despite this, great efforts by the main *Digital Twin software solution vendors* (such as Siemens, PTC, and Microsoft) are being made to address discrete manufacturing, automotive, energy, infrastructure, etc. challenges with the use of *DT applications.* Some of the more relevant examples of *DT applications* in the real world are presented below.

1.3.1 Example 1: Unilever Factory Digital Twin

To create a *Digital Twin* of their factory, Unilever, one of the largest global consumer goods companies, offering beauty and personal care products, food and refreshments, and home care products, is using IoT (Internet of Things) and intelligent edge services in the Azure IoT platform to generate a digital model of the factory environment. This platform allows them to connect machines and equipment within the factory so that they can send a mass of data (depending on the application requirements it can be from temperatures to production cycle times) into the digital model. By doing so they can generate a virtual representation of every machine and process, enabling visibility across the depth of the system of the plant. The data collection is carried out to get insights and identify patterns using advanced analytics and machine learning algorithms, which can then predict outcomes based on the collected historical data. The algorithm can be mature and autonomous enough to directly control part of a machine or process. This, in turn, allows the operators to make better-informed decisions and frees them up from repetitive manual tasks for more value-added functions (Sokolowsky, 2019).

1.3.2 Example 2: Tesla Electric Cars Digital Twin

Tesla is applying, basically, the same concept as Unilever, but to their main product, electric cars. System sensors at each car report back the data to the factory through a continuous stream. The data is then used by Artificial Intelligence (AI) algorithms or simulation programs on the *Digital Twin* to discover possible anomalies and provide corrective actions. This allows them to predict future behaviours of the physical car system. This is done without any experimentation with the physical system at hand. With this Tesla is then able to provide each car with a customized software update to resolve any issues it is facing (Puranik, 2021).

1.4 Research Question

Is it possible to develop a *Digital Twin Lifecycle Management Framework* considering the design, engineering, managerial, and decommissioning implications for the successful development, implementation, management, and retirement of a Digital Twin – considering its full lifecycle phases ?

1.5 Hypothesis (Design Proposition)

Most of the *Digital Twin Development Frameworks* only focus on the design and engineering stages of Digital Twins implementations (i.e. beginning-of-lifecycle) from a very technical perspective, not considering their whole lifecycle and also the importance of a managerial perspective for their successful deployment and management (i.e. middle- and even end-of-lifecycle). A *Digital Twin Lifecycle Management Framework,* as a comprehensive overview of the whole lifecycle of a Digital Twin, could support developers and managers in better understanding the implications of deploying and managing a Digital Twin from a technical and managerial perspective.

1.6 Objectives

1.6.1 General Objectives

To develop a *Digital Twin Lifecycle Management Framework* considering the whole lifecycle of a Digital Twin (viz. design, engineering, management, and decommissioning stages), and addressing the technical and managerial requirements for its successful deployment, management, and retirement.

1.6.2 Specific Objectives

- To develop a *Digital Twin Lifecycle Management Framework.*
- To populate the proposed *Digital Twin Lifecycle Management Framework* with relevant concepts, methods, tools, and guidelines.
- To demonstrate the comprehensiveness of the developed *Digital Lifecycle Management Framework* with the help of a panel of international experts from academia and industry.

1.7 Scope and Limitations

1.7.1 Scope

- The scope of this research is within the development of a *Digital Twin Lifecycle Management Framework* aimed at supporting *products/assets digital twins* in the *manufacturing domain.*

1.7.2 Limitation

The *Digital Twin Lifecycle Management Framework* presented in this thesis was validated by a panel of international experts from academia and industry. The developed *Digital Twin Lifecycle Management Framework* should be considered as a first version towards the development of more sophisticated "Digital Twin Frameworks" aimed at helping to better understandthe technical and managerial implications for the whole "Lifecycle Management".

1.8 Research Methodology

Figure 3 shows the "research methodology" used to develop the proposed *Digital Twin Lifecycle Management Framework.* In the first step of the research methodology, an initial approach is made to the theme of "Digital Twins" to identify where the international scientific community stands in terms of research maturity, and particularly in terms of the development of frameworks, models, and methodologies for implementing and managing *Digital Twins systems.* To understand which frameworks, models, and methodologies were being followed, in scientific and grey publications where different use cases for *Digital Twin applications* were established, a first explorative literature review of the state-of-the-art was carried out under the search expressions: "*Digital Twin Maturity Model*" and "*Digital Twin Lifecycle Model*" – in the following databases: Google Scholar, Scopus, Web of Science, and IEEE. From this first approach, it was found that there is a gap in the literature regarding the "Full Lifecycle Management of a Digital Twin". The publications found only talk about *Digital Twins* once they are deployed, but there is very limited information about the activities that must be carried out before and after this point. In Section 2.1.5 of this thesis, a reference is made to the article: "*Digital Twin – The Simulation Aspect*" by Boschert & Rosen (2016), which mentions the evolution of a *Digital Twin,* referring to the evolution of the DT system throughout the lifecycle of a product. Seeing that this same situation was indirectly repeated in other publications (where DTs for product design, DTs for product engineering, DTs for product production, and DTs for product-service systems are discussed), so a *Research Question* in Section 1.3 was raised. This question seeks to resolve the inquiry of whether it is possible to create a "full lifecycle management framework" that establishes the steps within the lifecycle management of a Digital Twin for its development and management. Up to this point, it is known that DTs can be used at any stage of a product lifecycle, but the question now is… *How the lifecycle of a DT itself should be managed?*

Taking this into account, a second literature review of the state-of-the-art was made, however, this new investigation was carried out in a more "in-depth way" taking into account what it was desired to find. Chapter 2 contains a description of the research process carried out, as well as a summary of the main articles taken into account for the development of *Version Zero of the proposed Digital Twin Lifecycle Management Framework* (see **Figure 18**). In general, this second investigation was carried out in two parts. The first part was to carry out a scientific investigation (i.e. a scientific literature review) in the following databases: Google Scholar, Scopus, Web of Science, and IEEE, where 29 articles were compiled from the general literary corpus of the investigation. After a detailed reading of these 29 articles, only 5 of them were considered since they represented useful ideas to reach the development of the aimed *Conceptual Framework* (see Section 2.1). Because the information found in the "scientific literature" was not sufficient for the elaboration of the aimed *Conceptual Framework,* it was decided to carry out an empirical investigation, taking as reference articles from the "grey literature". Of the 17 articles retrieved from the literary corpus, another 5 articles were considered for the elaboration of the "Version Zero" of the aimed *Conceptual Framework* (see Section 2.2).

The *inclusion criterion* for the articles retrieved from the scientific literature corpus and the whitepapers gathered from the grey literature corpus was according to their possible contributions to the development of the proposed *Digital Twin Lifecycle Management Framework.* Even though 29 articles were found in the scientific literature addressing the topic of interest (e.g. "Digital Twins Maturity Continuum" and "Digital Twins Levels of Sophistication"), 24 of them were discarded since they did not provide relevant contributions to the subject of matter (i.e. Digital Twins Lifecycle Management). The 5 remaining articles that were taken into consideration provided proposals for sophistication and maturity levels of *Digital Twins.* Although all these were different, they served to provide greater integrity to the proposed *Digital Twin Lifecycle Management Framework.* Regarding the grey literature whitepapers, the same *inclusion criterion* was taken into account, however, in this debugging effort of 17 whitepapers, only 5 whitepapers were taken into account due to the relevant roadmaps and general guidelines these provided for the implementation of *Digital Twins.* These served later for the construction of the general structure of the proposed *Digital Twin Lifecycle Management Framework.*

Once the *Version Zero of the Conceptual Framework* was developed based on scientific and grey literature reviews, a second empirical investigation was carried out, but this time through interviews with international experts from academia and industry (see Chapter 4). This second research process helped to enrich the framework with new concepts, guidelines, recommendations, and ideas from the experts. A total of 17 interviews were carried out to have broad enriched feedback. Once the *Conceptual framework* was improved, *Version One of the Digital Twin Lifecycle Management Framework* (see **Figure 19**) was released, and it underwent a validation process using a "peer-review process" with the help of the international experts interviewed, based on *nominal group discussions.*

This combination of academic and industrial perspectives provided a validation of the developed framework against the two largest R&D branches of Digital Twins. After being accepted under the *accepted as is* and *accepted with minor* parameters, the Final Version (Version Two) of the *Digital Twin Lifecycle Management Framework* was released.

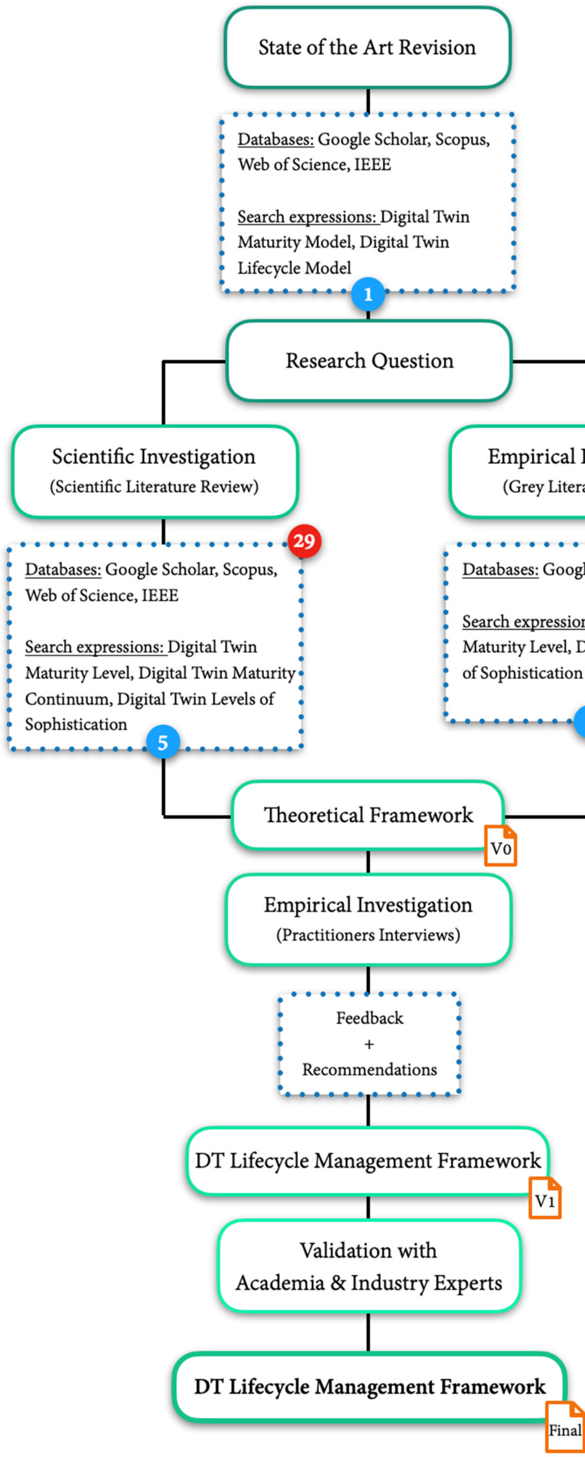

Figure 3. Research Methodology Used to Develop the Proposed Digital Twin Lifecycle Management Framework

1.9 Aimed Contribution

A *Digital Twin Lifecycle Management Framework* to support developers in better understanding the implications of deploying and managing a Digital Twin from a technical and managerial perspective, as well as proving them with relevant concepts, methods, and tools to pursue such development and whole lifecycle management.

The effort of managing a *Digital Twin* throughout its "whole lifecycle" represents a set of phases, stages, activities, and tasks that have not been fully explored, addressed, and systematized in detail by both the scientific and grey literature. It is expected that with the proposed *Digital Twin Lifecycle Management Framework* in this thesis, a first scientific contribution, at a conceptual level, can be recognized towards the systematization of all relevant concepts, methods, practices, guidelines, tools, and technologies needed for the full lifecycle management of a Digital Twin, and aimed at:

- Helping to shorten the time needed for a comprehensive *conceptualization* of a Digital Twin,

- Increasing the number of successful deployment cases of Digital Twin applications by closely supervising their *realization,*

- Ensuring the proper performance of a Digital Twin system within its threshold by using different (intelligent) maintenance strategies for each of its layers (i.e. physical product, digital thread, and digital product),

- Guaranteeing appropriate versioning management of a Digital Twin system throughout its evolution (i.e. modifications, upgrades, and new services development), and

- Providing strategic management of its historical data produced during its lifespan (e.g. for achieving for future usage, and for inheriting for immediate use).

Chapter 2: State-of-the-Art

The research presented in this thesis follows a systematic and explorative approach and therefore outlines a clear aim that is addressed in a repeatable and thorough manner. To be able to develop a *Digital Twin Lifecycle Management Framework* for the efficient development and management of a Digital Twin in a generalized way, the different proposals and points of view in the literature were researched. The result is described in the following section, based on a corpus of scientific articles and grey literature relating to the *Digital Twin* concept.

Before finding the need for developing a *Digital Twin Lifecycle Management Framework,* a general search was carried out in the scientific literature under the search expressions *"Digital Twin Maturity Model"* and *"Digital Twin Lifecycle Model"* in Google Scholar, Scopus, Web of Science, and IEEE databases. In the first search, it was found that there are different views to determine the maturity of a Digital Twin, within the community dedicated to DTs research. This means that there is no homogeneous vision when it comes to the maturity of the models and that there is a great variety of points of view. All these points of view show some logic and can somehow be applied to a large number of DTs use cases, therefore a need to concentrate on these models was observed. Regarding the second search, around 30 publications were reviewed where Digital Twins were used within the lifecycle of a product, *but no article refers to the lifecycle of a Digital Twin per se.* These publications include *"Digital Twin – The Simulation Aspect"* by Boschert & Rosen (2016) (see Section 2.1.5), where they expose the evolution of a DT throughout the product lifecycle phases. **Figure 4** included in this publication, in combination with the lack of a model that states the lifecycle of a DT, led to the approach of the *Research Question* of this thesis.

Once the *Research Question* was established, with a clearer vision of what was to be achieved, a scientific investigation was carried out requesting a systematic strategy that consisted, in the first place of searching on Google Scholar database for the concept *"Digital Twin"* followed by certain keywords. The first searching string was *"Digital Twin"* + *"Maturity Level",* limiting articles between 2003 (appearance of the concept) up to August 2021, yielding 342 results of which nine were taken into account to form part of the literary corpus, that was later filtered according to the usefulness of their content. Subsequently, *"Digital Twin" + "Maturity Continuum"* was searched under the same search conditions and five other articles were found, where one of them appeared at the first search. Finally, a search was made as *"Digital Twin" + "Levels of Sophistication"* where from the 43 results found, three were taken into consideration for the general literary corpus. This same procedure was carried out in Google Scholar, Scopus, Web of Science, and IEEE databases, forming a final scientific literary corpus of around 29 research articles. To filter out the information, it was searched between the final articles for those that presented a clear proposal for differentiation between the levels of integration, maturity and/or sophistication of Digital Twin systems. After this process, four scientific articles were taken into account (see Section 2.1) to develop the *Version Zero of the Digital Twin Lifecycle Management.*

Despite the recent interest in the *Digital Twin concept* observed in the scientific literature, there is little knowledge or research on the *integration level of a DT.* Without being satisfied with the result obtained in this systematic research, an explorative investigation of grey literature was carried out. Under the same search strings such as *"Digital Twin Maturity Level"* and *"Digital Twin Levels of Sophistication"* five main publications, out of 17, were retrieved from Google and Google Scholar. The main characteristic for which they were taken into account was the individual contribution or point of view that complements the levels of integration previously extracted from the scientific literature. One of them proposes a methodology for the development of a Digital Twin Roadmap according to the maturity and implementation practices of the DT. With this in mind, it was possible to start working on the general structure of the aimed *Digital Twin Lifecycle Management Framework,* taking into account the lifecycle phases of a DT as well as the different points of view when talking about the maturity levels of a DT. Making inquiries related to the subject, a guide for the implementation of Digital Twins was extracted from the LinkedIn of the company XMPRO[1], forming part of the basis of the Conceptual framework proposed in this thesis.

In total, the structure of the *Conceptual Framework* is based on five scientific articles and five publications from the grey literature. Each of these articles and publications will be detailed in the following corresponding sections.

2.1 Scientific Literature Review

A scientific literature review aims to describe relevant published "scientific" materials, which can provide an examination of recent or current literature on a topic, in this case about Digital Twins.

2.1.1 Article 1: Leveraging Digital Twin Technology in Model-based Systems Engineering

In this article, Madni et al. (2019) emphasize the vague and broad perception that is ongoing nowadays regarding the *Digital Twins.* In their publication, they mention that the fact of having a digital version of the system, component, or asset is enough to say that there is a "Digital Twin", as observed in the literature. In turn, they show that this interpretation leaves many empty spaces as well as a series of unresolved questions. Among them, they wonder if it is necessary to have a physical system first before being able to create the virtual representation of a Digital Twin. In another case, they wonder if, for a Digital Twin to be created, there must be prior communication of the physical system, made up of sensors and processors, with the virtual system where it is fed with information on the status, performance, health and maintenance data. Finally, there is the doubt if the arrival of the Industrial Internet of Things (IIoT) can generate a change in the definition of a Digital Twin since with this technology any physical asset can become "smart".

[1] XMPRO - https://xmpro.com/

Taking into account this series of questions that are raised, and in all those that are addressed in the literature regarding DTs and their various uses, Madni et al. (2019) decide to propose four levels of sophistication for the virtual representation of a Digital Twin. With this, what is intended is to encompass, in a general way, all the proposed *DT-driven applications.* These levels start from the consideration if there is a physical twin or not, continuously taking into account the type and characteristics of the information acquired from the physical model, and ends with the capacity of the system to implement Machine Learning (ML) models, either for the preferences of the operator or even more complex, for the autonomous operation of the system or environment. In this way, it can be observed in **Table 1** (Madni et al., 2019), that each of the levels presented has a purpose and a specific scope that facilitates decision-making and answering questions set throughout the lifecycle of the system. In turn, the main characteristics that make up each level, and that differentiate them from the others, are shown.

Table 1. Digital Twin Levels of Sophistication (Madni et al., 2019)

Level	Model Sophistication	Physical Twin	Data Acquisition from Physical Twin	Machine Learning (Operator Preferences)	Machine Learning (System/Environment)
1 Pre-Digital Twin	virtual system model with emphasis on technology/technical-risk mitigation	does not exist	Not applicable	No	No
2 Digital Twin	virtual system model of the physical twin	exists	performance, health status, maintenance; batch updates	No	No
3 Adaptive Digital Twin	virtual system model of the physical twin with adaptive UI	exists	performance, health status, maintenance; real-time updates	Yes	No
4 Intelligent Digital Twin	virtual system model of the physical twin with adaptive UI and reinforcement learning	exists	performance, health status, maintenance, environment; both batch/real-time updates	Yes	Yes

This first approach towards the maturity levels that a Digital Twin can reach, was taken into account to establish one of the points of view that make up the Conceptual Framework proposed in this thesis. Each of the four levels sent by Madni et al. (2019) is described later in Section 3.1.2.1.8. It is generally said that these proposed maturity levels correspond to the Machine Learning (ML) implementation capability of a DT system that will be part of the *Design and Engineering phase* of a Digital Twin.

2.1.2 Article 2: Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behaviour in Complex Systems

This second article is of utmost importance not only for the thesis but also for the *History of the Digital Twin concept* (Grieves & Vickers, 2017). This article is part of the first three publications that Grieves makes regarding the Digital Twins. It is said to be one of the most important since it was the article that broke the publication barriers and allowed general knowledge of the concept. Although in 2003 he spoke at the University of Michigan on the subject, the interest and impact the concept had, was not as expected. Later, in 2005 he made a second contribution to the subject, but once again, and due to the lack of exposure of his article, his vision was not shared with specialists who landed the idea. Finally, in 2016, this article arrives in collaboration with John Vickers, where he makes a compendium of his ideas and compares them with the successful applications that were made by NASA and the U.S. Army (Grives & Vickers, 2017).

One of the ideas that were taken up to shape the proposed *Digital Twin Lifecycle Management Framework* is the contribution made in its 2005 publication. Without giving more details of where they originate, Grieves (2005) proposes and defines three ways in which *Digital Twins* can manifest themselves. These types of DT manifestations can be (i) Digital Twin Prototype, (ii) Digital Twin Instance, and (iii) Digital Twin Aggregate. By making a perception match, the DT *"type"* can be changed by Digital Twin *"maturity level"*. In this way, the second point of view is obtained regarding the sophistication of the DT system, which allows it to be included in the proposed Conceptual Framework. The definition of each of these levels is detailed in Section 3.1.2.1.3 of this thesis, where the evolution is labelled under the heading *DT Classes and Instances* (Grives & Vickers, 2017).

2.1.3 Article 3: Digital Twin Technology for "Smart Manufacturing"

In this article, Evangeline & Anandhakumar (2020) explore the potential that a *Digital Twin* can have in terms of generating value within a business. Taking into account the current increase in storage capacity and computing costs, which in turn have led to the implementation of *Digital Twins* in a large number of use cases and possibilities, they managed to land their idea. Within this publication, they express and make companies see that they should begin to focus on issues that increase their business value such as strategic performance and marketplace dynamics, improved and longer-lasting product performance, faster design cycles, the potential for new revenue streams, and better warranty cost management. These types of problems, among many others that companies face, can be attacked and solved with *Digital Twin applications* that in addition to providing an adaptable solution help to increase value. **Table 2** shows a summary of these values by category proposed by Evangeline & Anandhakumar (2020), along with a series of specific points in which DTs could be incurred. In addition to the areas of business values mentioned, they clarify that these are not the only ones since a *Digital Twin* can also help solve many other key performance and efficiency indicators of manufacturing companies. The great potential that this type of technology has is that they are capable of offering different applications to add value to the business and step by step change how it is developed. This increase in value has the advantage of being measurable and quantifiable to rate the efficiency of the application concerning key business metrics.

Table 2. Digital Twin Business Value Generation (Evangeline & Anandhakumar, 2020)

Category of business value	Potential specific business values
Quality	• Improve overall quality • Predict and detect quality trend defects sooner • Control quality escapes and be able to determine when quality issue started
Warranty cost and services	• Understand current configuration of equipment in the field to be able to service more efficiently • Proactively and more accurately determine warranty and claims issues to reduce overall warranty cost and improve customer experiences
Operations cost	• Improve product design and engineering change execution • Improve performance of manufacturing equipment • Reduce operations and process variability
Record retention and serialization	• Create a digital record of serialized parts and raw materials to better manage recalls and warranty claims and meet mandated tracking requirements
New product introduction cost and lead time	• Reduce the time to market for a new product • Reduce overall cost to produce new product • Better recognize long-lead-time components and impact to supply chain
Revenue growth opportunities	• Identify products in the field that are ready for upgrade • Improve efficiency and cost to service product

This table was taken into account for the development of the *Digital Twin Lifecycle Management Framework* proposed in this thesis. By making some adjustments regarding importance and complexity, each of these categories was located to a certain level in which a maturity degree was assigned, making them match with the same logic of the points of view presented above. In Section 3.1.2.1.6, under the *Value Proposition label,* the definition assigned to each of these levels is found, as well as what is expected to be obtained in each one of them.

2.1.4 Article 4: Digital Twin and Cloud, Fog, and Edge Computing

In this article, Tao et al. (2019) refer to the fact that a *Digital Twin* has a certain degree of granularity and that for this reason, the complexity of the system and the technology required at each level is different in each one of them. For a *Digital Twin* to be able to integrate data from different objects, activities and processes, for better innovation and efficiency in product design, production planning, or implementation, it is necessary to take into account three complementary technologies in the system, which are, (i) edge computing, (ii) fog computing, and (iii) cloud computing. Each of them can be integrated at the different granularity levels to achieve specific objectives. This derives from the fact that the different levels of *Digital Twin* have different requirements to be able to execute a correct processing and circulation of data, taking into account latency, bandwidth, security, etc. They mention that when edge computing, fog computing, or cloud computing is implemented with its complementary properties, new ideas or ways of implementing each of these maturity levels can be generated. In general, both edge computing and fog computing provide good storage, computing, and network services between end devices and traditional cloud computing, opening a wide opportunity to generate smart manufacturing applications (Tao et al., 2019).

This comparison between each computing type and how it can be implemented in each of the *Digital Twin levels* was taken into account to build up the *Digital Twin Lifecycle Management Framework* proposed in this thesis. Each one of these technologies is considered in the Conceptual Framework as the degree of maturity, since according to the proposal of Tao et al. (2019), as the complexity of the system increases, the requirement of a certain level of computation increases proportionally. It is worth mentioning that this degree of maturity can be seen all the way around, starting with cloud computing and ending at edge computing, this occurs when computing capacity is prioritized or when considering how deterministic the system is. The definition of each of these levels is explained in Section 3.1.2.1.12 under the heading Computing.

2.1.5 Article 5: Digital Twin – The Simulation Aspect

In this article, Boschert & Rosen (2016) refer to the *Digital Twin's vision* as a full physical and functional description of a component, product, or system that includes all information that might be relevant in all phases of the lifecycle of a product, including the present and future information. In this article, they put special attention on the simulation aspect of the Digital Twin. They mention that modelling and simulation are now commonplace in system development, for example, to aid design tasks or to verify system features. The first simulation-based solutions are created for efficient operations and failure prediction during the operation and service phases of the lifecycle.

They strongly recommend focussing Digital Twins on reducing time-to-market, due to its present and future importance. The article remarks on the necessity to enforce the interrelation of simulation models at various degrees of complexity, across all the lifecycle stages. Also, they note the importance of focusing on the optimization of mechatronic products and systems throughout their usage or operation, such as a component of production equipment or a supply part, closing the gap between development and operation.

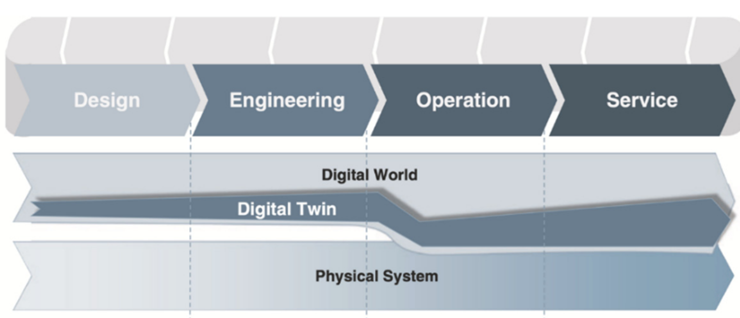

Figure 4. Digital Twin Evolution along with the Product Lifecycle Phases (Boschert & Rosen, 2016)

They explain in **Figure 4** how DT stores all the information and models needed to complete tasks in subsequent phases and develop new values, such as "help systems" for operators, users, and maintenance employees. During the design and engineering phases, the volume of the Digital Twin increases. The transition to the operation or use phase can be accomplished in a variety of ways, depending on the component, product, or system in question. As a result, Boschert & Rosen (2016) remark that it is conceivable that not all the information and models will be transmitted. During the operation and service phases, however, the amount of data captured and kept in the Digital Twin will expand again.

In general, this article led to the creation of the *Digital Twin Lifecycle Management Framework.* As explained in the *Research Methodology,* this article, specifically **Figure 4** cast doubt on whether it was possible to create a framework that dealt with the whole lifecycle of a Digital Twin itself, not on how it could play an important role in the PLM stages. Taking the Boschert & Rosen (2016) model as a reference led to the development of the proposed Conceptual Framework and the general idea of the need for a Lifecycle Management Framework for Digital Twins. That is to say, how the design stage (see Section 3.1.1), the engineering stage (see Section 3.1.2), and the operation and service management stage (see Section 3.2.1) of a DT must be carried out, and also how its possible retirement stage should be handle (see Section 3.3.1).

2.2 Grey Literature Review

A grey literature review aims to describe relevant published materials (e.g. whitepapers) outside of academic publishing, which can provide an examination of recent or current literature on a topic, in this case about Digital Twins.

2.2.1 Whitepaper 1: The Digital Twin Maturity Continuum

This first whitepaper of the grey literature corpus was published by Socha (2018) on the website of Smart Energy International, a leading authority magazine on the smart meter, smart grid, and smart energy markets that provides up-to-the-minute global news, incisive comments, and professional resources. In this post, Socha (2018) proposes the likely *evolution of the Digital Twin* in which it grows from a simple concept, becomes a standalone Operational Technology (OT) application, and then integrates with the Information Technology (IT) platforms of companies, finally reaching a point where this type of technology can be recognized and perceived as unique entities. Radically, he mentions that they can become so large and complex that they can even function as complete company models. The evolution model that he proposes (see **Figure 5**), is composed out of six stages that go up in such a way that there is a gradual integration between the OT and the IT world. The first three stages raise a question that summarizes the central functionality of the Digital Twin at that level. For the fourth stage, it shows that this level is a fundamental piece for the bridge between OT and IT integration and as the model evolves it becomes crucial to help in decision-making. Finally, the evolution of the system ends when it eliminates direct human interaction or supervision.

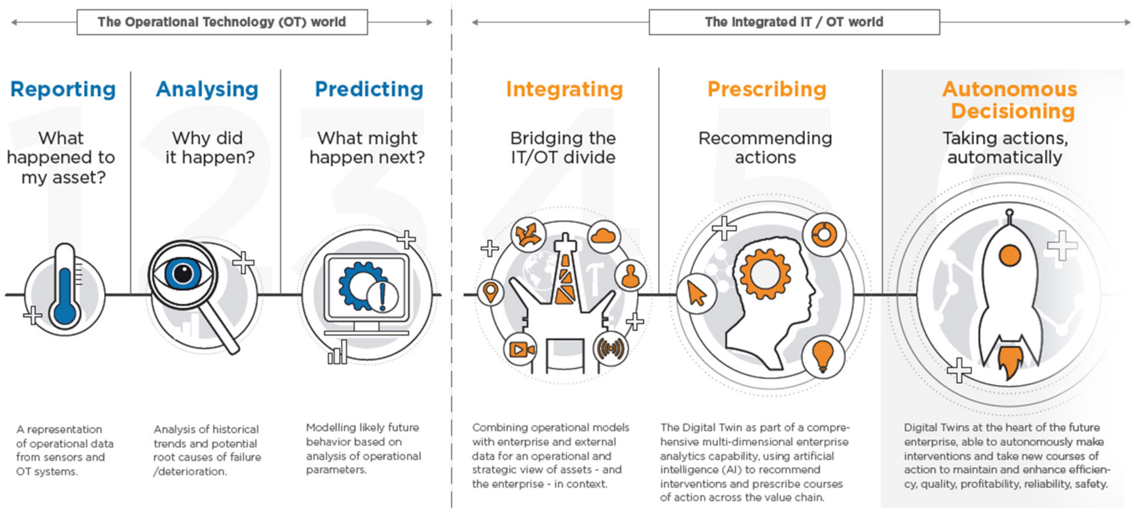

Figure 5. The Digital Twin Maturity Continuum (Socha, 2018)

If this model gets analysed in detail, and the background that exists in each evolution is appreciated, what changes between one and the other is the information that the Digital Twin contributes to the business. In this way and taking it to a matter of evolution in terms of maturity, this proposal was considered in the development of the *Digital Twin Lifecycle Management Framework* presented in this thesis. Because of how the data gives value in each step of the transformation, that is to say, it gives precise and useful information, that label is assigned to Section 3.1.2.1.4, where more details of each evolution stage are presented.

2.2.2 Whitepaper 2: Verdantix Says that Digital Twins Operate at Five Different Levels of Sophistication

This post by Russell (2019) on the Verdantix website, an independent research and consulting firm, is a summary of the highlights of the 2019 report "Smart Innovators: Digital Twins for Industrial Facilities". Russell (2019) mentions that in this whitepaper a prediction is made upon the statement that the *Digital Twin market* will bring with it a great change in the value that the operations of the industries will have and in the control of risks in real-time. Asset-intensive industries will be among the first to implement Digital Twins in their processes. However, she refers that despite the popularity that this technology begins to have, the market will grow at a very low rate for the next five years with operations of high monetary risk. In addition to this, she mentions that after the arrival of these new systems, large service providers such as Akselos, eVision, GE Digital, among others, have begun to offer *Digital Twins software* based on five main levels of sophistication. In **Figure 6** these sophistication levels, proposed when developing the software, are shown and are capable of deploying a Digital Twin that goes from integrating information from different sources up to one that can act autonomously and independently.

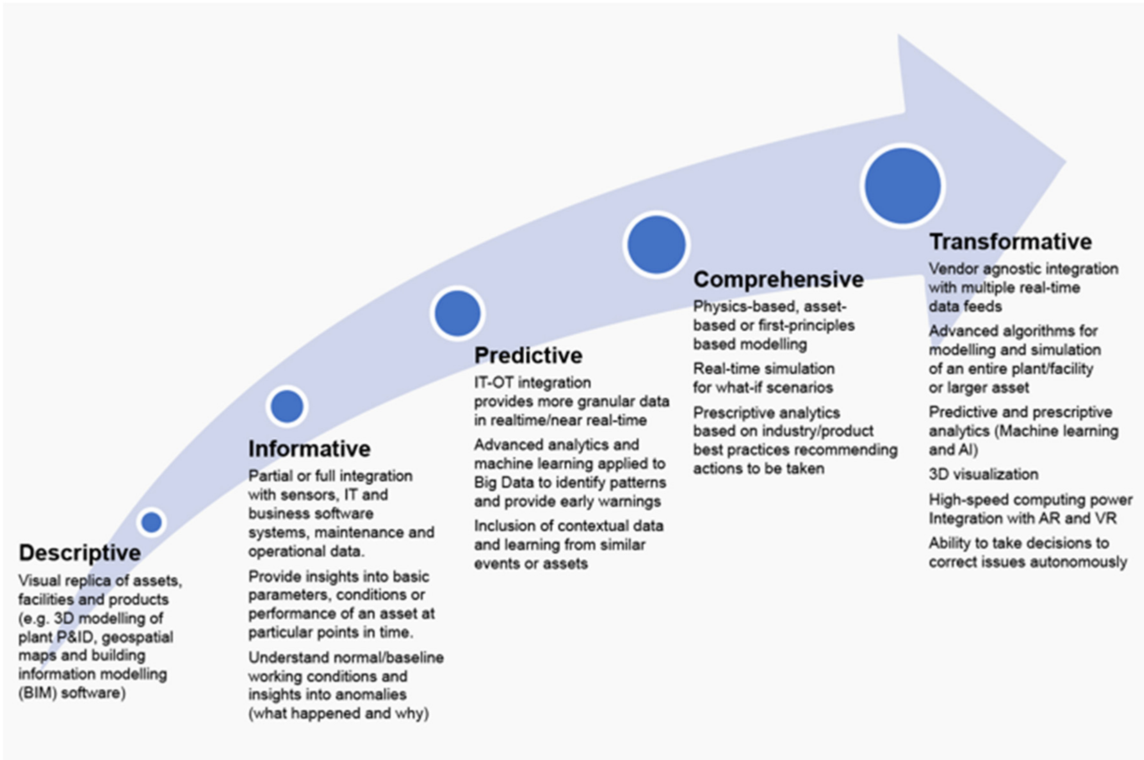

Figure 6. DTs' Levels of Sophistication (Russell, 2019)

This whitepaper does not show more information about these proposed levels of sophistication for Digital Twins, and access to the concerned report is restricted; however, Section 3.1.2.1.7 seeks to provide an explanation of these levels with additional literature found on the subject. This model was considered as a complement to the proposed *Digital Twin Lifecycle Management Framework*, despite the lack of further information, since it provides a natural representation of how the sophistication of data analytics changes according to the complexity of the system.

2.2.3 Whitepaper 3: How to Realize the Value of the Digital Twin

This is a Burande (2019) publication on the Dassault Systems portal in which he talks mostly about the importance of the Digital Transformation of a company and how it can help improve traditional areas such as revenues, margins, quality, and time-to-market, and later it could help monetize aftersales services and end-user experience as well as increase visibility and traceability of resources. Like Socha (2018), he mentions that a *Digital Twin* is capable of generating value from the information collected. In the first place, by monitoring operations and real-time behaviour of the product, asset or process deployed, or in the second place, through the prediction of failures and the correct prescription of corrective actions.

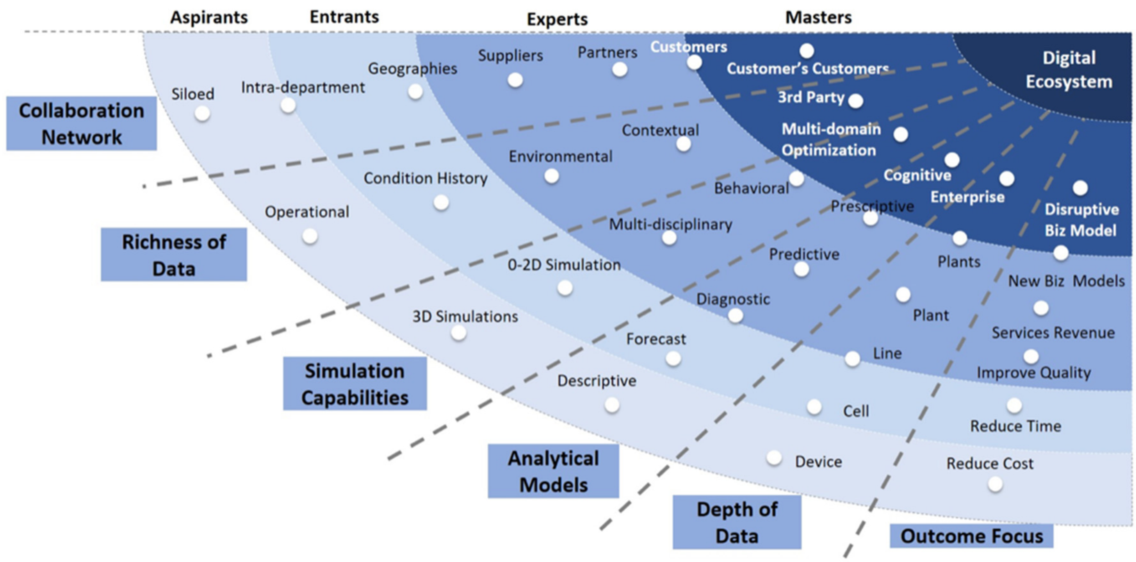

Figure 7. Digital Twin Roadmap (Burande, 2019)

At the end of this whitepaper in form of a summary of the main advantages that Digital Twins have, the challenges that are currently being presented and the areas of opportunity that have to be worked on in the future, Burande (2019) presents a roadmap (see **Figure 7**) elaborated by the HCL's Product Lifecycle consulting team and its customers. In this, it is sought that the client can choose the appropriate elements at the relevant maturity level according to the needs of the project. This roadmap presents six independent paths to take with four levels of complexity to choose from when *designing a Digital Twin.* After analysing the proposed paths, the Analytical Models and Outcome Focus were considered of greater relevance, since there were similarities with the models proposed by Socha (2019) and Evangeline & Anandhakumar (2020) respectively. The *Depth of Data path* was considered as a new point of maturity, which reflects the degree of granularity of a Digital Twin proposed by Tao et al. (2019). Section 3.1.2.1.2 refers to this, but the label is changed to *Depth of System*. In this section, the use of Digital Twin is reflected from its basic representation as a specific element unto modelling a supply chain in a general way.

2.2.4 Whitepaper 4: Data Leadership Guidance Note: Digital Twin

This whitepaper is a guide published by the Smart Cities Council Australia New Zealand, the world's largest network of smart cities companies, practitioners, and policymakers, embracing technology and data to accelerate liveability, workability and sustainability in our cities and towns, in 2020. In it, a brief introduction is made about the *Digital Twin topic* and how it gets involved with smart cities. Apart from mentioning the five main capabilities that a Digital Twin must have (viz. connect, integrate, visualize, analyse, and secure), they present the six main areas that they have managed to identify that are crucial for the successful implementation of a Digital Twin through a region. These areas are based on the different levels with which both the Australian and New Zealand governments are governed. In the first place, they mention that it is necessary to establish Policies between the departments in charge of developing a DT to operate coherently and carry out tasks following common standards, methods and protocols. Second, it is needed to establish a Governance structure to effectively manage each of the activities that present risk or that are of great importance to meet the overall business objectives of the organization. Third, it is important to start developing Standards to establish the ideas of what a DT should look like and thus be able to scale the opportunities that this type of technology offers. Fourth, it is considered relevant to establish Education and Training strategies to ensure that the maximum number of stakeholders can access opportunities for furthering their knowledge and skills. Fifth, it is necessary to promote Research and Development programs to increase the impact and innovation of Digital Twin technology. In sixth place, and the one most relevant for this thesis, it is mentioned that it is necessary to establish an Implementation Strategy. According to the maturity and implementation of the Digital Twin practices of a company, it is necessary to follow the methodology for the development of a roadmap (see **Figure 8**).

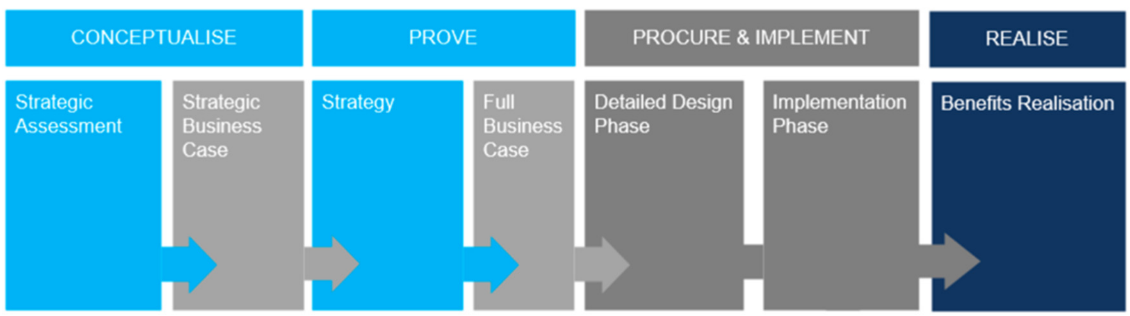

Figure 8. Methodology for Developing a Digital Twin Roadmap (SCCANZ, 2020)

This methodology is based on four main areas for the development of a *Digital Twin model.* In this, it is considered to start with a clear strategic evaluation of the desired application of the digital twin, in addition, include an analysis of the current situation of the company and the objective to be achieved. Subsequently, it is convenient to establish a strategic business case for the application and provide a delivery strategy. Finally, it is recommended to produce a complete business case accompanied by the development of a detailed implementation and procurement plan. It is said that this contribution was of great relevance to the proposed framework since it gave structure to the integration. These stages of the methodology proposed by SCCANZ are observed in Sections 3.1.1.1, 3.1.1.2, 3.1.1.3, 3.1.2.1, and 3.1.2.2.

2.2.5 Whitepaper 5: The Ultimate Guide to Digital Twins

This post was found on LinkedIn in the account of Peter van Schalkwyk, CEO of XMPro company, a global provider of software and services for Real-Time Operational Intelligence. In this whitepaper of 2019, in the beginning, he provides the *definition of Digital Twin* offered by the company, exposes the DT categories that can be developed (viz. Discrete Digital Twins, Composite Digital Twins, Composite Assembly Twin, and Composite System Twin) where it is no more than a reformulation of the three categories proposed by Grieves in 2016. Later, in chapter two, he talks about the main benefits that these technologies can provide to a business, among which is sharing data through silos, controlling operations in real-time, conducting simulations and experiments, increasing trustworthiness, and enabling collaboration. Later in chapter three, he mentions the three categories of Digital Twin that his company has a focus on. These categories are (i) Status Twin – used for basic condition monitoring applications, (ii) Operational Twin – where more extensive information is provided that is typically used in decision support by operators, reliability engineers, and other decision-makers, and (iii) Simulation Twin – that by using different types of simulation or Artificial Intelligence (AI) capabilities is capable of predicting, forecasting, or providing insight into future operational states. Making an extrapolation of these types of Digital Twin it can be seen the similarity in the levels of maturity proposed in the Burande (2019) roadmap, reviewed above. In the following chapters, van Schalkwyk (2019) makes recommendations on how to integrate Artificial Intelligence (AI) and Machine Learning (ML), within the Digital Twins, to perform real-time analysis, provide decision support and provide the company with prescribed recommendations and analyses, as well as in how to combine DTs with blockchain to store system information.

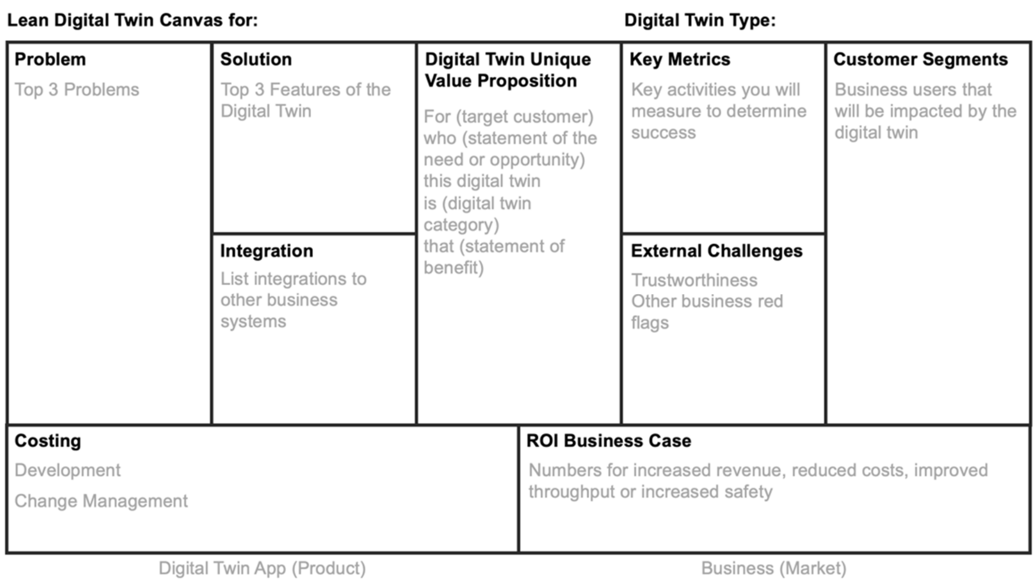

Figure 9. Lean Digital Twin Canvas (van Schalkwyk, 2019)

Finally, in chapter eight he makes a brief account of the steps to follow for the development of a Digital Twin, in which he proposes the use of a *Lean Digital Twin Canvas* (see **Figure 9**) for project planning. This canvas shows a great similarity to a Lean Business Canvas, with the slight difference that it is presented with a specific approach to planning "Digital Twins". These nine building blocks that make up the "Lean Digital Twin Canvas" are combined with part of the "Methodology for Developing a Digital Twin Roadmap" and in this way gives form to the *Digital Twin Lifecycle Management Conceptualization Stage* of Section 3.1.1 of this thesis.

2.3 Research Gap in Literature

After reviewing both the scientific and grey literature, it can be concluded that two main gaps in the literature led to the development of the proposed *Digital Twin Lifecycle Management Framework.* In the first place, there is a clear tendency to offer different proposals in terms of levels of sophistication or maturity of a Digital Twin. In them, each author proposes his/her own model based on his/her own experience or according to the *Digital Twins models* reviewed in the literature. To put together a compendium of these visions in one place, the central structure of the Conceptual framework is proposed, where the user is allowed to choose the most appropriate combination of technologies to develop their project (basing this idea on the proposed by Burande (2019) on his Digital Twin Roadmap). Moreover, it is observed that the literature only addresses issues of development and implementation of a Digital Twin. This means that research approaches only take an engineering approach and forget to mention what is behind the deployment of the application and what needs to be done after it is done. Taking this into account, a *Design stage* is proposed first, where it is sought that the project planning is developed. In the second place, the *Engineering stage* is found, which is a global vision of the degrees of maturity found in the literature. Finally, as a third stage, the *Management stage* is proposed where it seeks to constantly update the system and provide support when needed. What this framework seeks is to show the point that Digital Twin deployment goes beyond the *Engineering part,* it is necessary to form a work and implementation plan according to what is desired to be obtained, as well as it is also necessary to be aware of the system once implemented so that the benefits provided always have the necessary quality.

Chapter 3: Towards a Digital Twin Lifecycle Management Framework

After a comprehensive review of all the available and relevant scientific and grey literature, a clear research gap was found regarding the integration of the design, engineering, and managerial stages of a Digital Twin. This lack of integration led to the creation of the proposed *Digital Twin Lifecycle Management Framework* that is shown in **Figure 10** and it is the main contribution of this thesis.

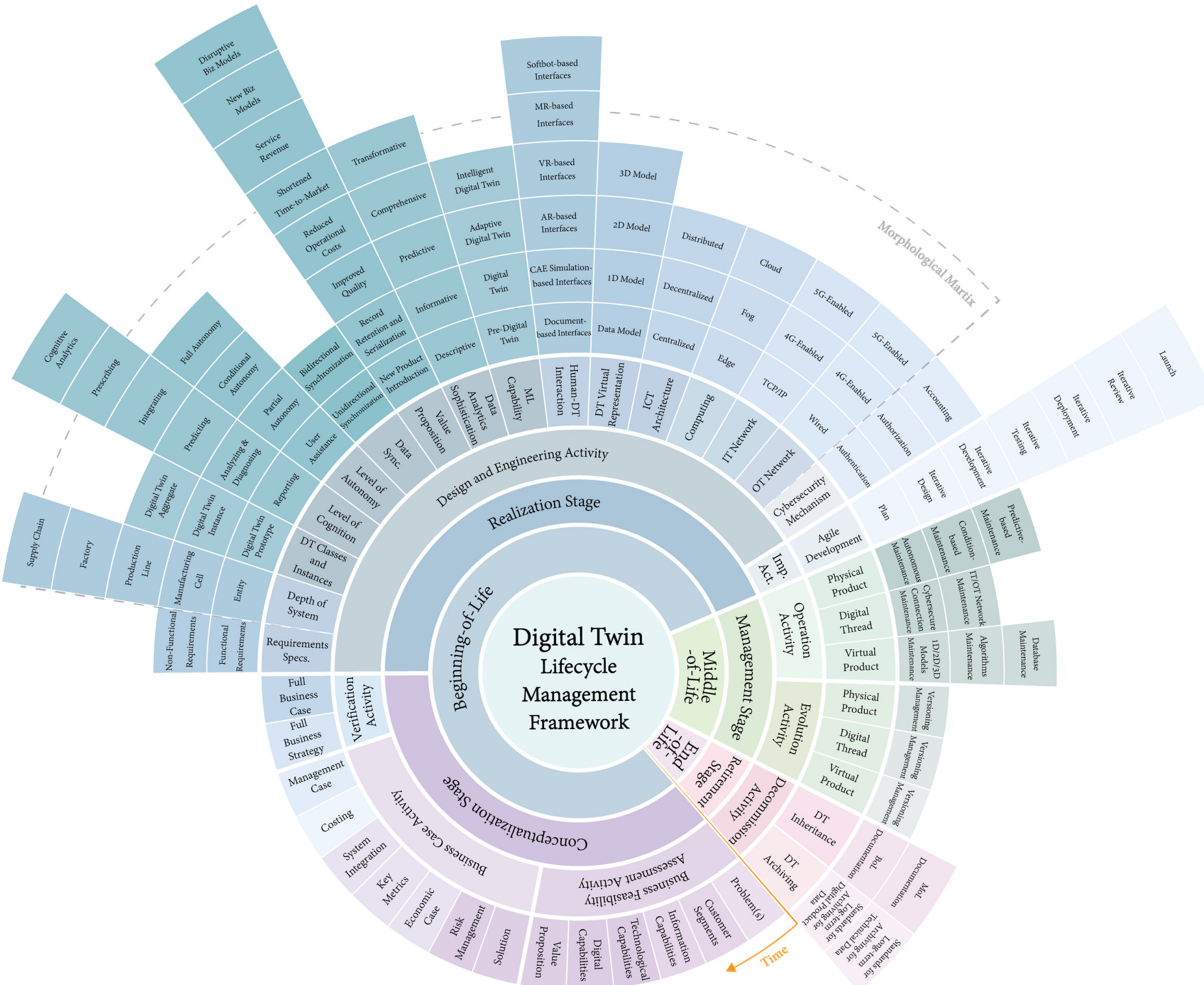

Figure 10. Digital Twin Lifecycle Management Framework[2]

[2] See also Annex 1: Digital Twin Lifecycle Management Framework for a Table Design View.

This *DT Lifecycle Management Framework* shows the different contributions found throughout the literature reviews and the empirical investigations, within a specific order to carry out the gradual and appropriate integration of any project where a Digital Twin solution is planned to be used. In the following sections, each of these lifecycle management phases will be described and what it is aimed to obtain from them while planning the development of a DT system. It should be noted that this framework is based on the common lifecycle stages of an entity (viz. beginning-of-life, middle-of-life, and end-of-life), which in turn are based on the three areas mentioned above (viz. design, engineering, and management). It is intended to be involved within the same framework so as not to forget that the construction of a DT goes beyond the engineering part. That is necessary to start previously with the design or planning in the form of a business plan, to later continue with the engineering part where the most appropriate technologies must be chosen to meet the needs raised in the previous step, and finally finish with a planning scheme for the development, implementation, and maintenance of the DT system.

Based on the above introduction planning schema towards the development of a *Digital Twin Lifecycle Management Framework*, in this thesis, a *Digital Twin Lifecycle* is defined as *"the lifecycle of the digital twin itself, including its conceptualization and realization (beginning-of -life); its use, maintenance, and any possible modification to it such as upgrades (middle-of-life); and possible retirement at the end of its lifespan (end-of-life)".*

3.1 Beginning-of-Life (BoL) Phase

The first stage at the beginning of the lifecycle of a Digital Twin comprises its *Conceptualization Stage*. It is said that this stage focuses, in the first place, on the planning of a DT project, through the analysis of its potential problems, capabilities, and limitations. Similarly, it focuses on its business planification, evaluating the viability and feasibility of the DT project, and on establishing the key points that will serve as a metric for a DT solution. This first stage of the BoL of a Digital Twin, which is called the *Conceptualization Stage* in this Lifecycle Management Framework, ends with a final review of the proposals and established conceptualization models.

The second stage of the beginning-of-life phase of a Digital Twin is sustained by its *Realization Stage*. It establishes all the important points, in the Design and Engineering fields, for the deployment of a DT project. Many of the DT concepts in this stage were taken from the scientific and grey literature while others were provided during the enrichment stage of the framework by international experts from academia and industry. The BoL phase of a Digital Twin ends when a DT project is successfully deployed and put into operation. To get to this point, the implementation of agile methodologies for the development of a DT project is recommended to guarantee a good and correct deployment of the DT application.

3.1.1 Conceptualization Stage

Conceptualization is understood as any previous activity necessary for the implementation of a DT. This stage is based on the strategy proposed by Pieter van Schalkwyk (2019) on its "*Ultimate Guide to Digital Twin*" whitepaper in combination with the whitepaper titled "*Data Leadership Guidance Note – Digital Twin*" from the Smart Cities Council from Australia and New Zealand (SCCANZ, 2020).

On one hand, from the first whitepaper, the main idea that was gathered was the one that proposes as a first step to have a clear idea of the problem that is worth solving with the implementation of a DT. For this case, Pieter van Schalkwyk (2019) suggests a prioritization approach to make an iterative rank of (i) multiple initiatives in an organization that could benefit from Digital Twins and then of (ii) assets or processes that collectively operate as a system. The first prioritization approach aims to determine which system is the most important, or convenient, to focus on. The second approach is used to provide a guide into which use cases of an asset grouping are candidates for being serviced by a single Digital Twin.

The second idea was taken from the whitepaper "*Ultimate Guide to Digital Twin*" was the implementation of a *Lean Digital Twin Canvas* (see **Figure 9**); which is a *single-page DT solution description.* Its structure is based on the Lean Canvas proposed by Ash Maurya[3], but with a few adaptations focused on the implementation of a Digital Twin. In general, it contains all the key elements of the problem and the proposed DT solution. This holistic approach considers all aspects required to deliver a successful Digital Twin project.

On the other hand, after reviewing the whitepaper "*Data Leadership Guidance Note - Digital Twin*", what was useful to recall for the proposed *Digital Twin Lifecycle Management Framework* is the methodology for developing a *Digital Twin Roadmap* (see **Figure 8**). In this whitepaper, the Smart Cities Council from Australia and New Zealand (SCCANZ, 2020) states as principal steps to (i) undertake a clear strategic assessment for the application of the Digital Twin, including the current and target state analysis, (ii) set a strategic business case, (iii) plan a delivery strategy, (iv) review the full business case, and finally (v) developing a detailed implementation and procurement plan. Each of these steps is further described in the following sections.

Moreover, what is important to appreciate from these conceptualization methodologies is that when taking a closer eye into both approaches, it is noticeable that some of the concepts are being shared in some way, resulting in a more enriched *Conceptual Framework*. Taking into consideration the synergy present in these two whitepapers is how the *Conceptualization Stage* of the proposed *Digital Twin Lifecycle Management Framework* is structured.

[3] Lean Canvas – https://leanstack.com/lean-canvas

3.1.1.1 Business Feasibility Assessment Activity

According to the SCCANZ (2020), the purpose of this assessment activity is to understand the current state regarding roles and responsibilities (in relation to information and data), current levels of awareness, knowledge, experience, and capability. This is in terms of digital working and information, management, standards, methods, procedures, and technology. This information will help understand the current 'as-is' state and helps to have a clearer vision of the objective to achieve taking into account the installed capacity.

This section is divided into (i) Problem(s), (ii) Customer Segments, (iii) Information Capabilities, (iv) Technological Capabilities, (v) Digital Capabilities and (vi) Value Proposition, where (i) and (vi) are concepts taken from the *Lean Digital Twin Canvas* and (ii) to (v) from the *Methodology for Developing a Digital Twin Roadmap.*

3.1.1.1.1 Problem(s) Definition Task

In this task, the prioritization concept is brought on to answer the question: *What is the business problem that is being tried to be solved?* The high-level business outcomes in the prioritization framework are the basis for scoring and agreeing on the business impact of a specific use case. The prioritization process starts with a list of potential Digital Twin use cases and ranks them based on their business impact for each desired business outcome. The business impact metrics are chosen to align with the strategic objectives of the organization. These are often referred to as the business drivers in digital transformation programs (see **Figure 11**).

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Use Case Prioritization

		Business Impact					Economic	Technical Feasibility							
#	Use Case/Scenario	Safety	Downtime	Throughput	Quality	Cost	Value/year	Automation	IT Systems	Analytics	Environment	Project	B Rank	T Rank	Impact
1	Use Case 1	Medium	High	High	High	High	> $10m	High	High	Medium	High	High	6	3	2
2	Use Case 2	Low	Low	Medium	customer satisf	High	> $10m	High	High	Low	High	High	7	6	2
3	Use Case 3	Low	Low	Low	Low	Low	> $1m	High	High	Low	High	High	3	7	1
4	Use Case 4	Low	Low	Low	Low	Low	> $1m	High	High	Low	High	High	8	8	2
5	Use Case 5	Low	Medium	High	Low	Medium	> $10m	Medium	High	Low	High	High	8	4	3
6	Use Case 6	Medium	Medium	Medium	Medium	Medium	> $1m	High	High	High	High	High	6	2	2
7	Use Case 7	Low	Medium	Medium	Medium	Low	> $1m	High	High	High	High	High	4	3	1
8	Use Case 8	Medium	Medium	Medium	Medium	Medium	> $10m	High	High	High	High	High	7	3	2
9	Use Case 9	Medium	High	High	High	High	> $1m	High	High	High	High	High	4	8	1
10	Use Case 10	High	Medium	Low	High	Low	> $1m	Medium	Medium	Medium	High	High	7	4	2

Figure 11. Use Case Prioritization (van Schalkwyk, 2019)

Once the business impact is scored for each scenario the technical feasibility (or complexity) is assessed for each scenario, again without over-analysing or getting into too much technical detail. It is a top-down approach and even though information from reliability engineering practices like FMEA can be helpful indicators, it is important to take care that this becomes a technical feature or requirements design session. The impact assessment is done based on the strategic drivers of the business such as Safety, Down Time, Quality, Throughput, Cost etc. Then, for the Technical Feasibility, the typical technical assessment criteria considered are (i) OT complexity, (ii) IT complexity, (iii) analytics, (iv) system complexity, and (v) project readiness. Technical assessment criteria can be adjusted to fit the requirements of the business, but the previous criteria correspond to a typical industrial installation.

The final step for the problem statement is to define the "order of magnitude" for each use case in terms of financial measures, to agree on the high-level impact of each new state or scenario. The objective is not to be accurate in estimating the value of a business case, but to get a high-level agreement between the different stakeholders on the potential impact of each scenario.

This "order of magnitude" is visually represented in a bubble chart with the business impact and technical readiness scores as the two major measures, as shown in **Figure 12**. The weighted average values of each of the measures are placed on the graph which is divided into four quadrants. The size of the bubble is determined by the value of the economic impact. The four quadrants represent the business readiness for each of the *Digital Twin scenarios.* The "Do Now" quadrant represents high business impact and a high level of technical readiness. Opportunities on the far right of the quadrant with the biggest bubble size often represent Digital Twin projects with the highest likelihood of success for all stakeholders.

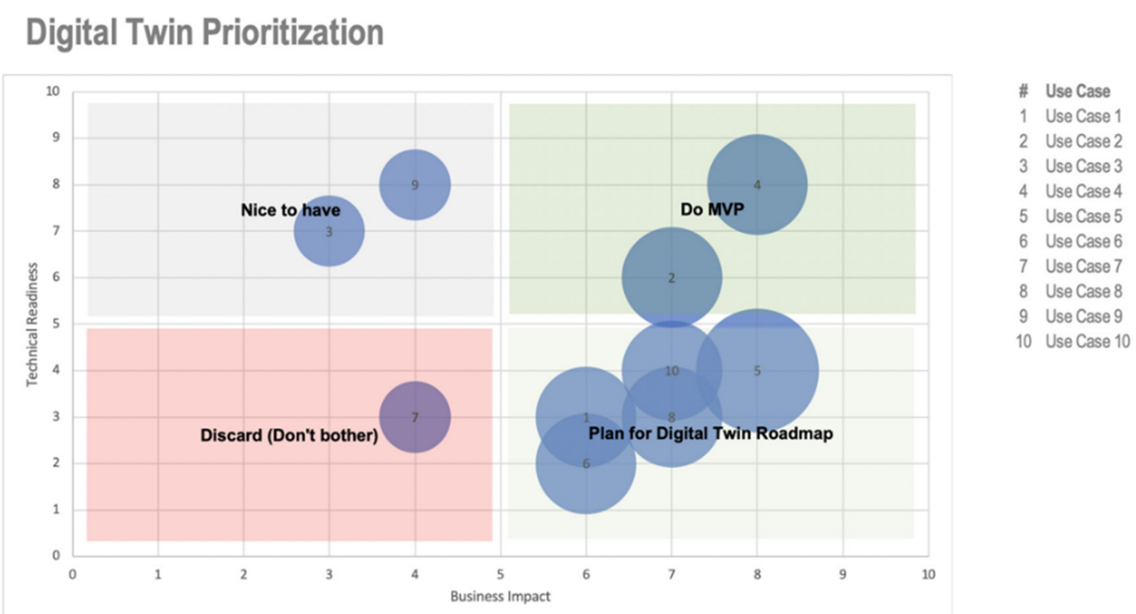

Figure 12. Digital Twin Prioritization (van Schalkwyk, 2019)

This approach provides a common understanding of the expected business outcomes and potential technical challenges in achieving this goal. It provides the basis for a more detailed analysis of those projects with a high likelihood of success.

3.1.1.1.2 Customer Segmentation Task

Once the Digital Twin prioritization is established and the Minimum Viable Product (MVP) has been identified, we proceed to the customer segmentation task. This section aims to have a clear idea of for whom the Digital Twin is being designed or which business users will be impacted by the Digital Twin.

Considering the MVP with which we are going to work we can find two types of clients: (i) internal, and (ii) external. By "internal customer", we mean each of the organizational areas that play a role in the production of a product. These areas can be divided into three main groups: (i) Design and Engineering; (ii) Maintenance, Repair, and Overhaul (MRO); and (iii) Production Management. On the other hand, an "external customer" refers to when the end-user is part of the company's supply chain (supplier) or when this end-user is a customer with whom there is a product-service system relationship.

3.1.1.1.3 Information Capabilities Building

It is important to have in mind that Digital Twins are both "information filtering" and "integration systems", from the data science point of view. On one hand, DT allows us to filter a massive amount of data to get useful information for the design of operations. On the other hand, DT can integrate different types of data to discover hidden patterns and cross-check analysis results (Tao et al., 2019). Therefore, before moving towards the implementation of the Digital Twin, the DT project development team must consider what kind, and in which amount, of information the system will have access. To accomplish this task, they also must consider the typical data lifecycle flow, in which they are going to determine the capability to realize the data collection, data transmission, data mapping, data storage, data integration, data processing, data cleaning, data analysis and data mining. If one or more of these stages cannot be obtained in the current system, it should be considered in the wight of the *Technological Feasibility* of the *Problem(s) Definition Task* (see Section 3.1.1.1.1). That is to say, it must be considered that to carry out the DT in the proposed "Use Case", greater technological investment will be required to fulfil the data lifecycle. Through the lifecycle, raw data is converted to useful information for designers to support their design decision-making.

3.1.1.1.4 Technological Capabilities Building

The next task, in combination with the information capabilities task, is to have an overview of the technological capabilities of the business. This, as in the previous point, will give a clearer idea of where the company is, in terms of technological resources, and what are they missing to set up the DT of the selected "Use Case". At the same time, it might provide some modifications in the wight of the *Technological Feasibility* on the *Problem(s) Definition Task.*

The DT technological capabilities architecture (see **Figure 13**) is constructed from three main perspectives: (i) data-related technologies, (ii) high-fidelity modelling technologies, and (iii) model-based simulation technologies (Liu et al., 2020).

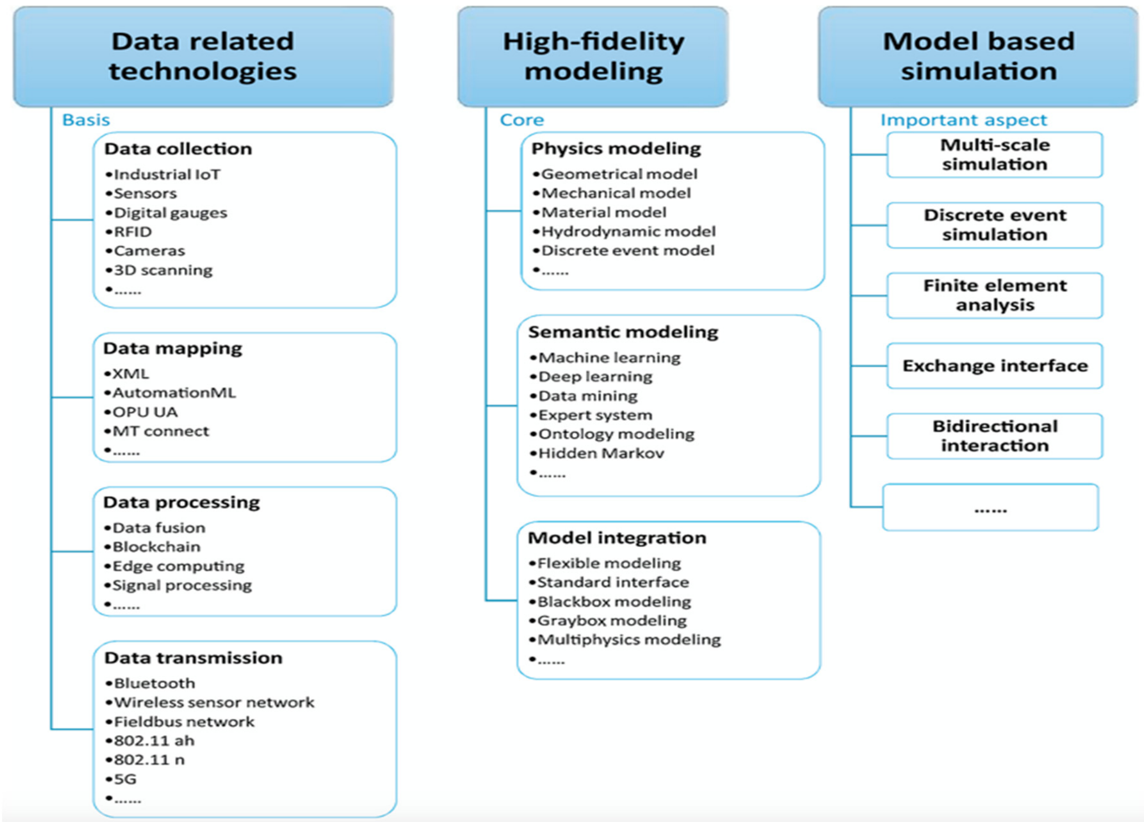

Figure 13. Digital Twin Technology Architecture (Liu et al., 2020)

The first perspective takes into account the information capabilities of the company and the available assets of the data lifecycle. The second technological perspective is for *High-fidelity modelling;* the core of the Digital Twin. These models are divided into two main groups: semantic data models and physical models. *Semantic models* are trained by known inputs and outputs, using artificial intelligence methods. *Physical models* require a comprehensive understanding of the physical properties and their mutual interaction. Thus, multi-physics modelling is essential for high-fidelity modelling of the digital twin. The final perspective, *Model-based simulation*, enables the virtual model to interact with physical entities in real-time or near real-time. In this perspective, we might find some simulation models such as the *Multi-scale simulation* where the model runs at different scales and resolutions simultaneously to describe the system (E & Lu, 2011). The *Discrete event simulation* monitors and predicts the behaviour of an event by codifying the behaviour of a complex system as an ordered sequence of well-defined events (Kiran, 2019). In third place, we have the *Finite element analysis* which divides complex structures into small elements and approximate solutions to boundary value problems (Athanasiou et al., 2017); helping with product design and failure analysis. In a general way, *Digital Twins* should provide an interface to different models and databases in different communication levels for *Data Synchronization* (i.e. unidirectional – bidirectional).

3.1.1.1.5 Digital Capabilities Building

This final task, in terms of capabilities, enables companies to assess where they are on the digital transformation journey. According to the Aerospace Technology Institute, there are four possibilities of digital capabilities sets (i) Technology, (ii) Data & Analytics, (iii) Digital Mindset, and (iv) Digital Trust.

The *Technology* set is intended to be any physical or virtual systems that connect to the world, generates information, host digital processes and enable the capacity to deliver the business expectations and impact through the use of disruptive technologies. In terms of *Data & Analytics*, companies must not just be able to gadder information, they should learn how to extract value from data to identify trends and challenges during the current stage. Through the use of algorithms, machine learning and data mining companies can process information, extract insight and make informed decisions from large data. For the *Digital Mindset*, companies on the way to digital transformation must set the bases of the formal and informal organizational aspects, to enable people to effectively realize and deliver a digital value proposition. All of this, taking into consideration the demographic challenges, enabling the digitally agile organization, and supporting rapid innovation. Finally, we say that a has conceived a *Digital Trust* when they achieve an optimal confidence level in security, connectivity, and collaboration on each digital interaction. Also, by ensuring resilience and managing risks and assets (Aerospace Technology Institute, 2017).

3.1.1.1.6 Value Proposition Definition

To ensure there is a fit between the product and the market, a *Value Proposition* must be defined (Ash, 2010). This, in time, ensures that a product or service is being positioned around the customer values and needs. With the view to address the customer needs it is also necessary to seek for the jobs they need to have done, the pains they want to get released from and the gains they're hoping for. A brief statement that helps to visualize the value is:

> *"For (target customer) who (statement of the need or opportunity) this digital twin (digital twin data value) that (statement of benefit)".*

In this statement, we will bring on the *Customer Segment* analysis discussed in Section 3.1.1.1.2 to fill the blank of the target customer. The second stage of the statement can be extracted from the *Problem(s) Definition task* in terms of prioritization and might be enriched with an analysis of opportunity areas currently presented in the use case. The next step is to determine which type of value is going to be extracted by the Digital Twin in terms of data (view Section 3.1.2.1.4). And finally, the statement is concluded with the desired benefit to be obtained from the DT (see more on Section 3.1.2.1.6).

The importance of having a *Value Proposition* statement relies on the fact that it helps to identify what will make the DT to be installed differently, in the selected use case, in comparison to what is currently being done. Also, it helps to englobe al the key elements that have an important role during the implementation of the desired project. It must be considered in each of the stages of the development of the DT since in a general way, it is the goal of the project with which the customer will be able to release those pains.

3.1.1.2 Business Case Definition Activity

Bringing on the definition from the SCCANZ (2020), reported at the *Data Leadership Guidance Note*, the purpose of the *Business Case Activity* is to confirm the strategic context of the proposal, to make a robust case for change, and to provide stakeholders and customers with an early vision of the way forward for the implementation of the Digital Twin in the chosen use case (without being the best option yet). In addition to this, the *Business Case Activity* can be complemented with a SWOT analysis, including all the available options and their respective cost.

Thanks to the information they provide and their relationship with the objective of this stage, the current section is divided into (i) Solution / Strategic Case, (ii) Risk Management, (ii) ROI Business Case / Economic Case, (iv) Key Metrics / Commercial Case, (v) Integration, (vi) Costing / Financial Case, and (vii) Management Case.

3.1.1.2.1 Solution / Strategic Case Definition Task

According to the SCCANZ (2020), this task serves to outline the fundaments for the DT proposal and argues the need for change at the strategic level. It sets out the background to the DT proposal and explains the objectives to be achieved. This idea is somehow being reflected as well on the *Solution* frame from the *Lean Digital Twin Canvas* of Pieter van Schalkwyk (2019). This building block of the canvas is intended to be filled with the Top 3 features of a Digital Twin.

The way this task can be worked out is by taking up again the second part of the *Value Proposition* generated in Section 3.1.1.1.6…

"…this digital twin (digital twin data value) that (statement of benefit)".

… and detailing a little more about the needs that are required to achieve the objective or fulfil this proposal. The aim is to have a vague idea of the engineering aspects to be dealt with but without being that specific. These details will be seen in Section 3.1.2.1. That is to say, that for this task, it is only necessary to have a list, or a statement will the most important features that will characterize a DT. To generate this list, the person or team in charge of the *Conceptualization Stage* must have a look at the value proposition and think about with which technological resources they might be able to achieve the intended data value (e.g. with Artificial Intelligence (AI) and real-time connection) and obtain the required benefit (e.g. by reporting, analysing, prescribing, etc.).

3.1.1.2.2 Risk Management Definition Task

Going forward with the filling of the *Lean Digital Twin Canvas* proposed in **Figure 9**, the second step in this *Business Case Activity* is to identify the external challenges that might be found throughout the development of a Digital Twin. These challenges might be seen as external business red flags.

According to the U.S. Air Force Research Laboratory (adapting its Airframe Digital Twin to the most general form of a Digital Twin), a whole DT project will have a massive collection of computer models that will be sustained by an effective high performance and parallel computing. The simulation of each model will create a huge database of simulations that must be analysed in detail to understand and study what the model has experienced to provide value to the data in the form of reporting, analysing and diagnosing, prescribing, etc. The mechanics of performing these calculations and maintaining the database of results are not trivial (Tuegel, 2012). However, other challenges must be addressed and taken into consideration previous to the implementation of the DT. Some critical red flags must be taken into account in terms of safety, connectivity, time, data access, and mission-critical services (Datta, 2017). The security design of a DT at the beginning of the DT project must meet with the architecture and design level provisions. Security in terms of roles and responsibilities must be determined concerning the human resources and assets involved with the Digital Twin (Lou et al., 2019).

On the other hand, Rasheed et al. (2020) highlight the main challenges within four categories in which the modelling team should focus. First, as it has been said previously, a successful DT is achieved when a real-time, two-way connection between the physical system and its digital instance is accomplished. The main challenges to ensure this, are related to the spatial-temporal resolution of sensor data, communication latency, large data volume, high data generation rate, large data variety, high data accuracy and online data processing. Secondly, a "synchronous time" evolution between the physical system and the models must be ensured, while maintaining backward compatibility. Third, since the majority of physical systems or assets, of a company, for which digital twin models can be implemented will require a high level of security and protection, greater transparency and interpretability of decisions taken based on the Digital Twins output will be required. This will then need models that are both interpretable and physically consistent. Finally, the difference between the Digital Twin and the physical system must be remarkable to the end-user; in the way that they notice the DT model as an easier and more intuitive to operate the system. All these challenges that require the immediate attention of DT designers are summarized in **Table 3** (Rasheed et al., 2020).

Table 3. Digital Twin Common Challenges and its Enabling Technologies (Rasheed et al., 2020)

Challenges	Enabling Technologies
Data management, data privacy and security, data quality	Digital platforms, cryptography and blockchain technologies, big data technologies
Real-time communication of data and latency	Data compression, communication technologies like 5G and internet of things technologies
Physical realism and future projections	Sensor technologies, high fidelity physics-based simulators, data-driven models
Real time modeling	Hybrid analysis and modeling, reduced order modeling, multivariate data-driven models
Continuous model updates, modeling the unknown	Big data cybernetics, hybrid analysis and modeling, data assimilation, compressed sensing and symbolic regression
Transperancy and interpretability	Hybrid analysis and modeling, explainable artificial intelligence
Large scale computation	Computational infrastructure, edge, fog and cloud computing
Interaction with physical asset	Human machine interface, natural language processing, visualization augmented reality and virtual reality

3.1.1.2.3 ROI Business Case / Economic Case Definition Task

The SCCANZ (2020) states for this task that its purpose is to evaluate the economic costs and benefits of the proposed DT project along with a list of the alternative options. In addition to this, a recommended way to proceed (including budget) must be provided. Moreover, Pieter van Schalkwyk (2019) states that on the Lean Canvas the way that the Digital Twin will deliver a Return-On-Investment (ROI) should be presented in terms of the increased revenues, cost reduction achievement, performance improvement, increased safety, etc. all according to the value proposition of the DT project. The analysis that a company must make when deciding on the implementation of technology to solve problems is complex; at the time of making an ROI analysis, an organization must consider how technology is linked to its strategic objectives (Stanic, 2003). As it has been mentioned, Digital Twins work thanks to its constant collection of varied information from a specific physical asset or system, creating a complete lifecycle, and runs statistical algorithms to be able to provide business outcomes, optimize operations, and gain better ROI (Raj & Surianarayanan, 2020). Analyses such as Cost-Benefit and ROI will help to indicate whether the investment of setting up the DT will have a profitable return over an acceptable time period for a specific production environment (Alexopoulos et al., 2020). Other types of indicators for investment, apart from the return-on-investment, are the payback period, and the Net Present Value (NPV) (Gallego-García et al., 2019).

3.1.1.2.4 Key Metrics Definition Task

As the fourth task on this *Business Case Activity*, Peter van Schalkwyk (2019) proposes as *Key Metrics*, all the activities to be measured to determine the successful deployment and running of the DT system. this task can be complemented with a list of the key activities or key metrics that are going to quantitatively measure the degree of success of the implementation of the DT. These metrics are going to be enlisted in the *Lean Digital Twin Canvas* in terms of KPIs. A *Key Performance Indicator (KPI)* is a quantitative management indicator of production system measurement process performance, such as DT efficiency, production cost, customer satisfaction, and so on. A KPI consists of various parameters, variables, and constants that the DT system operates, such as machine speed, fuel and power costs. The state of measuring the operation of a DT system can be derived from a combination of multiple KPIs, and the weight values between the KPIs are also different. The relationship between the state optimization of the DT system and the KPI is that only the KPIs that are concerned can be classified as optimal targets of the optimization model, and some KPIs become the constraints of the model (Zhang et al., 2020).

Two lists of KPIs may be generated for two different stages within the lifecycle of a Digital Twin. The first one is found in the BoL of the Digital Twin lifecycle, specifically in the *Implementation Activity*. In this part, to keep track of the implementation rhythm, the development of a burndown chart is recommended where the progress in the deployment of the DT application can be graphically appreciated. An implementation KPI can be then extracted from this chart where the delta between the currently remaining tasks, days, hours, etc. and the ideal ones, projected in the *Management Case Definition Task, is shown*. The second list of KPIs may be based on the DT performance, this means that it focuses on the MoL of the Digital Twin lifecycle. When talking about the performance of a DT, it cannot be generalized to a single situation, since it varies according to the use case where it is running. In general, it is said that this performance must fully guarantee *the Data Value (Service) Selection* in combination with the *Value Proposition Selection*. This KPI performance in turn is very useful when providing maintenance since it is an element that must be constantly monitored and acted quickly in case it exceeds its threshold. In turn, more general KPIs can be considered, for example in the physical product, by measuring the reliability of the sensors. These KPIs must be identified in a three-party collaboration between the stakeholder, the end-user and the team involved in the development of the DT project.

3.1.1.2.5 Systems Integration Task

An Enterprise Architecture includes all the principles, methods, and models used to design and implement organizational structures, processes, and Information Technology (IT) infrastructure. Enterprise architecture management includes, among other things, controlling the introduction and operation of information systems (Jonkers et al., 2006). For emerging systems such as *Digital Twins* in the Industry 4.0 era, these well-known and established fields must be used carefully, such as enterprise architecture management. It is necessary to examine how to integrate novel systems and existing systems into the organization, possibly due to the high degree of interconnection between the components involved, and possibly use "Agile" Methods for Enterprise Architecture Management (Wache & Dinter, 2020).

3.1.1.2.6 Costing / Financial Case Definition Task

Moving forward to the cost analysis of a DT project, this task seeks to examine the issues of affordability, and sources of budget funding. In other words, it takes care of seeing through the lifetime of the plan to cover the assigned costs. Once these costs have been planned, a discussion is generated around the affordability of a DT project.

In most of the DT projects, there are at least two major parties; each on one side of the contract. On one side of a DT project, there is a party that has a need and will or will not find the motivation and resources to develop it later. On the other side, is the party hired to get a DT project done (the contractor). These two principal parties can be found in almost every DT project, although their identities are often wrapped up in organizational complexities. In a typical DT project, the stakeholder must find all the funds and cannot usually expect any benefits until the DT project has been deployed. The project contractor, or DT vendor, on the other hand, can expect to receive interim payments (known as progress payments or stage payments) from the project owner, following the amount of work that can be certified as being completed. Thus, the project contractor does not usually have to fund the whole cost of a DT project up to completion and handover.

Most DT projects requiring considerable financial investment will involve more uncertainty and risk. For this reason, to avoid running risks in the investment of a DT application and take the most advantage as possible from its deployment, both the *Risk Management Definition Task* and the correct identification in the prioritization of the use case in the *Problem(s) Definition Task* becomes crucial. It is important to carry out an in-depth financial appraisal before the authorization of the DT project, taking into consideration the benefits in comparison with the total cost. It is worth mentioning that at this task there is still no solid proposal (the used proposal is the one that was given in the *Solution / Strategic Case Definition Task*), since there is still no clear definition of the technologies to be implemented, and therefore the quotation that is provided is only a general estimation of the DT project. Once this first quotation is accepted, the lifecycle proceeds to the *Design and Engineering Activity* where after selecting the most appropriate technologies to solve the problem and cover the value proposition, a second but more specific quotation is made. In theory, there should not be much difference between the first quotation and the final one, however, at the *Design and Engineering Activity,* new needs from the stakeholder or the final user may arise and may have an impact on the final proposal.

There are two common approaches to the financial appraisal of a DT project. One is the simple payback method and the other is based on discounting the forecast cash flows. Whichever of these methods is chosen, the appraiser needs to have a good estimate of the amount and timing of each significant investment (the cash outflows) and the revenue or savings expected (the cash inflows). The main cash outflow elements of a DT project can include items such as the following:

- The initial acquisition cost of software, plant, or equipment needed for the DT deployment. This might be a single purchase payment, a series of phased payments, or payments scheduled against a leasing or rental plan.
- Interest in financing loans.
- If a DT project is for new machinery or plant, the costs of operating, and maintenance.
- Commissioning, debugging, and other implementation costs.
- Staff or operator training costs.
- All other expenses and fees as a result of a new DT project introduction.

It is important to implement in this task a financial appraisal estimator. The Net Present Value (NPV) may provide a good and persuasive estimator. However, quite often this type of general estimators gets it wrong, and the payment plan may fail. To make some sense out of such uncertainty, two common methods are used (viz. sensitivity analysis and Monte Carlo analysis). Both of these methods deal with the possibility that the data are flawed. They deal with uncertainty, but not with risk events that might change the intended course of a DT project (Lock, 2012).

3.1.1.2.7 Management Case Definition Task

According to the guide specifications provided by SCCANZ (2020), this task should be linked to the DT project delivery schedule. That is to say that the planning of this task should be focused on program management or project management case method for the deliverability of the proposed Digital Twin.

The *Project Management Body of Knowledge* has defined project scheduling as "an output of a schedule model that presents linked activities with planned dates, durations, milestones, and resources" (Project Management Institute, 2013). It represents a feasible way to transform DT project goals into accomplishing goals; it creates a timetable and reveals the network logic that coherently interconnects project activities. Since the premise of project management is to complete a limited set of goals within a specified time frame, accurate project schedules are critical to success.

The *Work Breakdown Structure (WBS)* identifies all DT project deliverables, *according to the selections in the Design and Engineering Activity*. After determining the deliverables of a DT project, the scope is defined, and then the DT project team begins to develop a schedule. The DT project team should include in the project schedule all the activities required to produce project deliverables are those placed in the project schedule. This requires the project team to systematically check the deliverables following the requirements in the WBS, and then determine all the activities required to produce them.

A valid WBS only contains nouns at all levels, due that it only presents the deliverable content. In contrast, the list of DT project activities used to populate the project schedule contains only verbs, because activities are operations used to produce deliverables outlined in the DT project scope. Strictly focusing on deliverables first and then performing activities helps to ensure that no insignificant activities are included in the project schedule. This is a reasonable method since the only work performed within the DT project is to complete the basic tasks of the project, that is, to complete the deliverables of the DT project (Marion, 2018).

The DT project schedule describes the time taken to produce the project deliverables. The challenge is that the schedule requires more analysis, rather than simply adding the duration of each deliverable together to get the total time. The reason for this is that not all activities in the project schedule will be carried out sequentially. Some activities will be in series, while others will be carried out in parallel. Scheduling principles apply to all DT projects, no matter their maturity level. The detailed steps to construct the basic project scheduling goes as follows:

1. List all activities required to produce the DT project deliverables with their estimated duration.
2. Sort them to identify sequential and parallel activities.
3. Determine the longest path in the DT project (the sequence of project activities without slack or the sequence of "those activities cannot move without delaying the entire project").

After completing Steps 1 to 3, the project manager and project team will now be able to determine how long it will take to complete all the DT project activities, and can also determine which activities will not be delayed without delaying the entire project (Marion, 2018). This information will help to develop a project schedule. Once a timetable is established based on a pre-established list of activities, it is important to have in mind that most of the times resource requirements, availability, and cash flow restrictions usually expand the proposed project scheduling, while implementation date restrictions usually indicate a need to narrow down the project schedule.

Getting deeper into Step 3, the first task of making a DT project schedule is to determine the critical path, that is, "the sequence of schedule activities determining the duration of the project. Generally, it is the longest path through the project" (Wiewiora et al., 2010). Since this is the longest sequence of activities, the critical path determines the earliest possible end date of a DT project. Any time activity on the critical path is changed will change the end date of the entire DT project. If the project manager changes the activity on the critical path to starting on a later date, the entire DT project will end on a later date. If the workload of the activities on the critical path is increased, the DT project will be delayed and will end at a later date. On the other hand, if the activities on the critical path are executed faster than planned, the entire project may be completed faster. The critical path is named, not because it is the most critical in terms of cost, technical risk, or any other factors, but because it is the most critical in terms of time. Since almost everyone wants to complete the project at the agreed time, the critical path has attracted great attention (Kloppenborg, 2019).

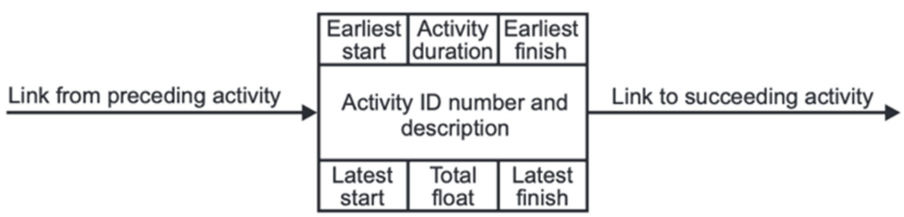

Figure 14. Notation of Activities in Precedence Diagrams (Lock, 2012)

Figure 14 shows the prioritization of the activity agreement. Although this must be the preferred mode when drawing a network manually, it cannot be achieved when drawing a network on a computer, because the software limits the amount of data that can be contained in each active box. Without this limitation, the network would take up too much screen space and would be difficult to draw (Lock, 2012).

3.1.1.3 Verification Activity

In this *Verification Activity,* what is expected is a more detailed vision of what is planned to be done regarding a DT project. This means that this activity serves as a second iteration to review and make the last modifications to the *DT Conceptualization Stage.* According to the roadmap proposed by SCCANZ (2020), this activity is based on two tasks: (i) Full Business Strategy Verification, and (ii) Full Business Case Verification.

3.1.1.3.1 Full Business Strategy Verification Task

The purpose of this task is to examine the final details for the Digital Twin development project and its agile implementation strategy. At this stage, the critical implementation path proposed in Section 3.1.1.2.7 should be reviewed, providing a more detailed view of it with the corrections proposed in the business model. This new critical implementation path must be taken as the final implementation proposal that will serve as a guide for the final activity in the *Realization Stage.*

On the other hand, the *Full Business Strategy Verification Task* also encourages testing the final DT solution upon any beta prototype that a company could have in development. Preparations will be required so that the DT project team is ready to design its change on its management plan. Organizations also need to provide support to the supply chain to ensure that all levels are not adversely affected by this new work plan.

3.1.1.3.2 Full Business Case Verification Task

The purpose of the *Full Business Case Verification Task* is to review the *Business Case Definition Activity* in more detail and determine the best option that can provide a higher value for the money to be invested. It also lists possible transactions i.e.: demonstrated affordability, detailed supporting procurement strategies, and relevant management arrangements provided for the successful implementation of the DT development plan. At this task, some of the following actions might be taken into consideration:

- *Strategic Case* – revised.
- *Economic Case* – completed.
- *Business Case* – outlines the envisaged transaction structure, KPIs, key contract terms, and payment mechanism.
- *Financial Case* – contains a detailed analysis of affordability and any funding gaps.
- *Management Case* – explain in more detail how to deliver the plan with the outline of the planned plan/project management plan, and whether to implement any project management methodology, i.e.: PMBOK, Agile, etc.

3.1.2 Realization Stage

Recalling the methodology for developing a *Digital Twin Roadmap* (see **Figure 8**) proposed by the Smart Cities Council from Australia and New Zealand (SCCANZ, 2020), after establishing Section 3.1.1.3.2 *Full Business Case Verification Task,* it is necessary to go into the *Realization Stage.* At this point, the Digital Twin project should start the development of the *Design and Engineering Activity* and the *Implementation Activity.*

Section 3.1.2.1 – *Design and Engineering Activity* – is a compendium of the levels of integration found throughout scientific and grey literature reviews. As mentioned above, when talking about the creation or development of a Digital Twin, authors usually focus only on this area, the "design and engineering area". In this, it has been found that there are different levels of integration, or maturity levels, in Digital Twins according to each author's perception. This maturity level varies depending on the focus wanted to be given to a DT system. That is, for some authors the data management is what can provide greater robustness to a DT system, but for some others may be focused on the value they can get from it. Due to this dispersed vision of the different nature and varying integration levels of Digital Twin concepts (Kritzinger et al., 2018), it was decided to annex to the *Digital Twin Lifecycle Management Framework* a maturity choice chart that allows the DT system designer to choose the most appropriate DT configuration, in the form of a morphological matrix, see Section 3.1.2.1. Moreover, under the *Realization Stage*, the *Implementation Activity* is presented. This point considers how the development of a DT project will be carried out once the final DT proposal has been approved by both the company and the DT project designer.

3.1.2.1 Design and Engineering Activity

To integrate the different maturity levels into a single methodology, without prioritizing any of them and to be able to create a selection chart that is complex enough to fit the needs of each project, this section proposes a morphological matrix for each of the parameters found and their maturity levels. The morphological matrix is a key methodology that can improve the effectiveness of the concept generation phase of a design process (Weber & Condoor, 1998). The method includes defining all the main parameters that the solution of the problem may depend on, displaying them as matrix rows, and then defining all possible combinations of a parameter in each row in the shape box. The resulting options can then be evaluated and analysed to select the best option (Rakov, 2020). It is important to mention that, as in the previous sections, this is an iterative process in which the DT designer must play with all the proposed options to arrive at the value proposition required by the company.

According to the literature reviewed, the parameters that can be evaluated for the detailed design of the Digital Twin are (i) Requirements Specifications, (ii) Depth of System, (iii) DT Classes and Instances, (iv) Data Value (Service), (v) Data Synchronization, (vi) Value Proposition, (vii) Data Analytics Sophistication, (viii) Machine Learning Capability, (ix) Human-DT Interaction, (x) DT

Virtual Representation, (xi) ICT Architecture, (xii) Computing, (xiii) IT Network, (xiv) OT Network, and (xv) Cybersecurity Mechanisms.

3.1.2.1.1 Requirements Specification Task

Requirements Engineering delineates the process of defining, documenting, and maintaining requirements (Chemuturi, 2013). It is differentiated into *Functional Requirements (FRs),* which provide the features and capabilities that an entity (e.g. a system) must have, and Non-*Functional Requirements (NFRs),* which specify the quality limitations (e.g. security, performance, and usability) of the features and capabilities. In general, such criteria should be derived to achieve a specified organizational purpose. Furthermore, firms use these strategies to create and achieve corporate goals for a variety of purposes (Becker et al., 2019).

3.1.2.1.1.1 Functional Requirements Specification Subtask

Basic system behaviours are defined by functional requirements (Mairiza et al., 2010). They are essentially what the system must or must not do in response to inputs. It then may be understood in terms of how the system responds to inputs; they are the characteristics that allow the system to perform as planned are known as functional requirements. Product features are referred to as functional requirements, and they are focused on the needs of the user. Calculations, data input, and business processes are frequently included in functional requirements, which specify if/then behaviours (Terzakis, 2013). In Digital Twins, functional requirements may be divided into requirements of the information layer, functional layer, and business layer (Steindl & Kastner, 2021).

When talking about the *information layer,* common functional requirements can be found. They are focused in the first place on how heterogeneous data can be integrated from different sources. They also state that to make time-series data interpretable for other services, DT should be able to connect it with context information (Tao et al., 2018b). Also, DTs should be able to handle the provided information and limit access to that information as well as guarantee the right exchange of information between services and other systems (Moyne et al., 2020). In terms of the *functional layer,* DTs should be able to monitor the sensors stream in real-time and this information should be received and accessible by any services at the same time so that they may be processed in parallel and the system's reaction time gets reduced. Finally, to allow one-to-one communication for information retrieval, DT services should be able to reply to specific requests (Tao et al., 2018b). The final role of functional requirements takes place in the *business layer,* in which a Digital Twin functional service is intended to be integrated into the business process to add value to the chain. Moreover, to promote human-machine interaction and identify service failures, service interaction states should be traceable (Moyne et al., 2020).

3.1.2.1.1.2 Non-Functional Requirements Subtask

Non-functional requirements, according to Mairiza et al. (2010) definition, are the properties, characteristics, or restrictions that a software product must have. Development limitations, business concerns, and external interfaces are all examples of non-functional software attributes. According to the literature review of Steindl & Kastner (2021), when talking about *Digital Twins services* non-functional requirements there might be found different groups of requirements such as data ownership issues and response times, where DT and its services should be able to be hosted both in the cloud and on-premises to increase performance (Alam & El Saddik, 2017; Borodulin et al., 2017); maintainability, stating that DT's services should be connected in some way so that new services may be added or removed without affecting existing ones (Moyne et al., 2020) and the maintenance of these services should be provided by different development teams; scalability, so DTs can manage requests eider from a single machine or the whole factory; and increasing reliability by the flexibility of a DT infrastructure to keep up with short downtimes (Kleppmann, 2017).

3.1.2.1.2 Depth of System Selection Task

This second task was taken out from the HCL's product lifecycle consulting team, which has worked with its customers to determine and define a unique DT roadmap for each customer based on their current maturity. This Digital Twin roadmap allows engineering a Digital Transformation process by picking the right elements at relevant maturity level targets (Burande, 2019).

Within this same roadmap, there are 6 different paths where one of them is *Depth of System*. It presents the different physical levels where a Digital Twin can be implemented, going from the singular (starting with a simple product or machine tool of the factory) to the particular (implementing a DT to the whole supply chain of the organization). In the manufacturing process, there is an advanced production planning and control system that has a centralized, layered and pyramidal structure that closely resemble the maturity levels described by HCL in *Depth of System* terms (Burande, 2019). This structure was created from automation technology and mainly in control architecture (Bartodziej, 2017). The DIN ISO standard 62264 defines the application fields of different levels of the automation pyramids (also called layers) in classical manufacturing (Schöning & Dorchain, 2014). In this way, a selective approach can be made either to the maturity levels proposed by HCL (Burande, 2019) or to its similar, automation pyramid.

3.1.2.1.2.1 Entity (Product / Machine Tool / Worker) Choice

The high competition presented in the market in combination with the ambition to shorten time-to-market and improve product development performance has led companies to seek complex virtual product models applications, giving as a result of the first maturity level in terms of *Depth of System*. Through the "digitization" of manufacturing, Cyber-Physical Production Systems (CPPSs), model-based systems engineering, and increasing efforts to collect and process data, these models are being reinforced by production and operational data. In addition, they can effectively predict the effects of product and process development, as well as operational and maintenance decisions on product behaviour, without the need for expensive and time-consuming physical models. Especially in design, this kind of realistic product model is essential for early and effective evaluation of the consequences of design decisions on the quality and function of mechanical products (Schleich et al., 2017).

Also, a product design phase involves the back and forth interaction between the expected, interpreted, and physical world (Gero & Kannengiesser, 2004). Based on the digital twin, the digital representation (i.e. virtual model) of the physical product is created in the interpreted world (i.e. virtual world). The virtual model not only reflects the designer's expectations but also reflects the actual constraints in the real world. *Digital Twins* can realize iterative optimization of design schemes to guide designers to iteratively adjust their expectations and improve design models to achieve personalized product design (Qi & Tao, 2018). In addition, virtual verification driven by Digital Twins can quickly and easily predict and verify product functions, behaviour, structure, and manufacturability (Schleich et al., 2017). Using Digital Twins, it can accurately find design flaws in the virtual world and make rapid changes, thereby improving the design and avoiding tedious verification and testing.

Moving forward to the machine tool's point of view, in the traditional virtual prototype modelling process, such as Computer Numerical Control Machine Tool (CNCMT), developers usually use Computer-Aided Design (CAD) software to design digital models based on design parameters. After verifying the virtual prototype, components will be produced and assembled to complete the physical prototype, and then improvements will be made based on the verification results of the physical prototype. However, the consistency between the design conditions and the actual conditions cannot be ensured. That's why the need to implement a sufficiently robust system, like a Digital Twin capable of providing a precise simulation (the model should consider data and information collected from physical equipment, integrate multi-domain modelling and simulation as well as accurate and reliable data), self-sensing (in terms of accurate and reliable data acquisition from the system or the component to inference meaningful information from the data), self-adjustment (to reduce the time and waste of the production task and to reduce the user contact with the system), self-prediction (before a serious failure occurs, the system can provide timely monitor and prediction failure according to the environment and its conditions) and self-assessment (where the system can evaluate the running status, optimize working parameters, and make decisions based on machine learning), is ideal (Luo et al., 2019).

3.1.2.1.2.2 Manufacturing Cell Choice

Taking the next step in this maturity path is where the *Manufacturing Cell* level is found. Getting into context, countries around the world actively participate in a common revolution by formulating national manufacturing development strategies; Germany's with Industry 4.0, China's Manufacturing 2025, and the United States' Advanced Manufacturing Partnership. But the characteristic they all have in common is that smart manufacturing is considered as the key that will help to embrace a notable competitive advantage of manufacturing in major countries (Zhou et al., 2018). For this reason, the research and development of new systems, such as the Knowledge-driven Digital Twin Manufacturing Cell (KDTMC), that is capable of maximizing product quality and throughput while maintaining flexibility and costs reduction through intelligent perception, simulation, understanding, prediction, optimization and control strategies, has been increasing day by day (Zhou et al., 2020).

It is known as KDTMC to the lowest realization unit of intelligent manufacturing, which corresponds to the four-dimensional limited intelligent manufacturing space of the production unit in cellular manufacturing, including physical space, digital space, knowledge space and social space (Ding et al., 2018). The integration of these four spaces can enable KDTMC to have strong cognitive and learning abilities, such as self-thinking, self-decision, self-execution, and self-improvement to maximize quality and throughput while maintaining flexibility and reducing costs. As a reference model for the interoperability and integration of physical space and manufacturing virtual space, Digital Twins can become a key supporting technology for the construction of KDTMC by bridging the gap between KDTMC's physical space and digital space. The Digital Twin model of a manufacturing cell is the foundation of KDTMC. This model connects the digital space and the physical space through an iterative loop of communication, calculation, and control. On one hand, in addition to traditional production capacity, physical space can also perceive manufacturing data related to people, equipment, materials, and the environment through a sensor network. Here, the sensor network is used to realize the interconnection and interaction of manufacturing units through wired or wireless sensors deployed on manufacturing resources. On the other hand, the digital space can simulate and visualize the manufacturing process based on perceived manufacturing data. Then, it can understand, predict or optimize the performance of the manufacturing process through the intelligent analysis and decision-making process realized by the dynamic knowledge base and knowledge-based intelligent skills. Finally, it generates real-time orders to control the physical manufacturing process (Zhou et al., 2020).

3.1.2.1.2.3 Production Line Choice

Modern production lines work with massive data flows (Botkina et al., 2018). The *Digital Twin's ability* to link large amounts of data to rapid simulation makes it possible to optimize not just the design of products, but also production lines in real-time using as a basis a digital copy of the physical system to perform real-time optimizations. The success of Digital Twins relies on first place in the fact calculation times has been shortened from hours to minutes, which makes it possible to explore the solution space to find the global optimum; and secondly, because simulation models can be reused in the production phase due to the increment in the use of sensors and online measurement equipment (Zhong et al., 2015), which use real context data instead of estimated or historical data as input (Leng & Jiang, 2016).

Even if it is not directly connected to the physical production line, many experiments can be created on a simulated system. For example, questions as; *What will happen to the entire production line after changing a certain parameter?*. In other words, the model allows to modify the production parameters and then monitor the behaviour of the system without the risk of financial loss on the actual production line. If the simulation model gets connected to the actual system, this will open up other possibilities for optimizing the production system (Vachálek et al., 2017).

3.1.2.1.2.4 Factory Choice

One of the most popular areas where Digital Twins have been implemented in the manufacturing industry (Uhlemann et al., 2017). However, previously, factory design was seen as an algorithmic optimization problem where the main constraints were the equipment and the area of implementation. In an actual factory, it is difficult to use mathematical equations to predict the dynamic behaviour of the manufacturing system. Therefore, optimization is valuable only when the manufacturing system is constrained by certain assumptions. Therefore, these algorithms can solve simple dynamic problems, but cannot model complex problems (Jiapeng Guo et al., 2019).

Factory design usually addresses three main design stages: (i) conceptual design, (ii) elaborate design, and (iii) final design. *Conceptual design* is the first design stage, and its focus is on designing the concept of a new factory, including factory layout, capital investment and production forecast. It has been said that about 75% of the production cost of a product is determined in the conceptual design stage (Zhang et al., 2019). The second stage of the design process of a factory is the *elaborate design.* It includes machine configuration, process design, production line or production unit configuration, material handling system configuration, and work shift configuration. The purpose of elaborate design, in most cases, is to look forward and verify the conceptual design. The last stage in the process is the *final design* which is related to the architecture. At this stage, control strategies for machines and logistics units are being designed, and the entire manufacturing system has also been integrated.

The importance of the Digital Twin, within a factory, lies in the fact that it can be used as a mirror or as feedback to the three physical design stages. Designers consider the simulation results of the digital twin model to establish contact with suppliers, shareholders, and design documents. Based on the output of the DT, the designer evaluates the current design and decides whether it can be approved. In the conceptual design phase, the digital twin reflects the design concept and visualizes it through animation. Animation can help designers further develop the concept more comprehensively and clearly explain the design to shareholders and suppliers. In the stage of elaborate design, the digital twin mirror reflects the detailed configuration of the factory, and the simulation verifies whether the configuration can perform mass production. In the final design stage, Digital Twin mirrors the final approved design and simulates it as a virtual factory. Thanks to the simulation, the control strategy and software design can be determined. In this way, the Digital Twin model gets modified from the conceptual design to the final design. At the same time, the similarity with the physical environment and its ability to predict it improves phase by phase (Jiapeng Guo et al., 2019).

3.1.2.1.2.5 Supply Chain Choice

Digital technologies, such as the Internet of Things (IoT), cyber-physical systems, and smart interconnected products, promote the development of new paradigms, principles and models in Supply Chain Management (SCM) and smart operations (Yang et al., 2017). Thanks to the combination of simulation, optimization and data analytics provided by a Digital Twin, a new data-driven vision of managing the disruption risks has been enabled for Supply Chains (SCs). SC twin models can have the network status at any given time and allow full end-to-end SC visibility to improve resilience and test contingency plans (Ivanov, Dolgui, & Sokolov, 2019).

Digital supply chains use as basis digital data and digital technology can improve processes, functions, activities, change processes to achieve certain benefits. The goal of this type of system is to increase revenue sources and create new business opportunities (Hagberg et al., 2016). Digitization of operations aims to improve production and SC capabilities and flexibility through real-time communication and intelligent, high-resolution data systems (Reddy et al., 2016). Digitization is a continuous shift towards the digital supply chain and has gradually changed most business processes.

Today, and looking forward to the near future, SC will be as good as the digital technology behind it. The latest example of SC's digital technology application puts forward a new claim that competition is not a competition between SCs, but a competition between SC services and the analysis algorithms behind SCs. Examples of SC and operational analysis applications include logistics and SC control with real-time data, inventory control and management using sensor data, dynamic resource allocation in Industry 4.0 custom assembly systems, use of big data to improve predictive models, for process control Machine learning technology, SC visibility and risk control, system optimization based on predictive information (for example, predictive maintenance), the combination of optimization and machine learning algorithms, and simulation-based random system modelling and optimization (Ivanov, Dolgui, Das, et al., 2019).

3.1.2.1.3 DT Classes and Instances Selection Task

This third selection takes into consideration the fact that Digital Twins in a framework are organized in a class structure to provide functions that are essential for optimizing a manufacturing environment; instances are stored in the DT pool, and the DT manager is responsible for handling the communication between DT instances and with decision-makers (Qamsane et al., 2019). For this, Michael Grieves (2016) in his paper *"Origins of the Digital Twin Concept"* shows that there are three types of manifestations of a Digital Twin in terms of *Classes and Instances*. Thus, the following maturity levels are obtained (i) Digital Twin Prototype, (ii) Digital Twin Instance, and (iii) Digital Twin Aggregate.

3.1.2.1.3.1 Digital Twin Prototype Choice

This first maturity level choice at the DT *Classes and Instances* scope aims to describe the prototypical physical system. Its main characteristic is that it contains the needed information sets to describe and produce a physical version that duplicates or twins the virtual version of the system. These information sets can be built from, Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal, but they are not limited to them (Grieves, 2016).

3.1.2.1.3.2 Digital Twin Instance Choice

At this maturity level choice of the DT a specific description of the corresponding physical product, in which a single Digital Twin maintains a link throughout the lifecycle of the physical product, is required. Depending on the required use case, this type of Digital Twin information set may contain: a fully annotated 3D Model with Geometric Dimensions and Tolerances (GD&T) used to describe the geometry of the physical instance of it and its components as well as electronics and software schematics due to the mechatronic nature of some products; listed Bill of Materials (BOM) of the current component and all past components; the Process List of the operations performed when the physical instance was created; and the results of any measurement and testing on the instance, Service Records describing the services performed in the past and the replaced components, as well as Operating Status, captured from actual sensor data, current, past and future forecasts (Grieves & Vickers, 2017).

Considering another perspective, *Digital Twin Instances* is a virtual model that represents a specific real-world object. In this case, the object might be considered as a physical product, a human being, a city, a process, or an event; anything that benefits from a virtual representation of it. Since Digital Twin Instances are single interfaces for real-world object data, they must always be available on the Internet to ensure the continuous flow of data. Each Digital Twin Instance also has a unique identifier, which can be used to connect to it from anywhere in the world (Autiosalo et al., 2020).

3.1.2.1.3.3 Digital Twin Aggregate Choice

The final maturity level choice on this scope is the compilation of all Digital Twin Instances. Its principal difference to Digital Twin Instances is that *Digital Twin Aggregate* is not an independent data structure. It is intended to be a computing structure that can access all Digital Twin Instances and consult them temporarily or actively. On one hand, temporarily, the calculation structure may ask *What is the Mean Time Between Failure (MTBF) of component X?.* On the other hand, Digital Twin Aggregate may actively check sensor readings and correlate these sensor readings with failures to make predictions (Grieves, 2016).

In general terms, Moyne et al. (2020) mention that a Digital Twin aggregation allows the combination of DT object instances. This combination of elements is carried out through the physical relationships between application environments of the individual instances, which is sometimes associated with some aspect of common purpose among the DT object instances. An example of this aggregation is when two DTs that have the same purpose and have the same output metric are combined, where the DTs are related to each of the individual components of a broad system.

In some aggregations, the existence of the component DT depends on the existence of the parent aggregation, or the existence of the parent aggregation requires the existence of some or all of the child components. One requirement of the aggregation is to specify that there are parent and child DTs in the aggregation. This requirement may be different for different components in the aggregation (Moyne et al., 2020).

3.1.2.1.4 Level of Cognition Selection Task

One of the most important steps in the development of a Digital Twin is the selection of *Data Value (Service)*. As it was observed in Section 3.1.1.1.6, this is of great help to build a solid and objective *Value Proposition*. The main outcome obtained from the *Data Value (Service)* is to know what the analysis of the information collected by the DT will yield. According to the HCL's proposed roadmap, by the product lifecycle consulting team, and the article *"The digital twin maturity continuum"* written by David Socha, there are six stages around this maturity model path that pictures out the evolution of the Digital Twin from a standalone application up to the heart of the future enterprise. This evolution allows the DT to be able to do (i) Reporting, (ii) Analysing & Diagnosing, (iii) Predicting, (iv) Integrating, (v) Prescribing, and (vi) Autonomous Decisioning.

3.1.2.1.4.1 Reporting Choice

The first and simplest form of a Digital Twin, to provide a service, in this maturity path is only by giving the necessary information to understand the performance of the model assets. DTs at this level uses sensors data to show the condition of the assets in a more intuitive and informative report or graphical way (Socha, 2018).

3.1.2.1.4.2 Analysing & Diagnosing Choice

Although the reporting function of a DT might be useful for some use cases others may need larger data processing to get better data value. In some cases, those reports presented by the DT might show concerning trends or issues that are not detected by the DT and that require the supervised analysis of a human eye to be detected. Taking into account this leakage is where the second evolution of the DT takes place. In this stage, the system analyses historical trends in the operational data, to spot the user potential root causes of failures or deterioration in performance (Socha, 2018).

3.1.2.1.4.3 Predicting Choice

Taking a step forward to the output of an *Analysing & Diagnosing* DT, the third choice is found. At this point, the system can model and predict how the asset will behave in the future, enabling the user to schedule repairs, reduce downtime, increase quality, among others. However, at this point, the Digital Twin still only has data from the OT system. Designers can create effective and useful models to predict behaviour, but these models are only based on the analysis of operating parameters (Socha, 2018).

3.1.2.1.4.4 Integrating Choice

As mentioned before, until the previous choice, the Digital Twin has just been communicating with OT systems and applications. From now on, the Digital Twin will also be able to interact with enterprise and external data, making a whole system integration. The user at this stage can see the assets and the operation and strategy of the enterprise in the context of these assets. The data of its maintenance methods might be used to improve the predictive model of asset behaviour; which operators have intervened; the possible future burden based on the contract and Service-Level Agreements (SLAs); and more. Future parts and labour requirements can also be predicted; not just assets but also cost models, to optimize business processes, can be created; and even inform future purchasing decisions (Socha, 2018).

3.1.2.1.4.5 Prescribing Choice

As the previous Digital Twin maturity level choice continues to integrate with enterprise IT, the next one focuses on considering other businesses related to analytics. Organizations mature enough to implement the fifth choice under this *Data Value (Service)*, have taken other steps to implement advanced analysis capabilities. That is to say, organizations that have explored or are exploring Artificial Intelligence (AI) in areas such as supply chain, resource management, and quality, etc. By integrating the data and models of Digital Twins, such companies can move to the prescription analysis of interventions and action, based on a comprehensive view of the most important aspects of the business. Users may still make final decisions, but these decisions are supported by recommendations based on comprehensive, multi-dimensional advanced analysis (Socha, 2018).

3.1.2.1.4.6 Cognitive Analytics Choice

Considering Digital Twins as the core of the future enterprise, which can intervene autonomously and adopt new courses of action to maintain and improve safety; efficiency; quality; reliability and profitability, is where the last level of maturity choice is. A system that can recommend actions is gradually allowed to take more and more actions automatically and not as a leap of faith. It is already happening in control systems all over the world. In such an integrated business driven by data, the digital model of physical assets remains as crucial as ever. At this stage, we can still refer to the visual representation of assets as Digital Twins. In addition, we can call a comprehensive visualization of the entire business, from raw materials to sales contracts, and all links between the DT of the new enterprise (Socha, 2018).

3.1.2.1.5 Level of Autonomy Selection Task

Like any other system capable of delivering or performing tasks automatically, a *Digital Twin* may also have four degrees of granularity to perform "autonomous actions". This degree of autonomy is closely related to the installed capacity of a DT system as well as the purpose for which the DT application was created. In other words, a review of the initial value proposition has to be made, comparing it with the installed or available capability in the company and finally verifying the level of cognition selected in the previous selection task (see 3.1.2.1.4). Once these points have been identified, it will be possible to choose between the different "levels of autonomy", being these: (i) User Assistance, (ii) Partial Autonomy, (iii) Conditional Autonomy, and (iv) Full Autonomy. It is worth mentioning that it is recommended to choose the option that provides the more efficient solution to the DT problem; later, when it is desired to increase the maturity level due to new requirements, the changes can be generated as long as it is technologically and economically feasible.

3.1.2.1.5.1 User Assistance Choice

At the lowest level of autonomy, Level 1, the *Digital Twin* should have at least one human support system that can provide any type of assistance when needed. The user is then still responsible for looking forward to the system and must be prepared to act upon the DT system for any reason at any time (Hughes & Huo, 2019).

3.1.2.1.5.2 Partial Autonomy Choice

On the other hand, Level 2 of autonomy of a *Digital Twin,* allows a DT system to perform all of its tasks autonomously. However, the active supervision of a human of the *Digital Twin* is still needed while the DT system is performing its operations. The human can then intervene when needed (Hughes & Huo, 2019).

3.1.2.1.5.3 Conditional Autonomy Choice

Level 3 of autonomy requires the presence of a human to supervise a DT, although at this point a DT system can be trusted to operate autonomously. It has the characteristic that when a DT application detects a problem it will alert a human immediately. The *Digital Twin* will not decide upon the problem since it is the human task to decide what action to take. This provides a human with a wide degree of freedom to monitor an aggregation of Digital Twins at once (Hughes & Huo, 2019).

3.1.2.1.5.4 Full Autonomy Choice

Full autonomy is the highest level of autonomy of a *Digital Twin,* where a DT is able and allowed to handle all decisions with no input from a human (Hughes & Huo, 2019).

3.1.2.1.6 Data Synchronization Selection Task

This selection refers to the type of communication that can be presented between the Physical Product and the Virtual Product. In other words, it states the synchronization level of the Digital Thread. This type of synchronization has a high relationship with the type of "Data Value" to be obtained since each of the levels in this section have certain requirements. In this way, the data flow of a Digital Twin can be given in two ways, unidirectional or bidirectional (Baltes & Freyth, 2017; Boschert et al., 2018).

3.1.2.1.6.1 Unidirectional Synchronization Choice

Most of the research works found in the literature implement Digital Twin with unidirectional data synchronization (Liu et al., 2021). This refers to the fact that the data flow runs only from the physical product to the virtual product, forming an open communication loop. This type of synchronization is useful when a DT is intended to do reports, analyses and diagnoses, predictions, integrations, or prescriptions. These *Data Values* only require obtaining information and do not send feedback to the system, the output of the analysis is used to make decisions from stakeholders.

3.1.2.1.6.2 Bidirectional Synchronization Choice

A Digital Twin with bidirectional synchronization enables dynamic communication (Angulo et al., 2019), between the physical system and its virtual counterpart, which allows the analysis of data and replication to production systems in real-time (Glatt et al., 2021). This is thanks to the ability to do two-way communication (send and receive data) that enables closed-loop communication; eliminating humans as an intermediary (Al-Sehrawy et al., 2021). By implementing bidirectional synchronizations, the system can make autonomous decisions. This means that the Digital Twin not only returns data to the stakeholder but is also now capable of making changes on its own if necessary.

3.1.2.1.7 Value Proposition Selection Task

When talking about the business value provided by Digital Twins, companies should focus on issues related to strategic performance and market dynamics, including improved and durable product performance, faster design cycles, potential new sources of revenue, and better warranty cost management. In particular, these strategic issues can be translated into specific applications that can provide the broad business value that DT may realize. In addition to the business value areas mentioned above, a DT is also able to provide some other key specific performance and efficiency indicators of manufacturing companies. Digital Twins are changing the way companies do business through the different applications to drive value. Such value can be measured by tangible results, which can be traced back to key indicators of the company (Evangeline & Anandhakumar, 2020).

Similarly, as seen in Section 3.1.1.1.6, the last part of the value proposition statement (taking into account a business model vision) encompasses the main benefit to be achieved with the implementation of a Digital Twin in the business. This new section, within the Engineering section, recalls the mentioned value proposition to obtain and define a more specific and detailed approach to the value-added by the DT. The proposed *Value Proposition* or Business Value maturity levels in this section are given from the combination of the concepts proposed by Preetha Evangeline & Anandhakumar (2020) in their article "Digital twin Technology for 'Smart Manufacturing'" and once again one of the proposed DT roadmap paths of the HCL's product lifecycle consulting team. This combination results in eight levels of DT maturity that a company can incur to improve its value proposition, in which these levels are: (i) New Product Introduction (Reduced Cost & Lead Time), (ii) Record Retention and Serialization, (iii) Improved Quality, (iv) Reduced Operational Costs, (v) Shortened Time-to-Market, (vi) Services Revenue, (vii) New Business Models, and (vii) Disruptive Business Model.

3.1.2.1.7.1 New Product Introduction (Reduced Cost & Lead Time) Choice

Recalling what was mentioned in Section 3.1.2.1.2.4, Digital Twins are integrated multi-physics, multi-scale, probabilistic simulations of complex products, and use the best available physical models, sensor updates, etc. to reflect the life of their corresponding twins. It can correctly map various physical data of the product to the virtual space. Virtual products can reflect the entire lifecycle process of corresponding physical products. Based on the DT, the product design process can be divided into conceptual design, detailed design and virtual verification (Tao et al., 2018a).

Conceptual design is the first and most important step in the product design process. In this stage, designers need to determine the future design direction of the entire product. By the implementation of a DT, the integration of various data and information in the physical space of the product can be done easily. The designer can quickly understand which areas should be improved thanks to the characteristics provided by a single information source. In addition, the communication between customers and designers is more transparent and faster by using real-time data transmission, thanks to its reliability in mapping the real product. It can make full use of customer feedback and the information of the previous generation of products problems to guide the improvement of new products (Tao et al., 2018a).

The next step is the detailed design where designers complete the design and the construction of product prototypes and develop tools and equipment for commercial production. It requires repeated simulation tests to ensure that the product prototype can achieve the required performance. However, due to the lack of real-time data and data affected by the environment, the effect of the simulation test is not reliable at all. *Digital Twins technology* can solve this problem well, due to its presence in the entire lifecycle of the physical object and can always be developed in coordination with it. It can record all the data of the product and the environmental impact (Boschert & Rosen, 2016).

In the last step, virtual verification, the effectiveness and feasibility of the design plan cannot be evaluated until the product design is completed and small batch production is carried out. Digital Twins can make full use of equipment, environment, materials, physical characteristics of customers, and data from the previous generation of historical data to provide a virtual verification. This method can test whether there are design defects and find out the reasons, making a faster and more convenient redesign. Moreover, it can avoid tedious verification and testing, thereby improving design efficiency. It not only describes the behaviour but also proposes solutions related to the actual system. In other words, it can provide operations and services to optimize auxiliary systems and predict physical objects based on virtual models (Tao et al., 2018a).

3.1.2.1.7.2 Record Retention and Serialization Choice

To have better management of warranty claims recalls and tracking requirements, Evangeline proposes that Digital Twins must be able to create business value through the storage of records from the produced serialized parts and the acquired raw materials. Digital Twins can capture product information from the design stage, to the manufacturing stage and up to the service stage, facilitating the flow of information throughout the organization, increasing productivity and efficiency (Ramesh et al., 2020).

DTs that can match with process information (process sequence information and process parameters, quality or defect rate of each batch, and rework), in other words, to do product traceability, need intelligent machines composed from sensors and data loggers that can capture all the data from the batch (Ramesh et al., 2020). Depending on the type of service that is planned to be provided or the control that is wished, there will be a certain degree of granularity on the data collection and storage system. This means that it must be taken into account from the beginning which element, assembly, subassembly, etc. is of interest to manage a record. Whether it is for warranty purposes, to keep track of a recall, to identify parts requiring repairs, to keep a record of remanufacturing pieces, to have a complex control of the original BOM, etc.

In this way, the establishment of a Digital Twin can help capture process sequences and process parameters to achieve excellent traceability and bring greater flexibility to manufacturing through self-organized manufacturing. This can also be used to improve the accuracy of prediction, scheduling and can help to capture unique service procedures and retain product data for years. This closed-loop between the production entities and Digital Twins ensures a continuous feedback system which leads to an improvement of the operational efficiency of the entire manufacturing field (Ramesh et al., 2020).

3.1.2.1.7.3 Improved Quality Choice

Digital Twins are being implemented during the design phase to improve product quality and production efficiency (Tao, Zhang, Liu, et al., 2019). In addition to this, they are also able to not just improve overall quality, but they might help to predict and detect quality trend defects sooner, control quality escapes, and to determine the beginning of a quality issue (Evangeline & Anandhakumar, 2020).

To accomplish these tasks, Digital Twins are being used to monitor the supply chain within a manufacturing industry. If a model can be established, such as linking the mechanical properties of the raw materials used for manufacturing with the quality of the final product, then the product quality evaluation data can be used to estimate these properties. The estimates then are potentially used to adjust process settings to improve quality and provide feedback to material suppliers (Wright & Davidson, 2020).

Due to the ability of Digital Twins to continuously monitor the machining process, they are becoming more and more important to maintain a constant quality of machined parts (Park & Tran, 2014). To obtain the actual status of manufacturing resources and workpieces, DT sensor-based monitoring systems have (with various sensors such as acoustic, vibration, force, etc.) become increasingly popular (Teti et al., 2010). A monitoring system that uses monitoring equipment to track the availability of machine tools facilitates adaptive overall scheduling (Mourtzis et al., 2016).

3.1.2.1.7.4 Reduced Operational Costs Choice

Many industries, such as the modern aerospace industry, are migrating from reactive to proactive and predictive maintenance to increase platform operational availability and efficiency, extend its useful lifecycle and reduce its lifecycle cost. In this way, Digital Twins can be used to actively identify potential problems with their actual physical counterparts. By combining physics-based models (physical models based on first principles) and data-driven analysis, the Remaining Useful Life (RUL) of physical twins can be predicted (Liu et al., 2018). Additionally, with this predictive maintenance strategy, maintenance frequency is being reduced to its lowest possible state leading to a huge cost saving in keeping resources in normal working condition (Mabkhot et al., 2018).

3.1.2.1.7.5 Shortened Time-to-Market Choice

Thanks to the implementation of new concepts such as cyber-physical production systems, digitization of manufacturing, model-based systems engineering, and the constant work companies are doing to collect and process as much data as possible (operational and production data) from their plants, have driven the application of complex virtual product models; better known as *Digital Twins* (Altintas et al., 2014). Thanks to the high level of data processing, they can effectively predict the effects of product and process development, as well as operation and maintenance decisions on product behaviour, without the need for expensive and time-consuming physical models (Roy et al., 2016). When talking about the design stage of a product, this realistic product model, DT, is essential for early and effective evaluation of the consequences of design decisions on the quality and function of mechanical products. Therefore, the Digital Twin's help to enter into a highly competitive market, where there is a constant challenging ambition to shorten time-to-market and improve product development performance.

Digital Twins in the shortened time-to-market field, are being implemented at the production line but there is a new strong interest for its implementation at the product design stage, as mentioned before (and in Section 3.1.2.1.2.4 – *Factory Choice*). In the search of fulfilling the gaps of current approaches to the implementation of DT in this area, models such as the comprehensive reference model have been proposed. The novelty of this reference model lies in its special attention to the "twin" between the physical and virtual domains. DTs are fed with abstract models that include all the characteristics that fully describe the physical twin at the conceptual level of the entire product lifecycle. Based on the simulation of these abstract models, Digital Twins can capture, understand and clearly describe at an abstract level the behaviour and environment of the physical twin.

3.1.2.1.7.6 Services Revenue Choice

Continuing with the categories proposed by Evangeline to generate business value, we have the last category, in which it is proposed that for there to be revenue growth opportunities the company must improve their efficiency and cost to service products (Evangeline & Anandhakumar, 2020).

On one hand, as mentioned in previews sections, maintenance is vital in any manufacturing industry, and so is for any business. From the very beginning, the product has been created through various processes, and even in the hands of the customer, must be kept under companies' care. The model can use a Digital Twins system to achieve efficiency in terms of time, price, operational performance, eradication of delays in receiving and providing products, best customer service, and efficiency in processing warranty, by effectively processing third-party suppliers and customers. This will help increase business opportunities (Raj & Evangeline, 2020).

On the other hand, in the current customer-based business model, since the customer is the centre of the business, it is more appropriate to respond actively and passively based on customer reviews and satisfaction surveys. It is indeed a masterpiece to improve company performance and market value, and it has found its rightful place in the manufacturing industry. In the early days, user design occupies a prominent position in the design phase, where user experience is also related to it. It responds positively by obtaining authorized feedback and by immediately adopting employee processes and work styles, thereby demonstrating the need for user experience. In this case, digital twins are the right and appropriate choice to maintain business by adopting environmental changes and fixing anticipated problems in appropriate locations in a demanding customer world (Augustine, 2020).

3.1.2.1.7.7 New Business Models Choice

As a result of today's blurred distinction between the production of an actual physical product and services, new business models such as "Servitization" and "Product-Service Systems (PSSs)" have emerged, as it is embodied on HCL's proposed DT roadmap (Zhang et al., 2019).

DT services can be applied to product design, production planning, manufacturing execution, Prognostics and Health Management (PHM) and other fields (Qi & Tao, 2018). In product design, taking into consideration the expected, interpreted and physical space. The DT-driven design aims to transform the expected product in the designer's mind into a digital representation in the interpretation space based on the existing physical product (Gero & Kannengiesser, 2004). On the other hand, at the production planning and production execution stage, DT provides an effective method to make plans and optimize the execution process (Rosen et al., 2015). On the shopfloor, Digital Twins can simulate plans and identify potential conflicts in virtual space even before production starts. However, building those systems is complex and professional work, especially when setting up the model with physical characteristics, rules, behaviours, etc. Models do not have to be created by the manufacturer, for physical equipment and general rules, models built by other manufacturers can be purchased and used in the form of services (Tao, Zhang, & Nee, 2019). Finally, PHM is essential for monitoring equipment status and predicting and diagnosing equipment failures and component life. Equipment failures cause high maintenance costs and tasks delays. In PHM DT, the virtual model of the physical device is synchronized with the actual state of the device. Real-time information of the operating status of the equipment and the health of the components is obtained. The high-fidelity digital mirror of the device can access the device even when the physical distance is not far away. In addition, the interaction of DT can reduce interference from the external environment, thereby improving accuracy (Tao, Zhang, & Nee, 2019).

3.1.2.1.7.8 Disruptive Business Model Choice

Today's business environment is constantly changing to seek business productivity, performance and innovation, which requires internal changes (viz. adaptation and adoption of new technologies, changes in organizational business culture, etc.) and external changes (viz. customers, markets, quality requirements, etc.). Disruptive innovation is an important aspect of these changes. Most of the current evaluation models mainly focus on technical aspects, and some of them also include market aspects (Jianfeng Guo et al., 2019). The external environment has received even less attention, aspects such as the macroeconomic situation or the industrial policy promoted by the government play a very important role in the process of creating disruptive innovations (van den Broek & van Veenstra, 2018).

Thanks to the technological boost provided by the implementation of a Digital Twin, companies can plant a business model in which the company responds to the challenges of strategic changes, transfer its resources to digital plans, redesign its organization and change its organizational culture; this by the corporative digitalization (Paniagua, 2018). In correlation with the *New Business Models*, companies should seek to incur a disruptive model to innovate in any of the three areas (market, internal factors or external factors). It has been seen that companies with solid and well planned and implemented DT can move towards the establishment of a Smart Factory in which all devices can be interconnected and can operate autonomously, thereby providing a valuable product range and internally developed solutions programs. As a result, companies with this maturity level in their business model can participate in many national and international R&D projects to stimulate the innovation needed to become a highly competitive company.

3.1.2.1.8 Data Analytics Sophistication Selection Task

This seventh selection takes into consideration the impact that Digital Twins have had as a relevant technology for an operation of excellence within the industry, taking into account the different needs and concerns of each customer. This leads to the fact that there is no 'one size fits all' Digital Twin technology, so customers must be provided with the ability to craft their systems according to their objectives, the maturity of their approach. to asset management, the requirements, and constraints of each industrial facility. For this, Metcalfe & Tohani propose a model of five levels of sophistication (see **Figure 6**) where the Digital Twins of type (i) Descriptive, (ii) Informative, (iii) Predictive, (iv) Comprehensive, and (v) Transformative are found, and where each of them has their intention and objective (Metcalfe & Tohani, 2019).

3.1.2.1.8.1 Descriptive Choice

At the simplest level choice, some customers believe that the visual counterpart of interconnected assets in information-covered facilities constitute a Digital Twin. At this level choice, DTs can address tactical problems at existing facilities. For example, when working with an offshore oil rig, a digital 3D image with a padlock icon might help to represent a pending or signed work permit. Another example, but now based on a 2D model, is used at Pipeline and Instrumentation Diagrams (P&ID) that contains asset information. Although these descriptive (Level 1) Digital Twins may appear to be simple, the P&ID of water treatment companies commonly include dozens of information about pipeline types, hazard levels, accessories, equipment, chemicals, piping materials, service fluids, level sensor, and flow meters.

Doing the Digital Transformation of P&ID with a series of real-time data can be a great beginning to start proposing a Digital Twin strategy of the existing assets. The advantage of these *Descriptive Digital Twins* is that they are inexpensive to implement, they do not require a large infrastructure to start data collection and they are capable of immediately improving existing processes without affecting the workflow routines that are been carried out during the moment of implementation.

3.1.2.1.8.2 Informative Choice

Taking a further step towards the evolution of a Digital Twin there is a second-level choice, which is focused on customers with the ability to acquire or who have an integrated IT system. Many of the companies in operation today make constant investments in historians, mobile forms for operator rounds, maintenance databases, monitors on safety-critical equipment and OEM-installed sensors. Despite this, operations managers must be able to use these sources efficiently to extract much value from the information in which they invest. It is necessary to establish a focused systems integration project to provide the system with information in real-time that allows them to save money on maintenance work and reduce unplanned events.

Due to the economic limitations that many companies present, the *Informative Digital Twins* that are implemented in this Level 2 very rarely have a striking 3D visualization. The information can be presented effectively and simply through a dashboard. In addition, advanced customers run analyses on spreadsheets or corporate business intelligence tools. These strategies do not affect existing processes or decision making.

3.1.2.1.8.3 Predictive Choice

There are also companies in the market with more robust asset management strategies and robust asset information systems. In this model, these companies are encouraged to start developing a Digital Twin strategy tied to an enterprise implementation of Asset Performance Management (APM) software. Once this kind of software is implemented, a predictive Digital Twin strategy (Level 3) could be reached where the existing capabilities of the APM software are used to predict equipment failures according to the reading of the data provided by the sensors and the rounds of the operators.

At this level, the Digital Twin changes the way engineering and maintenance decisions are made. This is achieved thanks to the visualization of the information on the state of the assets in real-time, ideally in a 3D view of the installation, and the proposal of solutions to avoid unplanned events. It should be noted that a predictive Digital Twin is only functional within those industrial facilities whose management has only one defined purpose. In turn, it is necessary to take into account that to reach this level a prior investment in the integration of IT systems is required to transfer data to the APM software. *Predictive Digital Twin* strategies can be implemented at existing sites as well as new construction facilities.

3.1.2.1.8.4 Comprehensive Choice

One of the great promises that make Digital Twins so important is their ability to simulate the current performance of a physical system in real-time. Being able to simulate with a certain degree of reality shows that there is a granular digital model of the system made up of hundreds of data sources, a library of asset-level standard operating models, and sufficient computing power to generate value in almost real-time. This Level 4 of Digital Twin requires in turn a custom-built information architecture that cannot only be superimposed on the current IT system. To obtain and analyse data in real-time and establish what-if scenarios, this *Comprehensive Digital Twin* requires a cloud-based computational scheme capable of loading and downloading data in the shortest time possible. In addition to the aforementioned, since a Digital Twin at this level represents a very complex system, the algorithms that are used to give value to the information in form of prediction, prescription, analysis, etc. are designed in their most basic part through physics principles.

This Digital Twin comprehensive strategy can only be applied to existing facilities with a specific asset class and very similar characteristics. The Level 4 strategy will start to be applied to new smart manufacturing systems that seek to take advantage of the Industry 4.0 principles.

3.1.2.1.8.5 Transformative Choice

Finally, companies that are building new industrial facilities can make use of Digital Twin technology within the entire Engineering, Procurement, and Contracting (EPC) process. Currently, different design and construction firms are taking advantage of this approach with Digital Twins by the previous simulation of plants, giving, as a result, the optimal distribution for the generation of better performance, and later they proceed to the construction of the same, with Digital Twin technologies embedded in assets. To achieve this, a good communication infrastructure capable of supporting the Internet of Things (IoT) data flows is required. Additionally, a robust cyber-security framework is essential so that it allows the free and secure use of cloud computing for DT calculations and equipment-attached sensors providing granular insight into asset health.

This Level 5 of Digital Twin sophistication, *Transformative Digital Twin,* can only be implemented in new-build facilities, as it requires an integrated information architecture across all assets. This last level gives rise to the use of powerful analytic tools to predict failures, prescribe optimal maintenance strategies and automated solutions. The communications infrastructure enables location tracking for worker safety and augmented reality technical support. The deployment of *Transformative Digital Twins* encourages EPC workflows to migrate from document-centric to digital-centric.

3.1.2.1.9 Machine Learning Capability Selection Task

As mentioned in previous thesis sections, to improve on the data value scale, the quality and quantity of data processing start to become more relevant. For a Digital Twin to be able to report, analyse and diagnose, predict, integrate, prescribe, or decide autonomously, the level of data analysis must be commensurate with the level of data value. To answer questions such as, if it is necessary that the physical system, with onboard sensors and processor, reports the performance, health, and maintenance data to the virtual system to call a *Digital Twin system,* four maturity levels/choices of virtual representation can be described. Each level has a specific purpose and scope and helps to make decisions and answer questions throughout the lifecycle of the system. This thesis section lists these different levels and the characteristics that define each level (Madni et al., 2019).

3.1.2.1.9.1 Pre-Digital Twin Choice

This first level choice is composed of the traditional virtual prototype created during the pre-engineering period (viz. product, manufacturing cell, production line, factory, supply chain pre-construction stage). It supports decision-making in conceptual design and preliminary design. The virtual prototype at this level is taken as a virtual general executable system model of an envisioned system that is usually created before the physical prototype. Its main purpose is to reduce technical risks and discover problems in the early stage of the project. Like most model-driven methods, virtual prototypes (or *Pre-Digital Twin*) involve models of the system early in the design process. However, virtual prototypes are usually not used to derive the final system. This is because virtual prototypes can be "obsolete" prototypes or "reusable" prototypes. The latter can be used to export the final system. Virtual prototypes are mainly used to verify certain key decisions about the system and mitigate specific technical risks early in the design process. In general, these pre-Digital Twins do not have any data acquisition system due to the lack of a reference physical system. As a consequence, for lack of data, the use of a data analytics tool such as Machine Learning (ML) is obsolete.

3.1.2.1.9.2 Digital Twin Choice

When the Pre-Digital Twin takes a step forward it evolves into a simple DT, where the virtual system model can incorporate performance, operating status and maintenance data from the physical system. The virtual representation is an example of a general system model that receives batch updates from the physical system and is used to support high-level decisions in conceptual design, technical specifications, preliminary design, and development. The data collected from the physical sensors and computing elements in the physical system includes health status data (e.g. battery level), and mission execution data (e.g. flight time). The data is reported back to the Digital Twin, which updates its model to include the maintenance plan of the physical system. Since the interaction with the physical system is two-way, it has enough opportunities to use the knowledge gained from one or more Digital Twins to improve their performance in real-time operations. This level of DT is used to explore the behaviour of a physical system under various hypothetical situations. As an executable digital representation, it is easy to manipulate when exploring system behaviour in the controlled simulation environment of a test platform. Any defects found will be used to modify the physical system and reflect the changes in the Digital Twin.

3.1.2.1.9.3 Adaptive Digital Twin Choice

The *Adaptive Digital Twin* provides a flexible user interface (in the spirit of smart product models) for physical systems and Digital Twins. The adaptive user interface is sensitive to user/operator preferences and priorities. Some key functions of this level are the ability to learn operator preferences and priorities in different environments (Madni et al., 1982) and also to be able to predict their behaviours

(Hribernik et al., 2021). These features are captured using supervised machine learning algorithms based on neural networks. Based on real-time "extracted" data from the physical system, the model used in the Digital Twins will be continuously updated. After using the system, it can also receive information in batches. This DT can support real-time planning and decision-making during operations, maintenance, and support. In this way, DT's can react quickly to sudden changes in the product lifecycle as fluctuations in demands, changes to product configurations or the supply chain, and disturbances in production (Hribernik et al., 2021).

3.1.2.1.9.4 Intelligent Digital Twin Choice

The final DT level choice proposed in the Madni et al. (2019) table (see **Table 1**) is the *Intelligent Digital Twin*. It has all the features of Adaptive Digital Twin (including supervised machine learning). In addition, it has an unsupervised machine learning function, which can identify objects and patterns encountered in the operating environment and strengthen the learning of the system and the state of the environment in an uncertain, partially observable environment. Digital Twins at this level have a high degree of autonomy. At this level, DT can analyse more detailed performance, maintenance, and health data from real opponents.

3.1.2.1.10 Human-DT Interaction Selection Task

Nowadays, in processes related to production, there are two ways of interaction between computer automation systems and humans. One way is considered when the computer system performs predefined tasks, which are triggered by user input. The other way is when the system is programmed to run fully automatically, where the user can observe and intervene in the system if necessary. A common method of integrating human employees into self-control technology systems is to transfer all decision-making tasks to a computer system and use human employees as support for process execution. Using Digital Twins as connectors between Cyber-Physical Production Systems (CPPS) and employees can enable employees to participate in certain planning and control processes, and to obtain better planning results (Graessler & Pöhler, 2017). How does this interaction between DTs and human resources take place? Thanks to what has been reviewed in the literature, in this section the different maturity levels in which this interaction lies could be proposed, having an evolution that goes from the *Document-based interface* up to the *Mixed Reality-based interface*.

3.1.2.1.10.1 Document-based Interface Choice

This first level choice of an interface between the human and the DT presents a unilateral communication in which the DT provides information to the human through a written report. This report can be presented in the form of a pdf document, a *.xlsx, .txt, etc. file. It is important to mention that the quality and level of information provided by such a report is directly related to the processing capacity of the system and the level of robustness of the model regardless of the interface selected by the DT designer. The information shown in this report depends firstly on the type of application where the Digital Twin was implemented and the *Depth of System* selection level. Secondly, it shows a direct relationship with the *Data Value (Service)* selected in Section 3.1.2.1.4 and the *Data Analytics Sophistication* selection level in Section 3.1.2.1.7. In other words, the selected interface will not be able to provide or display more information than it is capable of process and analyses. Customization of this report is subject to design criteria and the convenience of the user or decision maker; once again, taking into account the considerations explained above.

3.1.2.1.10.2 CAE Simulation-based Interface Choice

This second-level choice of maturity in terms of interaction with the human, as in the past level, only allows the user to extract information from the DT. In this case, there is a visual evolution of this information thanks to the implementation of design methods such as *Computer-Aided Engineering (CAE)* advanced tools. Designers are now using these tools for virtual prototyping, optimization and troubleshooting. Simulation tools enable designers to accurately predict performance early in the design cycle, analyse multiple designs, reduce reliance on multiple physical prototypes and expensive testing, optimize designs to achieve optimal performance and reduce design time and cost. Digital Twins, as an accurate virtual model of product physical and performance characteristics, can help product development organizations enhance and accelerate their digital simulation and understand the product performance in the real world (Ferguson et al., 2017).

3.1.2.1.10.3 AR-based Interface Choice

As one of the key technologies in Industry 4.0, *Augmented Reality (AR)* has been widely used in manufacturing environments. AR allows users to see the overlay virtual objects into the virtual world and instead of completely replacing it. It enables users to interact with the real world with the information processed by virtual objects and consequently perform tasks in the physical world (Bhouri, 2009). By integrating graphics, audio, and real-world objects, AR enables users to visualize and interact with DT data at a higher level. Digital Twin and AR are considered to be the key technologies of smart manufacturing. By using AR technology to visualize Digital Twin data, the physical and virtual parts of DT can be integrated and aggregated more intuitively and comprehensively (Zhu et al., 2019).

Digital Twin real-time data reflects the physical system and integrates historical data to provide the system with more useful information; improve itself. Depending on the characteristics of DT data, the use of AR to visualize Digital Twin data requires a physical part, a virtual part, a calibration process, an augmented process, and a control process. The control process allows the user to interact with the physical and virtual parts of the Digital Twin. After obtaining intuitive and comprehensive visualization data from the augmented process, users can use this useful information to directly make decisions and control the physical part through the AR device (Zhu et al., 2019).

3.1.2.1.10.4 VR-based Interface Choice

Virtual Reality (VR) technology is a computer simulation system that can create virtual spaces. It uses computer technology to generate simulation environments, multi-source information combinations of interactive three-dimensional visual scene and body behaviour system simulation. The VR system uses computer graphics to build models in real-time and depict the scene in three dimensions. It mainly focuses on perception, user interface, background software and hardware.

Digital Twins are being used in new process systems as virtual tests platforms to simulate and analyse the layout and applicability of selected systems, configuration, components, etc. The interface based on immersive VR can better visualize and understand the DT process. By implementing technology such as VR the early detection of design errors during virtual commissioning before actual implementation, can be done. Therefore, the company can avoid costly and potentially unmanageable consequences. In addition, after implementation, with the help of a Virtual Reality interface, the digital twin can be used for operator training; for real-time process monitoring, thanks to the real-time information received from the sensors; and to test future changes (Pérez et al., 2020).

3.1.2.1.10.5 MR-based Interface Choice

Mixed Reality (MR) combines the real world and virtual space to create a new visual environment. In the new visual environment, physical objects and digital objects coexist and interact in real-time. The goal of MR is to seamlessly integrate virtual and reality to form a new virtual world that includes the characteristics of the real environment of virtual objects (Lovászová & Palmárová, 2013).

Although the operation and basis of each of the 3Rs (AR, VR, and MR) are different, the tasks that can be achieved with them are the same. Each of them can help to monitor, control, and provide maintenance to the systems, depending on the application the DT designer is looking for. The degree of maturity of the interface to be implemented in each project will depend on the needs of the project. According to the literature, technology such as AR can mainly help to visualize clusters of information in the field, while technologies such as VR and MR allow companies to provide training outside the field, saving time and money. On the other hand, it is expected that with technologies such as MR, station or manufacturing managers will be able to visualize and control their systems from anywhere in the world as if they were inside the plant.

3.1.2.1.10.6 Softbot-based Interface Choice

The final maturity level choice of the Human-DT interaction interface *is Softbot-based.* A softbot, a name derived from a software robot, is a computer program that communicates with a user or another software and acts on their behalf (Schwartz et al., 2016). They are becoming of great importance in the industry since they can support operators when management and automation of business processes, computer systems, and production assets come along. When implementing softbots within the Digital Twin system, they act as intermediaries between the DT and production managers interaction in Industry 4.0 production scenarios (Rabelo et al., 2021). In general, softbots can enhance the autonomy and interactivity of DT in smart manufacturing systems so that they can adapt fast to unforeseen situations without needing to re-plan (Rosen et al., 2015).

3.1.2.1.11 DT Virtual Representation Selection Task

The virtual representation of the Digital Twin model is directly related to the Human-DT Interface. In general, this maturity selection level indicates how the manifestation of the virtual product of the system will take place. These representations may go from the zero-dimension model up to the third-dimension model. Depending on the type of virtual representation chosen, the desired interface can be displayed. These models are subject in the same way to the installed capabilities; however, it is possible to mature the system by integrating new technologies that enable them.

3.1.2.1.11.1 Data Model (A Datum) Choice

A *Datum-based Digital Twin model* is the simplest and easiest way to conceive the results of a Digital Twin. This is characterized by being a mathematical or machine learning model that at the end of its execution only provides a numerical, binary, or written result that meets the characteristics of reporting, analysing, diagnosing, predicting, or prescribing. Depending on the type of interface that is selected is how the results can be displayed, but they must preserve this 0D (dimension) attribute.

This makes processing time faster and consistent, and implementation costs lower. Later, the data collected in this model can be saved in a database for future analysis or increase the model by one dimension.

3.1.2.1.11.2 1D Model (A Graphic) Choice

Digital Twins are complex systems that are made up of mechanical, electrical, pneumatic, and hydraulic components, as well as sensors and microprocessors with variable degrees of interaction. During any operational condition, the physical qualities of all interrelated components and sub-systems have an impact on one another. Depending on the *Value Proposition* and the *Service* planned to be done by the DT, certain mathematical interactions need to be stated, and their behaviour must be extensively examined using simulation. Simulating systems in 1D is the first visual throughput of a DT that allows engineers to better grasp how the various components inside the system interact by analysing the resultant plot. It is possible to work with fewer parameters to define one-dimensional objects, requiring fewer equations to be included in the simulation. This simple simulation model reduces the requirement for prototype testing, reducing the time and cost of development (Gurney, 2001).

3.1.2.1.11.3 2D Model Choice

A 2D model is the first visual representation of a product on one of their Euclidean or Cartesian plane. With this model, mechanical and fluid simulations can be performed. The given results are not just numerical, they also provide visual results that helps decision-making and understanding phenomena in the system. In 2D models, numerous effects may be explored in a short amount of time due to its numerical efficiency, and the influence of several process factors, such as bending forces, rolling mode and line contact trajectories, contact pressures, side length change, and spring back ratio, can be studied (Zehetner et al., 2021). One of its disadvantages is that as a dimension is missing, some of the provided results may not describe the complete reality.

3.1.2.1.11.4 3D Model Choice

A 3D model is a collection of points joined geometrically by lines, curves, triangles, surfaces, etc. and is used to make three-dimensional representations of physical or imaginary objects (Tsygankov & Pokhilko, 2017). 3D models are commonly used as virtual representations of Digital Twins as they enable a realistic virtual environment. In geometric analysis, they allow the user to create cross-validation against the physical twin by evaluating functionality, movements, trajectories, restrictions and other factors of the modelled system (Lohtander et al., 2018). When it comes to physical analysis, Computational Fluid Dynamics (CFD), Computer-Aided Engineering (CAE), and Finite Element Methods (FEM) simulations upon 3D models, helps stakeholders to recognize the conditions in which a product has to undergo and to plan forthcoming maintenance based on the PLM (Phanden et al., 2021).

Among their main disadvantages, despite being faithful representations to reality, is that in the first place they are difficult to achieve. It takes several hours of modelling to be able to represent a complex system, however, if the application allows it, the models may be coarse representations of reality. Secondly, there is the fact that to carry out the necessary simulations, the computational level required is much higher than that of a simulation of a 1D or 2D model (Zehetner et al., 2021).

3.1.2.1.12 ICT Architecture Selection Task

All static and dynamic components of the framework defining the Digital Twin Information and Communication Technologies (ICTs) structures are included in the ICT architecture. It may be seen as the starting point for the description and coordination of the components and structures of a DT ICT system. Hardware, software, network devices, and communication applications are some of the most tangible building components of ICT architecture. Three types of ICT architecture configurations will lead the Digital Twin to provide the required service, according to the established *Value Proposition Selection* and that will play an important role when establishing the *Data Synchronization Selection* and enabling the corresponding *Cybersecurity Mechanisms Selection*.

3.1.2.1.12.1 Centralized Choice

In a *centralized architecture,* there is a central coordinating system or server in which each node of the system is linked. It has the characteristic that all the exchanged information between nodes must pass through the coordinating system. One of the main problems of this architecture lies in the fact that if the central coordinating system fails (single point of failure), all these individual nodes will be disconnected, and the network would be shut down (Aggarwal & Kumar, 2021). Since a centralized system requires a single owner to connect all other users and devices, the network's availability relies on a single owner. This fact makes them vulnerable to cyberattacks that disrupt the operation and reliability of the Digital Twin. Another limitation is the slow communication time between users, or nodes, that are far from the coordinating system. Among the advantages found, is its quick and easy implementation and low maintenance costs. In addition to this, it allows a practical control of the information as it is concentrated in the same place.

3.1.2.1.12.2 Decentralized Choice

In a *decentralized system,* instead of a single coordinating system, there are several, and all the coordinators and their nodes cooperate. If one or more nodes fail, they can link to the other coordinators or individual nodes. They can share information or complete tasks with the help of available coordinators. If several nodes fail at the same time with this architecture, individual nodes may be unable to interact with each other, and the network may get disconnected (Aggarwal & Kumar, 2021). The performance of this architecture is somewhat variable, on the one hand, it can offer faster solutions and communication, but if the architecture is not properly optimized the performance can become inconsistent. Another advantage of this architecture is that it allows Digital Twins to be more diverse and flexible systems.

3.1.2.1.12.3 Distributed Choice

Unlike centralized and decentralized architectures, in *distributed systems,* there is no need for a coordinating system. Each node in this system is linked and coordinated with the rest of the nodes. They can share information and collaborate as a group. Users are provided with access to hardware and software resources, which lead to the increment of the system's performance in specific instances. A distributed system is protected against component failures that occur independently, which can significantly increase its uptime. If one or more nodes fail, the remaining nodes can still share information or execute tasks through coordination and cooperation (Aggarwal & Kumar, 2021). Although distributed architectures present higher maintenance costs and a complex deployment, Digital Twins may be benefited from this type of architecture as they enhance security and privacy and increase data storage while improving the performance of the system.

3.1.2.1.13 Computing Environment Selection Task

New Smart Manufacturing environments produce a large amount of data. To meet the different needs according to the selections realized at this *Design and Engineering Activity*, the three complementary technologies of *Edge* computing, *Fog* computing, and *Cloud* computing help to accelerate the development of DTs (Qi, Zhao, et al., 2018). The *cloud-based smart manufacturing paradigm* promotes a variety of new applications and services to analyse large amounts of data and achieve large-scale manufacturing collaboration. However, different factors such as network unavailability, bandwidth overflow, and latency time, limit its availability in high-speed and low-latency real-time applications. *Fog computing* and *edge computing* extend the computing, storage, and network capabilities of the cloud to the edge, which will respond to the above problems (Qi & Tao, 2019).

3.1.2.1.13.1 Edge Computing Choice

Edge computing is a decentralized computing infrastructure where application services and cloud resources are interconnected and controlled by various entities. Edge computing is based on proximity: where sensor nodes are easier to use when they are closer than far away, intelligence: the system gets miniaturized when autonomous decision-making is implemented at the edge, control: application management and coordination also come from edge machines that can allocate or commission computing (Garcia Lopez et al., 2015). The main advantages of using this type of technology are faster processing, compliance, data privacy and improved performance. However, Edge computing might be affected by lag, network resilience and link failures. The Internet of Things (IoT) transfers large amounts of data between the cloud and devices, so high-bandwidth connections are required, and the calculations in such applications are also data and resource-intensive (Francis & Madhiajagan, 2017).

On a Cyber-Physical System (CPS) framework, Edge computing forms part of the Unit level (Kim, 2019) conformed by small units, such as components and equipment (such as CNC machine tools, intelligent robots, etc.), materials (such as RFID-equipped raw materials, AGV with built-in sensors, etc.) and environmental sensors. At this point intelligent CNC machine tools can use knowledge to make decisions based on changes in spindle load, they can adjust the feed speed, such as increasing the feed speed when the load is small, and reducing the feed speed when the load is large, to shorten the processing cycle and improve the processing efficiency and quality (Qi, Zhao, et al., 2018).

3.1.2.1.13.2 Fog Computing Choice

Fog computing was proposed by Cisco to transmit data wirelessly to the devices along with the IoT network. Fog computing has advantages in reducing latency, power consumption, and network data traffic. It is also considered an extension of cloud computing to the edge network, providing services (such as computing, storage, network, etc.) closer to user equipment (such as network routers) instead of sending data directly to the cloud (Rao et al., 2015). Fog computing makes applications more convenient and meets a wider range of node access thanks to the fact that data storage and processing rely on local devices than cloud data centres. In some of the researched papers, Fog computing is considered to be quite the same as Edge computing. As seen on edge computing, it follows the principle of proximity as it takes place closer to the end user's network. It is also a virtualization platform between the end-user and the cloud data centre hosted on the Internet. The difference between Fog computing and Edge computing relies on the Fog capability to establish interconnections between nodes, while edge computing runs on isolated edge nodes (Qi, Zhao, et al., 2018). When setting it into a CPS framework, it is considered to be on the System level (Kim, 2019) where the integration of multiple unit levels cooperate.

3.1.2.1.13.3 Cloud Computing Choice

Cloud computing is Internet-based computing in which shared resources (for example, storage and computing facilities, software, data, applications, etc.) are accessed and used in a "pay as you go" manner (Wei & Blake, 2010). The main advantage provided by this technology is that users obtain high-quality services at a low cost.

According to Kim (2019) Cloud computing fits the Service level on its CPS framework, that in correspondence to the hierarchical levels proposed by (Qi, Zhao, et al., 2018) is where some applications such as personalized customizations, smart design, remote maintenance, etc., can be achieved. Moreover, Cloud computing has dominated the virtualization technology and provided the users with a variety of services in a transparent manner, including IaaS (Infrastructure-as-a-Service), PaaS (Platform-as-a-Service) and SaaS (Software-as-a-Service) leading to a trend of Everything as a Service (XaaS) (Banerjee et al., 2011). However, as the collected data from machines and sensors is sent to the cloud, and the desired output is sent to the desired device again, a strong response delay is presented. In addition, this massive transfer of data requires high and expensive bandwidth (Shu et al., 2008). As the network becomes unavailable, these problems become obstacles for applications that require delay constraints (Shu et al., 2010).

3.1.2.1.14 IT Network Selection Task

Networking is a sector of Information Technology (IT) that is one of the fastest-growing segments of the industry. It entails the creation, use, and maintenance of computer networks (including hardware, software, and protocols) for many computing devices to communicate data. These networks are of great importance since they allow the transmission of information within the highest levels of the automation pyramid in which the Digital Twin systems are embedded.

3.1.2.1.14.1 TCP/IP Choice

TCP/IP is a common internetworking protocol that is now nearly universally used (Muskinja et al., 2003). TCP/IP-oriented networks for a Digital Twin have a great capacity to bind to a variety of physical media, from wired to wireless or LAN to

WAN, and to encapsulate nearly any sort of data at the other end. For this reason, TCP/IP becomes crucial for networking flexibility. Its applicability is essentially endless since it can adapt to both the physical layer and the application layer in virtually any way (OPTO, 2005). Among the most common advantages provided by TCP/IP protocol are the lower development times and cost for host applications, thanks to the widespread of libraries and applications that have led to the integration of the protocol in the most host operating systems; take advantage of common TCP/IP services and easy maintenance and debug activities (Muskinja et al., 2003).

3.1.2.1.14.2 4G-Enabled Choice

Businesses may use 4G technology for the DT IT network as a primary, backup, or hybrid network connectivity option since it is constantly on and cost-effective. 4G is the fourth major generation of mobile network technology, and it addresses the connectivity issues that have been choking companies. According to Place & Keeping (2012), about 67 per cent of organizations in the United States who have already implemented 4G/LTE claim greater productivity across all departments, with sales, customer service, and other departments that deal with customers seeing the greatest advantage. Whether considering 4G for DTs as a backup, failover, or primary network option, the benefits of the technology make it more appealing than ever to organizations all over the world (EnableIP, 2015).

3.1.2.1.14.3 5G-Enabled Choice

With the high bandwidth and low latency, provided by 5G networks, large volumes of data, such as the one collected from the DT system, may be collected and analysed to produce actionable insights that might enhance factory/plant operating efficiency (Jamnadass, 2020). 5G may be used to provide remote visualization of the processes through AR/VR since its higher bandwidth density allows better video clarity, less visual latency, and more users in any given space. It also allows seamless mobility within and outside of the manufacturing facility. It could also be used to execute end-to-end traceability as 5G has higher scalability, supporting larger device density, more and higher-resolution CCTV cameras for tracing, and communications assurances when employing ultra-reliable, low-latency connections. Continuous traceability is ensured across the production plant and warehouse, as well as into national and international contexts, thanks to 5G’s seamless mobility support (GSMA, 2021).

3.1.2.1.15 OT Network Selection Task

OT, also known as Operational Technology, is a type of computing system that processes operational data such as telecommunications, technical components, and computers. It is used to monitor devices, various industrial processes, and some industry events, as well as make necessary adjustments in an industry or enterprise. In other words, OT is useful for *Digital Twin applications* as it makes use of a combination of software and hardware used to perform real-time operations to detect any changes that occur during a process. This can be done by directly controlling industrial equipment and some of the enterprise's events, making them more reliable and increasing their rate of availability and reliability.

3.1.2.1.15.1 Wired Choice

The simplest Digital Twin uses common industrial networks for its OT network. The IEC 61158 standard defines a series of industrial computer network protocols for real-time distributed control. Only two devices could interact with each other using serial connections, like RS 232, before the introduction of field-bus protocols. Hundreds of analog and digital nodes can connect simultaneously utilizing Fieldbus protocols by providing only one communications point at the controller level. Network topologies such as daisy-chain, star, ring, branch, and tree are all supported. The most significant advantage of field-bus has been the significant decrease in plant wiring (Powers, 2016).

3.1.2.1.15.2 4G-Enabled Choice

Digital Twins may have great benefits from cellular connectivity, for the requirements of digital transformation and smart wireless manufacturing, by utilizing dedicated networks on 4G/LTE. With the arrival of the latest advances in 4G (LTE) network, Digital Twin in industries will have at their disposal a series of more effective technologies to connect all the devices they use in their system. This will allow them to better manage their resources, increase the communication technology and enhance reliability on the network (IT Digital Media Group, 2019).

3.1.2.1.15.3 5G-Enabled Choice

In industrial contexts, 5G as 4G mobile technologies are considerably more suitable to the operational technology network, giving a more acceptable technological foundation for large volume, high reliability, always-on manufacturing, production, and logistics solutions. Moreover, they ensure higher levels of consistency, interoperability and certification for devices (GSMA, 2021).

When deploying Digital Twins from robots and cobots for automation based on a 5G network, an improvement of throughput, quality, and safety by using real-time or near-real-time control, may be observed. This is due to the higher density support of robotic/cobot equipment. Moreover, additional camera angles and higher-resolution footage are supported. In terms of smart connected tooling, the low latency and high reliability allow update of setting in real-time/near real-time, as well as data recording and tool control. Also, the power optimization features may provide battery standby times (GSMA, 2021).

3.1.2.1.16 Cybersecurity Mechanisms Task

Regardless of the type of Digital Twin solution that has been deployed in a project, the amount of data that is transferred during operation is enormous, whether to establish communication, create databases, feed, and manage an ML model, generate new 3D models, run finite element simulations, etc. To do this, DTs face the challenge of exchanging information most transparently and reliably possible (Gehrmann & Gunnarsson, 2020). Because a Digital Twin application relies on data from external systems, it is necessary to implement an architecture protocol that allows the secure interaction and placement of information inside and outside the network.

Digital Twins must deal with the access control to the system as it is vulnerable to cyberattacks or internal sabotages when maintenance strategies need to follow. For these reasons and to keep track of the access the users' identities must be validated, and after this is done successfully, the users must be granted the appropriate rights to conduct the actions they are expected to accomplish. Authentication, Authorization, and Accounting (AAA) are universally accepted as critical components of a secure distributed digital environment (Paolini et al., 2020).

3.1.2.1.16.1 Authentication Subtask

The Federated AAI (Authentication and Authorization Infrastructure) framework should be responsible for the whole process of obtaining the user's identification, verifying that identity, and transparent delegation and propagation of that identity throughout the entire environment (Paolini et al., 2020).

Transparent delegation is founded on the idea that each service along the execution chain must function in the context of a specific end-user. To do so, the user's identity must be transmitted to each service involved. A traditional method to do authentication is to simply provide the current user's identity at each service call. The problem with this traditional method is that it has various drawbacks, such as the developers having to manually supply the user's identification every time, and, worst of all, this may be easily corrupted. The AAA system allows users to delegate their identities in a completely transparent manner. The identification of the user is automatically communicated across all components engaged in the execution of the services (Camarinha-Matos et al., 2008).

3.1.2.1.16.2 Authorization Choice

The modules in this service category of the Federated AAI framework operate as gatekeepers. Its job is to transparently validate the corresponding rights and permissions of the user's identity according to what is stated in the security database. Security filters evaluate rights at each access point (portal, web service, database, etc). The authentication modules are used to determine the user's identity for authorisation modules. Every time a user calls a portal's functionality, or a portal invokes a web service, or a web service invokes another web service, or a web service accesses a database, authorization modules are employed (Camarinha-Matos et al., 2008).

3.1.2.1.16.3 Accounting Choice

Accounting is the last plank in the AAA architecture security framework, and it measures the resources a user spends during access. This can involve the system's time, or the quantity of data transmitted and/or received by a user during a session. Accounting entails logging session statistics and using data, which is utilized for authorization control, charging trend analysis, resource consumption, and capacity planning (Camarinha-Matos et al., 2008). Another way to see the Accounting stage on the AAA frameworks is that it is also responsible for storing the user's actions history. In the future, this helps to identify changes that have been made in the algorithm, database, model, etc along with the information of who and when made them. With this, good version management and access monitoring to the system can be carried out.

3.1.2.2 Implementation Activity

As mentioned in the introduction of Section 3.1.2, this activity of the DT development project is in charge of planning and supervising the progressive implementation of the Digital Twin taking into consideration all the key aspects and requirements stipulated in the *Digital Twin Lifecycle Management Framework.* For this section, the adoption of the *Agile Methodology* is recommended to carry out a correct development of the Digital Twin project, however, any Project Management implementation tool can be used instead.

3.1.2.2.1 Agile Development Task

Agile Methodology provides an iterative approach to project management and software development. Its main characteristic is the fact that helps development teams to obtain value from their customers, in terms of feedback, that delivers faster results with fewer flaws. Compared to current development teams, whose aim is to deliver the entire project at the deadline, an agile team delivers small consumable portions of the project until they reach the final delivery. These deliveries in terms of requirements, plans, and results are evaluated continuously, by the team and the stakeholder, so they have a natural mechanism for responding to quick changes (Atlassian, 2021). Agile development provides a variety of methods that allow development teams to evaluate the trend of the project throughout the lifecycle. Using agile methodology, if a certain achievement is required, regular tasks such as sprints are required between the teams in charge of the project. In the agile model, every aspect is for this purpose and is often re-examined throughout the lifecycle (Gangadhar et al., 2015).

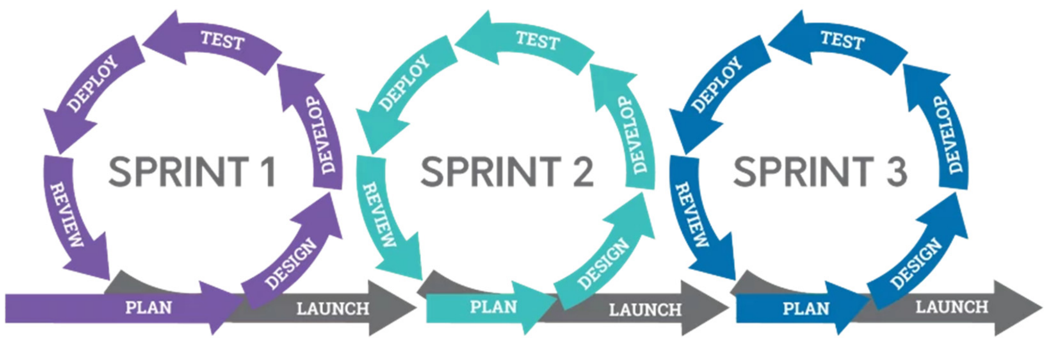

Figure 15. Agile Development Methodology (BairesDev, 2021)

Figure 15 shows the structure that must be considered when establishing an *Agile Methodology*. In it, each sprint is made up of seven concepts that complete the cycle, and there can be as many sprints as needed. Each of them starts by setting up a (i) Plan, continues with the (ii) Design, then the (iii) Develop followed by a (iv) Test if the system works it can be (v) Deploy, if the final user accepts the project on the (vi) Review then it finally can be (vii) Launch.

3.1.2.2.1.1 Plan Subtask

Each sprint should begin with the planning stage, which tells the agile team what is going to be done and how much time they have to have it done. To reach this conclusion, it is necessary to first establish the list of tasks to be developed throughout the DT project, this is known as DT backlog (Srinidhi et al., 2020). Accompanying these tasks, it is necessary or advisable to assign a duration to each one of them, it is worth mentioning that this step has already been established in

Section 3.1.1.2.7 at the DT project schedule. Once this DT backlog has been established, at the beginning of each of the sprints, tasks must be chosen according to the project scheduling sequence. In the case that one of these tasks is not fulfilled in the sprint that was run, it must be carried over to the next one so as not to lose the workflow or affect the proposed precedence diagram. Similarly, it is recommended that the sum of the duration times of the tasks chosen in each sprint does not exceed the total number of hours that the team can work. This means that it is necessary to take into account the working hours for which they were hired and see that the tasks to be performed during the sprint do not exceed these times, if they do, the tasks will be taken up in the next sprint with the remaining times.

3.1.2.2.1.2 Iterative Design Subtask

This second subtask, before beginning with the development of the DT project, encourages the agile team to design or update the tasks that will be developed in that sprint. The design can be focused both on the visual part of the system or on the architecture that is going to be proposed for the transmission and reception of data, security, design of spaces, design of the *Human-DT Interaction* interface, etc. as required on the task that is being worked on (DataVaults, 2021).

It is advisable to carry out the visual design stage together with the final user to reach the results that best suit him. Doing it in another way could lead to taking longer due to the corrections made by the stakeholder and delaying the progress of the following sprints. For this, a first rough mock-up of the interface must be carried out and shown to the user. The ideas can be taken from the current competition, seeing what is having better results and what other details do not add or even subtract value. The refinement of the design of the interface, as mentioned above, must be carried out in small iterations with the consumer to suit the new features (Dziuba, 2019). Regarding the architectural design of a *Digital Twin,* when working on subjects of a higher engineering degree, the constant presence of the stakeholder can be forewarned. Despite this situation, it is always necessary to take into account the requirements previously specified by him without exceeding the limitations.

3.1.2.2.1.3 Iterative Develop Subtask

The development of the DT system must be carried out based on the previously defined requirements. The instructions outlined in the *Design and Engineering Activity* must be followed to adequately meet the goal (Srinidhi et al., 2020). At this subtask, when developing a *Digital Twin,* the "agile development" team can start working with the machine learning model according to the *Data Analytics Sophistication* selected by the user and the *Data Value* that the stakeholder wants to generate from it. Also, they can start developing the *Human-DT Interaction* interface or build the necessary architecture for the *Computing Environment* type required in the system. It should be mentioned that there may be many changes within the internal iterations of this stage, but it is always recommended to save and document each change or each update that is made. In this way, it is possible to keep a history of it and be able to return to past configurations without further ado.

3.1.2.2.1.4 Iterative Testing Subtask

Once a part of the *DT system,* a set of parts, or the complete DT system has been built, it should get tested. In this stage, it is sought to ensure good quality in what is being delivered, taking into account the different testing criteria that have been proposed by the team to achieve compliance with the requirements (DataVaults, 2021). To obtain reliable results, it is necessary to carry out both internal tests (within the same work team) and external tests (looking for other areas to provide support) that shows if there are flaws in what has been developed (Srinidhi et al., 2020).

Landing this idea to *a CAE Simulation-based Interface* Digital Twin project, at this subtask it must be verified that the constraints of the CAD are well set according to the physical system, that the communication of the data is getting into the server in time and form, that the Machine Learning (ML) analysis of the data collection is providing an accurate result, etc.

Later, this subtask will not only serve to perform functionality testing or guarantee that the system is bug-free, but also for systems integration, interoperability, and user acceptance testing, etc. (Dziuba, 2019). Once again, it is important to gather up the necessary documentation of the results with the tested configuration.

3.1.2.2.1.5 Iterative Deploy Subtask

This subtask of the cycle is the delivery of the partial or complete *DT project* to the customer. It shows all the functionalities of the system up to the scope of the sprint that is being run. It is very important that at this task the customer gets in charge of testing each of the parts of the system so that the next subtask provides feedback on what he has observed. Future iterations at this subtask will be responsible for updating the demo or current system by introducing new features and resolving bugs (Dziuba, 2019).

3.1.2.2.1.6 Iterative Review Subtask

Once all the previous development subtasks are completed, in the sixth step of this Agile cycle, a meeting with the customer should be held once he has finished testing the part of the system that was presented to him. At this meeting, the feedback based on whether the requirements were fulfilled completely should be noted. Once the product owner finishes making his points, the team presents their ideas to solve the problems that arose during the previous phases and the stakeholder considers these proposals (Dziuba, 2019).

3.1.2.2.1.7 Launch Subtask

In this last subtask, the idea upon if they should move to the followed sprint or if it is necessary to make changes in the current sprint, based on the customer's review, must be reformulated. In case everything has gone well, and there have been no observations from the stakeholder, a new sprint can be started beginning with the planification subtask. In case there have been problems, these must be solved immediately within the same sprint to be able to give way to the next subtask of the DT development. If there was a case in which there were unfinished tasks in this sprint, it is recommended to pass them on to the next sprint so as not to postpone working times or delay the tasks of the other teamwork.

3.2 Middle-of-Life (MoL) Phase

The Middle-of-Life (MoL) phase refers to when Digital Twins has already been deployed and working. This phase of the life of a Digital Twin is normally not considered within its lifecycle since in some cases, DT applications with wide maturity, can cope with this stage on their own. In this phase, it is assumed that DTs require constant monitoring after their implementation to guarantee the correct performance of their application at all times. To achieve this, good maintenance practices must be followed, for each of the layers that make up a Digital Twin, as well as the correct management of versions when making modifications, upgrades of the DT system, or even when new DT services need to be developed.

3.2.1 Management Stage

The stage that represents the whole MoL phase of a Digital Twin in the proposed framework is the *Maintenance Stage*. Organizations may benefit from Digital Twins in terms of enhancing analytics, diagnostics, predictions, and descriptions of physical assets. However, handling the implementation costs, maintenance protocols, guaranteeing accurate information modelling, embracing new technology, and leading the organization through the changes that an implementation entails are all significant challenges (Blomkvist & Ullemar Loenbom, 2020). As mentioned in previous chapters, the researched literature does not show the need to provide maintenance to the already implemented

DT system. However, in this thesis it is proposed that performing this task can support the upgradeability of the system, adapting to changes in production needs as established by Industry 4.0.

As a Digital Twin is a system made up of three technological layers, being these the physical product, digital thread, and virtual product, it is necessary to establish a management strategy for each of them. These strategies, despite being naturally focused on each layer, are directly related to the other two. This means that if an upgrade or downgrade change is made, in any of these three layers of the system in question, the corresponding update should be considered in the two remaining layers. In this way, perfect synchrony between the three layers can be guaranteed when it comes to maintaining the whole system. It is worth mentioning that this *Maintenance Stage* is applied in the first instance when the Digital Twin is in operation, and it is useful to guarantee that the performance of the system is always within its boundaries. Second, the maintenance stage plays an important role in establishing a service to the Digital Twin. In this stage, what is sought is to make the correct and most suitable transition of the Digital Twin towards the incorporation of new technologies.

3.2.1.1 Operation Activity (Maintenance)

This activity considers the time in which the Digital Twin is deployed. This means that while the DT system is in operation, it is necessary to create a maintenance strategy to ensure that the performance of the application is always within the acceptable ranges and in this way, guarantee the scope of the key metrics established in the *Business Case Activity*. Despite this conclusion, some experts on the subject comment that a Digital Twin, at its most mature stage, must be able to self-maintain, avoiding human intervention in its entire lifecycle.

3.2.1.1.1 Physical Product (Smart Connected Product) – Physical Layer of a Digital Twin

As mentioned above, it is necessary to give separate maintenance to each of the layers that make up a Digital Twin. The first corresponds to the one where the physical part of the system is located, and which is characterized by being a smart connected product. The complexity of this would depend on the *Depth of System Selection* since as the level of granularity increases, the number of sensors, actuators, mechanisms, etc. that make up this physical entity increases in the same way.

At this layer, it is considered that there is wear in these physical elements by the simple fact of being in constant operation. For this, the development and planning of maintenance strategies that keep the system in optimal conditions are needed. As they are physical assets, it is possible to implement business as usual maintenance protocols such as (i) Autonomous, (ii) Condition-based, and (iii) Predictive Maintenance.

3.2.1.1.1.1 Autonomous Maintenance Strategy

The first strategy proposed to attack the maintenance of the physical components of a Digital Twin is *Autonomous Maintenance (AM)*. Despite what is recently known as autonomous maintenance, which implies that the same system is self-diagnosing, this concept lays its foundations with another ideology in the Lean Manufacturing philosophy. This maintenance approach aims to increase efficiency by training operators to continually monitor the equipment, make changes, and execute small maintenance operations. This strategy allows them to focus on more important and urgent maintenance duties by reducing time-consuming scheduled maintenance.
The two fundamental objectives of Autonomous Maintenance are to avoid equipment degradation via good operation and to restore and maintain equipment in a *"like new"* state through restoration and proper management. To guaranty this, a 'man-machine' relationship must exist, referring to the coworking and communication system that exists between maintenance personnel (also known as the machine owner) and machine operators (also known as the machine user) to eliminate the sources of a machine (Musman & Ahmad, 2018). For this, operators must acquire abilities including irregularities recognition by knowing the machine's components, making adjustments, identifying quality concerns, and determining quality deficiencies causes (Trout, 2020).

The seven steps that go into implementing Autonomous Maintenance are increment of operators' knowledge, initial machine cleaning and inspection, removal of sources of contamination and improving access, development of standards for lubrication and inspection, inspect and monitoring, standardizing visual maintenance, and ensuring continuous improvement (Tajiri & Gotoh, 2020).

3.2.1.1.1.2 Condition-based Maintenance Strategy

The second proposal to provide maintenance to the physical assets is *Condition-based Maintenance (CBM)*. This strategy is based on the assessment of the asset's current condition to decide what repair is required. Unlike *Autonomous Maintenance*, which employs constant monitoring by operators to determine when to perform maintenance, Condition-based Maintenance is based on the idea that maintenance should be performed when the real-time indicators show irregularities or signs of declining performance (Trout, 2020).

CBM aims to continually monitor assets for signs of the impending breakdown so that maintenance may be arranged ahead of time. The aim is that this real-time monitoring will allow maintenance teams to react before a failure or a decline in performance. These monitoring activities are not performed by operators as in AM, instead, it uses sensor readings for collecting real-time data for posterior analysis. Sensors, for example, can be mounted on rotating equipment to measure vibrations, heat, displacement, etc. The mounted sensors may be programmed to send an alarm to the maintenance staff when vibrations exceed a certain threshold. It is important to mention that CBM is only viable when companies have the needed architecture to collect and analyse the corresponding data (Trout, 2020).

One of the key advantages of Condition-based Maintenance is the uptime increment that has as result the reduction of the machine tool downtime (Mourtzis & Vlachou, 2018). Furthermore, maintenance failures and maintenance costs can be decreased while total equipment performance is improved (Prajapati et al., 2012). Finally, condition-based maintenance contributes to better maintenance management efficiency by promoting more precise maintenance activity planning.

3.2.1.1.1.3 Predictive Maintenance Strategy

The final maintenance strategy proposed *is Predictive Maintenance (PdM)*, which monitors the performance and condition of equipment under normal operating conditions to minimise the chances of failure. The goal of predictive maintenance is to first predict when failures may occur and then prevent the failure through scheduled corrective maintenance, similar to preventive maintenance and closely related to CBM (Trout, 2020).

A PdM strategy is based on three main steps that consider in the first place the data acquisition, which is then followed by the data processing and ends with its characteristic step of maintenance decision-making. PdM data gives both diagnostics and prognostics information (Jardine et al., 2006), indicating trouble issues such as what and where the problem is, why is it happening, whether is it a failure or a defect and when a failure will occur. In this way, maintenance work becomes more proactive, and hence successful and efficient, thanks to all of this knowledge produced from PdM data (Selcuk, 2017). PdM approaches may also be used for purposes other than maintenance, such as estimating fuel cell running time (Onanena et al., 2010), assessing the quality of second-hand products (Yeh et al., 2011), and analysing cutting tool wear (Vallejo et al., 2008).

3.2.1.1.2 Digital Thread (Connections & Interfaces) – Connection Layer of a Digital Twin

The second maintenance during the *Operation Activity* of a Digital Twin has to do with the layer that ensures a secure, efficient, and correct bidirectional transfer of data between the "physical product" and the "virtual product".

It is necessary to guarantee the proper functioning of the *Digital Thread* since it is a fundamental basis for a DT. At this layer, it is assumed that if the physical part of a Digital Twin, as well as its virtual counterpart, are in their optimal functioning and state, but there is a problem in the DT throughput, the next step in troubleshooting would be to check the state of the network. It should be mentioned that for this layer, the maintenance team should not only work on corrective solutions, but it is also necessary to establish maintenance strategies that are under constant monitoring. Additionally, in this maintenance stage, the state of network security must be monitored to protect the transferred data and the general integrity of the plant.

3.2.1.1.2.1 Cybersecure Connection Maintenance Strategy

One of the challenges that Digital Twins face is being able to guarantee security between their connections, due to the sensitive information they transmit and their direct connection with the physical environment, which makes them prone to cyberattacks (Rasheed et al., 2020). To help mitigate the risk and potential cyberattack surface, Digital Twin systems must implement a security organization and adopt active security processes. However, reducing risk and anticipating weaknesses in the system requires more than a one-time installation of cutting-edge technology. It is also necessary to implement regular or routine equipment maintenance, which includes patch management and system security updates. (Gauci et al., 2017).

Technology vendors disclose a list of vulnerabilities, their descriptions, the related corrective patch, and sometimes a suggestion for preventions on their impacted products. The cybersecurity team must then confirm that the installed items are affected by the warning by checking with their system inventory platform. The product name, product number, and, finally, the serial number, as well as the vendor product firmware version, must all be identified (Gauci et al., 2017).

This implies that the cybersecurity team must establish a dedicated strategy for creating a complete inventory of their system's electronic equipment and keeping it up to the current version. If a problem has been identified, the cybersecurity team then must proceed to assess the implementation risk. They must contain a clear statement about the impact of installing the corrective patch on their runtime application context. As a result of this point, impacted items must be clearly defined, the stakeholder must always have a complete awareness of its installed base, and the implementation risk must be correctly assessed (Gauci et al., 2017).

Implementing the corrective patch directly on the product may affect the running process and may cause uncontrolled downtime. It is important to test the patch and determine whether the system will continue to operate normally and whether there are no incidental effects that will cause the system to fail partially or completely. This means that the cybersecurity team should have access to a testing platform hosting all the installed products of the system. In addition, the testing platform should configure its runtime application to ensure that there will be no unexpected failures related to the implementation of the application. The testing platform can be located in-house (it might be an instance of the virtual product model or a built-up platform) or part of the support services provided by the supplier. This kind of testing in a non-production environment is an effective way to confirm the implementation of the risk assessment of the patch (Gauci et al., 2017).

3.2.1.1.2.2 IT/OT Network Maintenance Strategy

IT/OT network maintenance is critical, however, new initiatives like building and deploying a new network segment or deploying a new application for the Digital Twin system or Digital Twin aggregation may obstruct essential maintenance duties. Regardless of how urgent these initiatives are, network teams cannot ignore the following network maintenance plan (Jacobs, 2021):

Data Backups: the first and most important step when talking about IT/OT network maintenance. It is critical to be able to retrieve up-to-date data regardless of what sort of network trouble occurs. Depending on the Digital Twin application, and the available resources some projects might need an end-of-day backup, while others might require continuous backup. Backups can be performed locally or via a network. Local backups should be stored off-site to avoid being damaged by fire or other natural disasters. Network teams should verify that backups are being made and that they are readable on a useful standardized basis.

Malware Protection: this maintenance task has become vital by keeping track of new attack types, updating security software, and running scans. In addition to this, critical action is to maintain DT server operating systems and network device software updated. Furthermore, as mentioned before, it is important to have a test network apart from the main DT network so updates might be tested before.

Network Monitoring: monitoring is critical for any DT network maintenance strategy because it allows possible problems to be identified and resolved before they have a detrimental impact on the DT operations. Autonomous, condition-based, and predictive maintenance strategies might be implemented to keep up with these monitoring tasks. When monitoring a network, it is critical to keep track of any possible issues to ensure that everything within the DT system is running properly.

3.2.1.1.3 Virtual Product (Models, Algorithms, Database) – Virtual Layer of a Digital Twin

The last entity to give maintenance in the *Operational Activity* of a Digital Twin is focused on the virtual product part. Being linked to the physical product part, its complexity will also depend on the *Depth of System Selection*, although the *DT Virtual Representation Selection* will play a more important role. This means that it is not the same to maintain a 3D model as a DT database, each of them will have its complexity level and specific requirements.

3.2.1.1.3.1 Database Maintenance Strategy

Despite the Digital Twin works with a SQL or a NoSQL database, maintenance activities should be carried out to keep the system running smoothly. There are typical routines that main to improve the performance of the database, free up disk space, check for mismatched data, hardware defects, update internal statistics, and a variety of other critical tasks. Duarte et al. (2013), proposed that the creation of a reliable database maintenance strategy requires cooperation between the Original Equipment Manufacturer (OEM), customers, such as equipment owners, and independent maintenance providers (as seen in **Figure 16**). These three agents form part of a collaborative triangle that must be formed to improve production system efficiency, namely through dynamic maintenance planning.

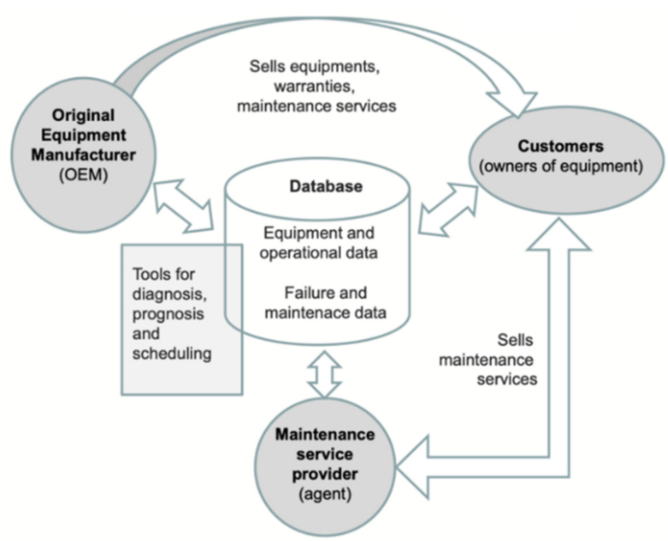

Figure 16. Maintenance Database Collects Specific Information and is a Supplier of Processed Information (Duarte et al., 2013)

At this point, the introduction of e-technologies has enabled the integration and processing of data generated by a variety of sources, assisting in the creation of such a database. The database then must be enhanced by a collection of tools that can compute or predict the reliability and maintenance metrics once it has been populated with data. These tools should also be capable of making diagnoses, prognoses, and maintenance programs. As a result, they should be regarded a significant component of a decision-support system (Duarte et al., 2013).

3.2.1.1.3.2 1D/2D/3D Models Maintenance Strategy

Although there are no proposed models within the literature to be able to provide maintenance to models of any dimension, it is possible to rely on the proposed model in **Figure 17**. This model seeks to guarantee the optimal and correct performance and condition of the model. Once the model is created and it is running, it is important to constantly monitor its status to know if the model needs to be rebuilt or its features need to get modified. For this, it is important to define key points or values that will provide the insights to measure their performance. Finally, it is important to monitor that these models reflect reality as closely as possible.

3.2.1.1.3.3 Algorithm Maintenance Strategy

Machine Learning algorithms have appeared to be the most popular application when it comes to predictions, prescriptions, and autonomous decisions services. However, the combination of data pre-processing, algorithm selection, hyperparameter tuning and testing to produce a model with the desired performance, produces a large number of iterations that have aroused the concern of the scientific community to propose managing models of this *experimental loop* (blue arrows in **Figure 17**). Despite this, these models do not contemplate the drift of the algorithms generated initially during the operational phase. For example, in industrial situations, because of tool wear, sensors in machines might be faulty or produce erroneous results upon the prediction of streams of sensor data. For this, it is necessary to establish a solution where the model is capable to adapt to the changes presented (Weber et al., 2019).

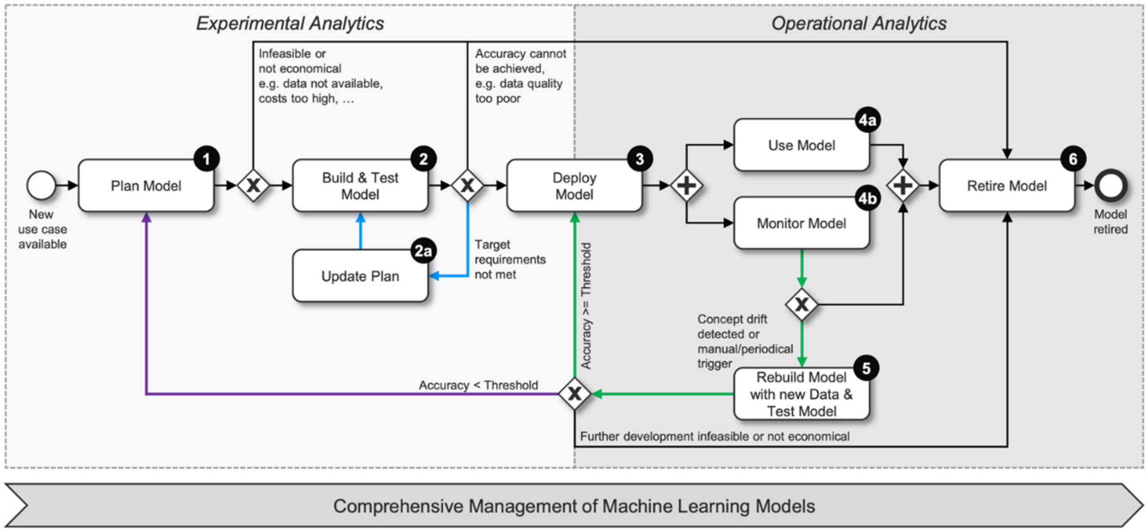

Figure 17. Process Model for the Comprehensive Management of Machine Learning Models (Weber et al., 2019)

In **Figure 17**, Weber et al. (2019) propose a machine learning algorithm management model capable of coping with these changes by re-training the model with more recent data. In other words, the model is rebuilt, but the data preparation, algorithm, and hyperparameters stay unchanged. The model's old version has been replaced by a new one. This might happen numerous times, resulting in the loop referred to as an *update-loop* (green arrows in **Figure 17**). If update-loops do not provide the needed precision, more drastic adjustments are required. Additional data and various pre-processing stages, for example, must be tested with a different algorithm, resulting in a new model variant for the same use case. To this re-engineered model process the authors refer to the model's *upgrading-loop* (purple arrows in **Figure 17**). Because stakeholders must make choices on these loops, it is also important to assess the upgrade and update loops in the total lifecycle of a model and related functions for model management. They must, for example, decide whether to pursue update/upgrade methods, stakeholder accountability for maintenance, supporting tools, and the model's economic feasibility. The final step on this model considers the end of the lifecycle of the ML model. The retirement of the model can be produced due to economic and resources availabilities, poor quality performance, or if the model has been in use for some time and is no longer needed.

3.2.1.2 Evolution Activity (Modifications, Upgrades, and New Services Development)

This second activity within the *Management Stage* refers to when Digital Twin systems need to be modified, upgraded, or simply reassign the development of a new service. Once again, when one of these cases occurs, the necessary modifications are independently replicated through the three layers that make up a Digital Twin (viz. physical product, digital thread, and virtual product). A Digital

Twin model can evolve due to engineering modifications to its physical part, changes in modelling interests over the physical counterpart's existence, or other factors. The various versions of a Digital Twin model throughout time should be acquired, preserved, and integrated into these circumstances. For the management of multiple versions of a Digital Twin model, snapshot-based and change-based version management methods can be used (Yuqian Lu, Liu, Wang, et al., 2020). Taking into account the *Cybersecurity Mechanisms*, correct version management must be carried out either of the assets installed in the physical environment or the interfaces and connections, algorithm models and databases. Despite being "isolated" management strategies, there must be a general administration process of the Digital Twin where the different independent versions (of the physical product, digital thread, and virtual product) are associated with each version of the Digital Twin itself, are grouped.

3.2.1.2.1 Physical Product (Smart Connected Product) – Physical Layer of a Digital Twin

When modifications or upgrades are made to the physical product of a Digital Twin, or a new service is to be developed by the DT, it is necessary to save the current configuration of the physical system. For this, it is recommended to keep a track of all the components that have been used up to the moment (Bill of Materials) before the modifications are made as well as the different configurations that have been programmed, details of maintenance carried out, and the status of the performance in which it is found. By integrating a database of this type, or library, a good inheritance process can be carried out when developing a new DT based on one previously deployed.

3.2.1.2.2 Digital Thread (Connections & Interfaces) – Connection Layer of a Digital Twin

As in the physical product and the virtual product, it is necessary to implement tools that help to manage the versions on the network. In collaboration with the *Cybersecurity Mechanisms*, a library must be built that includes the list of the different versions of the networks used with their configurations, server properties, user access to options and settings.

3.2.1.2.3 Virtual Product (Models, Algorithms, Database) – Virtual Layer of a Digital Twin

All the models, algorithms or databases of a Digital Twin should be saved on an Asset Library. The Asset Library is an asset management application that runs on the web. It holds all past data and serves as a version control system as well as a template for future versions. The features of a system may be separated properly, reused, and implanted into the structures of another model thanks to the modular nature of the system. As a result, the Asset Library saves time and money by allowing for central management of existing features. The feature's location is kept in the model's package structure and may be retrieved when it is placed into another model. Then the modeller may access the Asset Library databases through an Asset Library bridge. The modeller updates the Asset Library if the newly produced version is not yet in the library. Finally, the virtual product is updated with the new version's data. As a result, all components affected by the change are labelled with a state that may be used to select test cases (Land et al., 2020).

3.3 End-of-Life (EoL) Phase

As the same case as in the Middle-of-Life phase, for the End-of-Life phase of a Digital Twin, there is no further research either about this lifecycle phase. It is necessary to take into account that even if the DT system is getting provided with the best maintenance practices and updates, the Digital Twin will have to be decommissioned at some point. When a Digital Twin reaches this point, it should not be decommissioned as a simple asset, the information that these systems have can be very useful for the next DT systems that are to be developed or simply to guarantee the traceability of the product information. To do this correctly, good inheritance and archiving practices are recommended.

3.3.1 Retirement Stage

This final stage is achieved when a DT must be retired after construction and testing owing to cost concerns, poor quality, or if the DT model has been in use for some time and no longer serves a purpose, such as due to changes in the domain or the completion of a DT project. When a DT model is retired, the associated data and metadata should be stored as a reference for future trials (Weber et al., 2019).

3.3.1.1 Decommission Activity

Decommissioning is the act of formal retiring or removing a system from its active service. Such as IoT devices, Digital Twins can be decommissioned for a variety of reasons, including device failures, misbehaviours, replacements, or because they will be commissioned in another network. This must be documented in the record. Device replacements due to upgrades and faults are captured in the identity management and access control methods in the architecture, allowing DT applications to adapt to changes in dynamic settings (Ranathunga et al., 2020). To increase usability and adaptability, these decommissioning activities should be handled appropriately (Bass et al., 2003). Disconnecting the device from servers is another key step in the decommissioning process. Once again, the system gets informed that the device is no longer available, allowing it to promptly adjust to the change (Rahman et al., 2018).

3.3.1.1.1 Digital Twin Inheritance Task

DT Inheritance should be a key feature for Digital Twins just as it is for object-oriented paradigm which has a great effect upon software reusability. Inheritance allows attributes and operations sharing based on the parent-child relationship (Ilyas et al., 2017). This feature allows the creation of Digital Twin Instances (child) from a Digital Twin Prototype (parent). This translates into a saving of time when deploying a new DT system since important characteristics of the documentation can be retrieved, either from the *Beginning-of-Life (BoL)* or the *Middle-of-Life (MoL),* from a retired DT. It is for this reason that archiving also becomes important.

3.3.1.1.1.1 BoL Documentation Subtask

Inheritance of Beginning of Life Documentation of a parent Digital Twin is used to accelerate the process of planification both in the *Conceptualization* and *Realization Stages*. When a Digital Twin is running or has been retired, and there is a plan to incorporate a new one (either in the same production line or in another factory), which meets the same specifications or seeks to meet the same *Value Proposition Selection*, this information inheritance can be reached. The same can be done if this Digital Twin is going to present an upgrade in its design and engineering phase. All attributes can be stored in the same way, but only the one that is aimed to update gets modified. In this way, the lifecycle gets shortened.

3.3.1.1.1.2 MoL Documentation Subtask

The inheritance of attributes from the Middle-of-Life of a Digital Twin can be translated into the retrieval of maintenance reports, models, algorithms, protocols, etc. In this way, by considering the most common failures that affected the assets from the DT parent, design flaws can be detected easily. Moreover, this can lead to component modification to ensure greater production availability. Furthermore, a geographically based analysis can offer information on the distribution of failures, allowing for the creation of links between failures and environmental circumstances that can be used to redesign components as needed. This information might be incorporated into instruments and tools for identifying and tracking critical flags in assets and components.

3.3.1.1.2 Digital Twin Archiving Task

One of the most important tasks to carry out when the *Digital Twin Retirement Stage* is reached is the archiving of all the important information and documentation of the system. Long-term digital preservation refers to the techniques and technologies that ensure that digital material is accessible and used for decades, if not centuries after it has been archived. Although this appears to be a simple task at first appearance, it is important to remember that preservation is more than just preserving bits and bytes. Rapid innovation has resulted in rapid changes in technology such as hardware, media, operating systems, application software, and file formats in today's world (Brunsmann et al., 2012). Digital preservation systems are archiving systems with built-in preservation support that try to overcome such problems. The Open Archival Information System (OAIS) is frequently used in these preservation systems. This ISO standard describes a high-level reference architecture for a long-term archive, which consists of a group of people and systems tasked with preserving information for a certain domain's defined community. Digital Twins must start planning a strategy such as the LOTAR project which aim is to do long-term archiving for legal requirements (certification, product liability) and business needs (protect intellectual property, product reuse, support of product operation).

3.3.1.1.2.1 Standards Adoption Subtask for Long-term Archiving of Digital Product Data

In the LOTAR project, the commercial necessity becomes evident as the aircraft's product lifecycle might last up to 70 years and product data, that is necessary for certification, must be kept for up to 99 years. As a result, the product data must be archived for future use based on the ISO 14721, Open Archival Information System (OAIS) Reference Model. When storing product data in native format, an opportunity to be able to access the information with new software releases is created. When product data is preserved in native format, it must be exported before it can be used with the next CAD generation tool suite. However, after the data exportation, it is required to verify that all data has been correctly saved, which is a time-consuming operation. It is recommended to convert the original product model data into a standardized, vendor-neutral format for long-term archiving without loss of information (LOTAR, 2021).

3.3.1.1.2.2 Standards Adoption Subtask for Long-term Archiving of Technical Data

The LOTAR project address legal and business concerns around the preservation of digital product information. When the prEN9300 standard is utilized, the application and interpretation of law vary from country to country and are most likely to alter over time. The criteria for long-term archiving of technical documents in prEN9300 are derived from legal and certification norms and regulations. To meet these objectives, the standard specifies the architecture, operations, and data formats. It does not provide tools for proving the authenticity of digital technical evidence in legal or certification proceedings. The technical archiving of documentation is used for the future proof of legal and certification constraints, contractual constraints, reuse of data belonging information, manufacturing processes, and modifications on products and documents (LOTAR, 2021).

3.4 Digital Twin Lifecycle Management Framework – Implementation Guidelines

The correct way to use and read the *Digital Twin Lifecycle Management Framework* is from the inside out, considering that the starting point in lifecycle time is given at the *Beginning-of-Life (BoL) Phase,* specifically within its *Conceptualization Stage,* which has as its first activity performing the "Business Feasibility Assessment" (at the bottom of **Figure 10**, this starting point is shown with an orange arrow under the "time" label). From this point on, each of the stages, activities, selections/task(s), and subtasks/choices must be carried out clockwise, respecting the hierarchy of the circumscribed circles and the way of the time flow. Following this logic, the development of the *Conceptualization Stage,* within the *Beginning-of-Life Phase,* follows a natural clockwise circular flow throughout every task. On the contrary, the *Realization Stage* has a somewhat different logic since the "selection tasks", delimited in grey dotted lines (going from the *Depth of System Selection Task* to *OT Network Selection Task*), seek to establish a morphological matrix of option selection that better comply with the problem-solution characteristics established in the *Conceptualization Stage.* In this way, both the *Requirements Specification* and the *Cybersecurity Mechanism* remain outside the morphological matrix, forcing the DT designer (or DT design team) to carry out the subtasks within each of these tasks.

Finally, the flow of the *Digital Twin Lifecycle* must follow the same clockwise course, under the same hierarchical considerations, towards the *Middle-of-Life (MoL) Phase* and the *End-of-Life (EoL) Phase.* The activities, tasks, and subtasks within each of the stages of the aforementioned phase, must be developed in the same way as the *Conceptualization Stage* was carried out. It is only necessary to consider that for the "physical product", within the *Operation Activity,* there are three different maintenance strategies that can be carried out. As in the morphology matrix, each of these options is better in the past, but it does not mean that it is needed to always have to opt for the best option or strategy, on the contrary, the DT designer (or DT design team) should always seek to choose the most efficient options for the development of the DT project. Additionally, it is recommended to take into account the general considerations and recommendations described in the following section.

3.5 General Recommendations on Deploying and Managing Digital Twins across their whole Lifecycle Phases

Regarding the obtained recommendations, after having carried out the enrichment and validation processes throughout semi-structured interviews with 17 experts from both academia and industry, the following points were identified to be considered in terms of the implementation of the Digital Twin Lifecycle Management Framework for the deployment of a real case Digital Twin application:

- In the first place, and as the most important point within these recommendations, given the agreement among the majority of the interviewees, is the fact of the need to form multidisciplinary teams. These teams must be integrated by at least people trained in the area of mechanics and mechatronics, to assist in everything related to the physical product; networks, in charge of everything concerning the digital thread; as well as in the area of computing and data science so that they carry out everything associated to the virtual product. It is worth mentioning that these teams must work collaboratively at all phases of the lifecycle and must have good communication skills to guarantee a good synergy between the three layers that make up the Digital Twin. This need arises due to the close relationship that exists between these three layers in which a change in one of them invariably affects the others, according to the definition of a Digital Twin, stated in Section 1.1.3.

As mentioned above, these teams should not be limited to personnel only from those areas, as progress is made in the lifecycle, new members can come to support the DT project according to its needs and requirements. For example, within the BoL of a Digital Twin, specifically in the *Conceptualization Stage*, a Project Management Professional (PMP) could be included to provide support in that first stage of the project, as well as a specialist in the industrial sector where the DT project will be implemented, so that it provides the best recommendations, insights, metrics, etc. of the use case to which a DT solution will be deployed.

- As a second recommendation and observation, it is mentioned that there are two main triggers for the development of a Digital Twin project. The first of them is called a technology-driven project whose central objective is to test the operation and measure the potential of this type of application in the industry. Most of the DT projects discussed in the scientific articles and those implemented by academic and industry experts have this type of approach. They can be seen as somewhat more experimental projects that seek to test the DT systems implementation methodology. On the other hand, there is a more specific trigger, by developing business-driven projects the objective goes beyond testing this technology. This type of trigger is mostly executed by consulting firms and only in some academic works. In these projects, a specific analysis is done to identify the best use case of implementation of a DT within a business. With this, what is sought is to make it more efficient and focalize resources towards a specific value proposition.

  In other words, it could be said that for a technology-driven project the *Conceptualization Stage* of the Digital Twin Lifecycle Management Framework could take a back seat, paying more attention to the *Realization Stage* to make the best selection of technologies to be tested or investigated. On the other hand, in business-driven projects, the *Conceptualization Stage* is the backbone of the DT project. At this point is important to emphasize each of the activities and tasks to be carried out to guarantee a correct and efficient solution to the problem.

- Finally, in the general considerations provided by the interviewees, it was found that there is the possibility of carrying out a DT project through an in-house or outsourced implementation or a combination of these options. Each of them has its advantages and disadvantages, depending on the needs of the DT project. In general, it could be said that the best option to carry out a DT project is in-house since in this way the entire project can be planned internally, in an easy way, thanks to the fact that everyone involved in the project knows the business. Similarly, when maintaining the DT system, it becomes an easier task in the sense that it does not depend on the availability of a third party. The main disadvantage lies in the fact that if the employees do not have sufficient experience or knowledge to carry out the DT project, the possibility that the DT project does not reach its deployment stage exits. On the other hand, this could be overcome by opting for an outsource implementation. The fact of involving an outsource DT vendor facilitates the development process but increases the cost of implementation, coupled with this, there is the possibility that the DT solution cannot be tailored to the problem as it would be in an in-house implementation. When a combination of these options is chosen, where only an outsource DT vendor is hired to carry out certain tasks, it can be a good balance for development, however, it may hinder maintenance tasks due to the existence of a third party.

Chapter 4: Digital Twin Lifecycle Management Framework Enrichment & Validation Processes

This Chapter describes both the "enrichment" and "validation" processes that were carried out to generate a more robust *Digital Twin Lifecycle Management Framework.* To achieve this, a "pseudo-Delphi study" divided into two stages was carried out. In the first of these two stages, for the DT Lifecycle Management Framework enrichment process, semi-structured interviews were conducted with experts from academia and industry on the subject matter: "Digital Twins". From these semi-structured interviews, different suggestions and recommendations were extracted that were included in the framework (taking the framework from its *Version Zero* (see **Figure 18**) to its *Version One* (see **Figure 19**) and other more general ones that were added as considerations to take into account during the development process of a Digital Twin. Later, in the second stage, which includes the validation process of the Digital Twin Lifecycle Management Framework, a copy of the framework was sent along with its written part (see Chapter 3) to the 17 experts in academia and industry. From this validation process, they were asked to validate the research work using the parameters of "accepted as is", "accepted with a minor", "accepted with major" or "rejected" as in a peer-review process, according to additional comments on Version One of the Digital Twin Lifecycle Management Framework.

4.1 Digital Twin Lifecycle Management Framework Enrichment Process

As previously mentioned in the *Research Methodology* section of this thesis, the initial framework underwent an enrichment process to validate the information found in the scientific and grey literature and additional, to include themes not registered in the literature corpus, but that are of great importance for the deployment and management of a Digital Twin application. In this process, a second empirical investigation was carried out by interviewing experts from academia and industry on the subject to find the contributions previously described. Through this enrichment process of semi-structured interviews with experts on Digital Twins, both from academic and industry, a 32% enrichment of the framework was achieved. This percentage reflects the number of subtopics added to or edited in the Version Zero of the framework, based on the experience and knowledge of the interviewees, concerning the number of subtopics proposed in both scientific and grey literature. The following sections describe, first, the process carried out to enrich the framework, as well as the recommendations that were obtained from the semi-structured interviews and finally, the actions that were taken on these suggestions and recommendations.

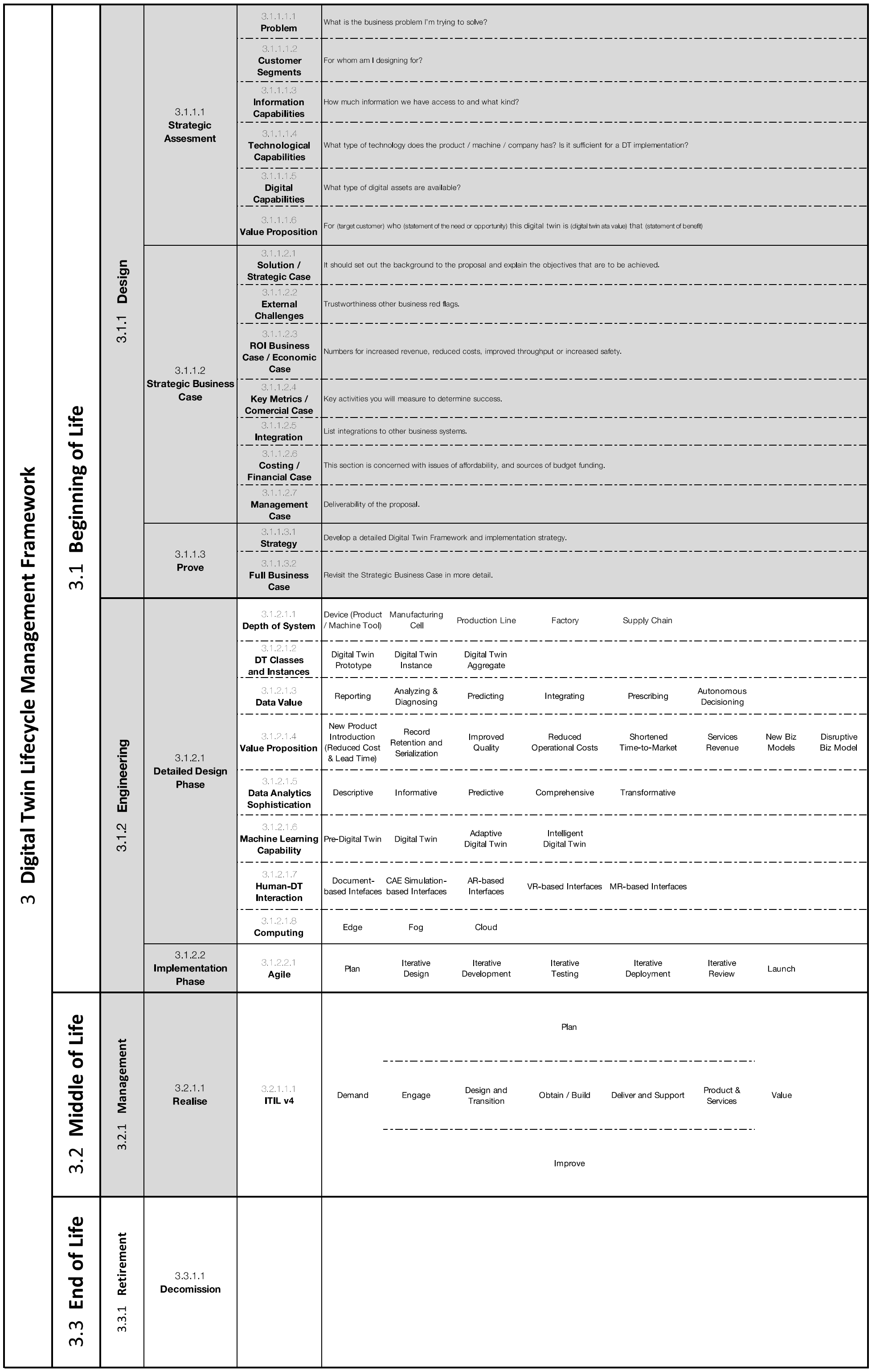

Figure 18. DT Lifecycle Management Framework – Version Zero
(White Boxes correspond to Concepts taken from the Scientific Literature
while Grey-shaded Boxes correspond to Concepts taken from the Grey Literature)

4.1.1 Framework Enrichment Process

Given that the development of the proposed framework was carried out through a generative process, it was decided to take it through a process of "enrichment" to make it more robust and comprehensive. This enrichment process was conducted, in the first place, by the elaboration of semi-structured interviews to deepen on the methodology followed for the development, deployment, and management of a Digital Twin, and finally, showcase the draft of the *Digital Twin Lifecycle Management Framework* built out from scientific investigation (scientific literature review) and empirical investigation (grey literature review). A total of 17 experts were interviewed, of whom ten were academic experts and seven were industrial experts (see **Table 4**).

Table 4. List of Interviewees from Academia and Industry[4]

No.	Name	Affiliation	Sector	#
1	Prof. Marco Macchi	Politecnico de Milano, Italy	Academia	1
2	Prof. Andrea Matta	Politecnico de Milano, Italy	Academia	2
3	Prof. Martin Fabian	Chalmers University of Technology, Sweden	Academia	3
4	Prof. Ricardo Rabelo	Federal University of Santa Catarina, Brazil	Academia	4
5	Dr. Karl A. Hribernik	Institute for Production and Logistics (BIBA), Germany	Academia	5
6	Dr. Stefan Wiesner	Institute for Production and Logistics (BIBA), Germany	Academia	6
7	Dr. Guodong Shao	National Institute of Standards and Technology (NIST), USA	Academia	7
8	Prof. Matthias Thurer	Chinan University, China	Academia	8
9	Prof. Shaun West	Lucerne University of Applied Sciences and Arts, Switzerland	Academia	9
10	Prof. Thorsten Wuest	West Virginia University, USA	Academia	10
11	Eng. Steve Ghee	PTC, USA	Industry	1
12	M.Sc. Prakash Samal	McKinsey & Company, USA	Industry	2
13	M.Sc. David Wang	McKinsey & Company, USA	Industry	3
14	B.A. Torrey Sullivan	Siemens, North America	Industry	4
15	M.Sc. Shankar Raman	Siemens, North America	Industry	5
16	MBA. Flavio Arssani	Siemens, Mexico and Central	Industry	6
17	Eng. Salvador Barrena	Centric Software, Mexico and LATAM	Industry	7

These semi-structured interviews were guided by four main questions that encompassed the proposed *Digital Twin Lifecycle Management Framework*. The first of these three questions sought to make a sense among the interviewed community to know… *How conscious they were about the idea of the lifecycle of a Digital Twin?*. From this first question, *Have you ever thought about the need to establish a full lifecycle for the management of a Digital Twin?*. The majority of the answers were confused, that is to say, that most of the interviewees thought about the implementation of the Digital Twin within the lifecycle of a product instead of the lifecycle of a Digital Twin itself. This misunderstanding of the question was not uncommon in the sense that it was to be expected due to the large number of publications devoted to these practices of a Digital Twin. After clarifying this point it was observed that most of this group had not thought about the lifecycle of a Digital Twin, but that they found the subject interesting. They accepted that nowadays most of the research and

[4] **Disclaimer.** The opinions expressed by the experts do not purport to reflect the opinions or views of their affiliations.

development of this type of technology or application is strongly focused on the deployment of it, far from also considering and giving importance to the processes before and after the deployment. Another small group has considered the lifecycle of a Digital Twin, but only in its early stages and in a general way they consider that this topic is in the state of the art and has to be brought into practice.

Once the conversation turned towards the lifecycle of a Digital Twin, thanks to the clarification of the first question, a second more specific question was raised upon… *What do they consider to be the main phases that made up the lifecycle of a Digital Twin?*. After thinking about it a bit, they considered that the same model that exists for a product could be applicable (where the main phases are: Beginning-of-Life, Middle-of-Life, and End-of-Life). For the latter, a discussion environment was created on whether this phase exists or not in the lifecycle of a Digital Twin. For some of the interviewees the ending theme of a Digital Twin was coherent, that is to say, that they agree that DTs have a final phase, but for others, this End-of-Life of a Digital Twin, is nothing more than an extension of the life of the Middle-of -Life of a Digital Twin. What they mean by this is that a DT is simply capable of evolving on its own and adapting to new applications, but this option is seen as a state of the Digital Twin in which its maturity has reached its maximum point.

Subsequently, in the third question, it was sought to go further into these main phases by asking them… *What were the main activities to take into account within each of the phases?*. Without having shown the proposed lifecycle management framework, many of these activities matched with those already present on the framework and others were taken into account for discussion in the next stage of the interviews (where the framework was shown). Finally, interviewees were asked to *provide general recommendations on deploying and managing Digital Twins across their whole Lifecycle Phases* that were included in Section 3.4.

4.1.2. Suggestions and Recommendations for Enrichment

The second stage in these semi-structured interviews was characterized by the presentation of the *Digital Twin Lifecycle Management Framework* (Version Zero) to the interviewed experts. At this point of the semi-structured interview, the general structure of the framework was explained to them and the phases and activities they mentioned, during the first stage of the interview, were emphasized. Each of the phases, stages, activities, tasks and subtasks in the framework were explained in detail, and they were asked to interrupt the presentation if they had any comments, suggestions or recommendations. The results of this enrichment process are shown in the next section and are based on feedback obtained from international experts.

4.1.3 Actions Taken for Enrichment

As mentioned above, this enriching process of the *Digital Twin Lifecycle Management Framework* had two important outputs. In the first place, all those recommendations that were directly related to the framework structure were considered. Within them, changes were found in the name of the concepts, for more general and known terms in the Digital Twin literature, as well as adding or removing tasks and subtasks from the framework. On the other hand, the second output was regarding the general recommendations to consider for the correct deploying and managing of Digital Twins. Each of these will be described in the following sections accordingly.

4.1.3.1 Included in the Digital Twin Lifecycle Management Framework

As mentioned at the beginning of Section 4.1, through this enrichment process carried out by semi-structured interviews with international experts in Digital Twins, both from academia and industry, an approximate 32% enrichment was achieved. Regarding changes in terminology, the following recommendations were given:

- Design → Conceptualization Stage
    - Strategic Assessment → Business Feasibility Assessment Activity
    - Strategic Business Case → Business Case Activity
        - External Challenges → Risk Management Definition Task
        - Integration → System Integration Task
    - Prove → Verification Activity
        - Strategy → Full Business Strategy Verification Task

- Engineering → Realization Stage
    - Detailed Design Phase → Design and Engineering Activity
        - Device → Entity Choice

- … within the Management Stage
    - Realise → Operation Activity
      → Evolution Activity

Finally, the feedback obtained brought with it the introduction of several concepts to the framework, which were: Requirements Specification Task, Data Synchronization Selection, DT Virtual Representation Selection, ICT Architecture Selection, IT Network Selection, OT Network Selection, Cybersecurity Mechanisms Selection, Digital Twin Inheritance Task and Digital Twin Archiving Task, each of these with their own choices or subtasks respectively. After taking these considerations, the theoretical framework evolved towards its Version One, where it began to have the robustness and be more comprehensive in the sense of landing different points of view in a single framework.

3 Digital Twin Lifecycle Management

Phase	Stage	Activity	Concept								
3.1 Beginning of Life Phase	3.1.1 Conceptualization Stage	3.1.1.1 **Business Feasibility Assessment Activity**	3.1.1.1.1 **Problem(s)**	What is the business problem(s) I'm trying to solve? >> (One or more use cases or problem to solve)							
			3.1.1.1.2 **Customer Segments**	For whom am I designing for?							
			3.1.1.1.3 **Information Capabilities**	How much information we have access to and what kind?							
			3.1.1.1.4 **Technological Capabilities**	What type of technology does the product / machine / company has? Is it sufficient for a DT implementation?							
			3.1.1.1.5 **Digital Capabilities**	What type of digital assets are available?							
			3.1.1.1.6 **Value Proposition (Value Added)**	For (target customer) who (statement of the need or opportunity) this digital twin is (digital twin data value) that (statement of benefit).							
		3.1.1.2 **Business Case Activity**	3.1.1.2.1 **Solution / Strategic Case**	It should set out the background to the proposal and explain the objectives that are to be achieved.							
			3.1.1.2.2 **Risk Management**	Trustworthiness of the project or business red flags (internal and extrenal challenges).							
			3.1.1.2.3 **ROI Business Case / Economic Case**	Numbers for increased revenue, reduced costs, improved throughput or increased safety.							
			3.1.1.2.4 **Key Metrics**	Key activities to be measured to determine success.							
			3.1.1.2.5 **Systems Integration**	List integrations to other business information systems.							
			3.1.1.2.6 **Costing / Financial Case**	This section is concerned with issues of affordability, and sources of budget funding.							
			3.1.1.2.7 **Management Case**	Deliverability of the proposal >> (Work Breakdown Structure & Project Schedule - Critical Path)							
		3.1.1.3 **Verification Activity**	3.1.1.3.1 **Full Business Strategy**	Develop a detailed Digital Twin Framework and implementation strategy.							
			3.1.1.3.2 **Full Business Case**	Revisit the business case phase in more detail.							
	3.1.2 Realization Stage	3.1.2.1 **Design and Engineering Activity**	3.1.2.1.1 **Requirements Specifications**	3.1.2.1.1.1 Functional Requirements	3.1.2.1.1.2 Non-Functional Requirements						
			3.1.2.1.2 **Depth of System**	3.1.2.1.2.1 Entity (Product / Machine Tool / Worker)	3.1.2.1.2.2 Manufacturing Cell	3.1.2.1.2.3 Production Line	3.1.2.1.2.4 Factory	3.1.2.1.2.5 Supply Chain			
			3.1.2.1.3 **DT Classes and Instances**	3.1.2.1.3.1 Digital Twin Prototype	3.1.2.1.3.2 Digital Twin Instance	3.1.2.1.3.3 Digital Twin Aggregate					
			3.1.2.1.4 **Level of Cognition**	3.1.2.1.4.1 Reporting (Descriptive)	3.1.2.1.4.2 Analyzing & Diagnosing	3.1.2.1.4.3 Predicting	3.1.2.1.4.4 Integrating	3.1.2.1.4.5 Prescribing	3.1.2.1.4.6 Cognitive Analytics		
			3.1.2.1.5 **Level of Autonomy**	3.1.2.1.5.1 User Assistance	3.1.2.1.5.2 Partial Autonomy	3.1.2.1.5.3 Conditional Autonomy	3.1.2.1.5.4 Full Autonomy				
			3.1.2.1.6 **Data Synchronization**	3.1.2.1.6.1 Unidirectional Synchronization	3.1.2.1.6.2 Bidirectional Synchronization						
			3.1.2.1.7 **Value Proposition**	3.1.2.1.7.1 New Product Introduction (Reduced Cost & Lead Time)	3.1.2.1.7.2 Record Retention and Serialization	3.1.2.1.7.3 Improved Quality	3.1.2.1.7.4 Reduced Operational Costs	3.1.2.1.7.5 Shortened Time-to-Market	3.1.2.1.7.6 Services Revenue	3.1.2.1.7.7 New Biz Models	3.1.2.1.7.8 Disruptive Biz Model
			3.1.2.1.8 **Data Analytics Sophistication**	3.1.2.1.8.1 Descriptive	3.1.2.1.8.2 Informative	3.1.2.1.8.3 Predictive	3.1.2.1.8.4 Comprehensive	3.1.2.1.8.5 Transformative			
			3.1.2.1.9 **Machine Learning Capability**	3.1.2.1.9.1 Pre-Digital Twin	3.1.2.1.9.2 Digital Twin	3.1.2.1.9.3 Adaptive Digital Twin	3.1.2.1.9.4 Intelligent Digital Twin				
			3.1.2.1.10 **Human-DT Interaction**	3.1.2.1.10.1 Document-based Intefaces	3.1.2.1.10.2 CAE Simulation-based Interfaces	3.1.2.1.10.3 AR-based Interfaces	3.1.2.1.10.4 VR-based Interfaces	3.1.2.1.10.5 MR-based Interfaces	3.1.2.1.10.6 Softbot-based Interface		
			3.1.2.1.11 **DT Virtual Representation**	3.1.2.1.11.1 Data Model (A Datum)	3.1.2.1.11.2 1D Model (A Graphic)	3.1.2.1.11.3 2D Model (A Design)	3.1.2.1.11.4 3D Model (A Design)				
			3.1.2.1.12 **ICT Architecture**	3.1.2.1.12.1 Centralized	3.1.2.1.12.2 Decentralized	3.1.2.1.12.3 Distributed					
			3.1.2.1.13 **Computing Environment**	3.1.2.1.13.1 Edge	3.1.2.1.13.2 Fog	3.1.2.1.13.3 Cloud					
			3.1.2.1.14 **IT Network**	3.1.2.1.14.1 TCP/IP	3.1.2.1.14.2 4G-Enabled	3.1.2.1.14.3 5G-Enabled					
			3.1.2.1.15 **OT Network**	3.1.2.1.15.1 Wired	3.1.2.1.15.2 4G-Enabled	3.1.2.1.15.3 5G-Enabled					
			3.1.2.1.16 **Cybersecurity Mechanisms**	3.1.2.1.16.1 Authentication	3.1.2.1.16.2 Authorization	3.1.2.1.16.3 Accounting					
		3.1.2.2 **Implementation Activity**	3.1.2.2.1 **Agile Development**	3.1.2.2.1.1 Plan	3.1.2.2.1.2 Iterative Design	3.1.2.2.1.3 Iterative Development	3.1.2.2.1.4 Iterative Testing	3.1.2.2.1.5 Iterative Deployment	3.1.2.2.1.6 Iterative Review	3.1.2.2.1.7 Launch	
3.2 Middle of Life Phase	3.2.1 Management Stage	3.2.1.1 **Operation Activity (Maintenance)**	3.2.1.1.1 **Physical Product (Smart Connected Product)**	3.2.1.1.1.1 Autonomous Maintenance	3.2.1.1.1.2 Condition-based Maintenance	3.2.1.1.1.3 Predictive-based Maintenance					
			3.2.1.1.2 **Digital Thread (Connections & Interfaces)**	3.2.1.1.2.1 Cybersecure Connection Maintenance	3.2.1.1.2.2 IT/OT Networks Maintenance						
			3.2.1.1.3 **Virtual Product (Models, Algorithms, Database)**	3.2.1.1.3.1 1D/2D/3D Models Maintenance	3.2.1.1.3.2 Algorithms Maintenance	3.2.1.1.3.3 Database Maintenance					
		3.2.1.2 **Evolution Activity (Modifications, Upgrades, and New Services Development)**	3.2.1.2.1 **Physical Product (Smart Connected Product)**	3.2.1.2.1.1 Versioning Management							
			3.2.1.2.2 **Digital Thread (Connections & Interfaces)**	3.2.1.2.2.1 Versioning Management							
			3.2.1.2.3 **Virtual Product (Models, Algorithms, Database)**	3.2.1.2.3.1 Versioning Management							
3.3 End of Life Phase	3.3.1 Retirement Stage	3.3.1.1 **Decommission Activity**	3.3.1.1.1 **Digital Twin Inheritance**	3.3.1.1.1.1 BoL Documentation	3.3.1.1.1 MoL Documentation (Maintenance Reports)						
			3.3.1.1.2 **Digital Twin Archiving**	3.3.1.1.2.1 Standards for Long-term Archiving of Digital Product Data	3.3.1.1.2.2 Standards for Long-term Archiving of Technical Data						

Figure 19. DT Lifecycle Management Framework – Version One (Shaded Boxes correspond to the Added or Modified Concepts, according to Experts' Recommendations on the Enrichment Process)

4.1.3.2 Included in a Complementary List of General Recommendations on Deploying and Managing Digital Twins across their whole Lifecycle Phases

For the general recommendations that were made, without considering the framework, it was opted to build up a compilation of these in form of a list. These recommendations arose through two main ways, the first, through the direct question asked in the first stage of the semi-structured interviews and secondly, they were obtained through the discussions that were generated throughout the presentation of the framework. The result of this list of general recommendations can be found in Section 3.5.

4.2 Digital Twin Lifecycle Management Framework Validation Process

To obtain the latest version of the proposed framework for Digital Twin Lifecycle Management, *Version One* was subjected to a validation process. It should be noted that this version was obtained in the enrichment process, by removing and introducing new concepts and changing the labels of others by recommendations of the 17 Digital Twin experts interviewed. In this new validation process, an expert's peer review was carried out to obtain a verdict (i.e. accepted as it is, accepted with minor changes, accepted with major changes, or rejected) of the 17 experts interviewed on the *Digital Twin Lifecycle Management Framework.* After receiving their verdicts, the necessary changes were made in the framework to reach its *Final Version.*

4.2.1 Framework Validation Process

The validation process was carried out with the same 17 experts on Digital Twins, belonging to both academia and industry. To get a verdict on the *Version One framework,* an expert's peer-review process was performed using a nominal group technique. The main difference between the "nominal group technique" and classical "brainstorming groups" is that in a nominal group there is no direct interaction between individuals during the initial 'generation of ideas' stage (Delbecq & Van de Ven, 1971). This initial stage was performed at the beginning of the semi-structured interviews. Then, it is followed by a 'sharing of ideas' stage and a 'group discussion' stage, performed in the second stage of the interviews when Version Zero was presented to the interviewees. The final stage of the nominal group technique is the 'voting and ranking' stage (validation process), in which the group decides upon the proposed ideas, or in this case the proposed framework. The nominal group technique is a powerful technique to structure the discussion of expert panels since it ensures relative equal participation of all experts and ends with a resolution upon the proposal. A copy of the written work was shared with the group of experts, where each of the phases, stages, activities, tasks and subtasks are described in detail, to carry out an exhaustive analysis of the work. At the end of their review, in addition to new comments and recommendations that emerged, they were asked to provide a final evaluation under the parameters "accepted as is", "accepted with a minor", "accepted with major", or "rejected".

Once the verdicts were obtained, on *Version One* of the *Digital Twin Lifecycle Management Framework,* 5 experts from the peer-review assigned the parameter "accepted as is", of which 2 were members from the academia and 3 from the industry. On the other hand, 12 verdicts were obtained under the parameter "accepted with a minor", where 9 of them belong to academia experts in DTs and 4 to industrial experts (see Table 5). After having obtained the best two parameters in which the nominal group was asked to assign a grade to the proposed framework, the validation of the *Digital Twin Lifecycle Management Framework* was given before the two large branches (being them the academia and industry) focused on Digital Twins research and development. Once the minor changes in the framework had been made, the **Final Version of the Digital Twin Lifecycle Management Framework,** presented in **Figure 10**, was achieved.

Table 5. List of Peer-Reviewers from Academia and Industry

No.	Name	Affiliation	Sector	Verdict
1	Prof. Marco Macchi	Politecnico de Milano, Italy	Academia	AWMC
2	Prof. Andrea Matta	Politecnico de Milano, Italy	Academia	AAII
3	Prof. Martin Fabian	Chalmers University of Technology, Sweden	Academia	AWMC
4	Prof. Ricardo Rabelo	Federal University of Santa Catarina, Brazil	Academia	AWMC
5	Dr. Karl A. Hribernik	Institute for Production and Logistics (BIBA), Germany	Academia	AWMC
6	Dr. Stefan Wiesner	Institute for Production and Logistics (BIBA), Germany	Academia	AWMC
7	Dr. Guodong Shao	National Institute of Standards and Technology (NIST), USA	Academia	AWMC
8	Prof. Matthias Thurer	Chinan University, China	Academia	AAII
9	Prof. Shaun West	Lucerne University of Applied Sciences and Arts, Switzerland	Academia	AWMC
10	Prof. Thorsten Wuest	West Virginia University, USA	Academia	AWMC
11	Eng. Steve Ghee	PTC, USA	Industry	AWMC
12	M.Sc. Prakash Samal	McKinsey & Company, USA	Industry	AWMC
13	M.Sc. David Wang	McKinsey & Company, USA	Industry	AAII
14	B.A. Torrey Sullivan	Siemens, North America	Industry	AWMC
15	M.Sc. Shankar Raman	Siemens, North America	Industry	AAII
16	MBA. Flavio Arssani	Siemens, Mexico and Central America	Industry	AWMC
17	Eng. Salvador Barrena	Centric Software, Mexico and LATAM	Industry	AAII

*Accept With Minor Changes (AWMC) *Accept As It Is (AAII)

Chapter 5: Conclusions & Further Research

This section presents the conclusions of the work carried out *Towards a Digital Twin Lifecycle Management Framework* as well as a series of points to be considered as future work and research.

5.1 Conclusions

After having made a comprehensive review of the literature regarding Digital Twins, since its inception, in 2003, until this year (2021), a sudden interest was identified in the implementation of this type of application that facilitates and integrate into the Industry 4.0 environment. Undoubtedly the Digital Twins promise to bring great changes to the industry, thanks in principle to the granularity level of implementation (starting from its application for a simple entity to being developed for a complete supply chain) and secondly thanks to the different value propositions it can cover. In turn, in this same investigation, it was found that there are no standards or guides that lead to the correct implementation of this type of DT application. Due to this fact, there are various definitions for what a Digital Twin is, how it is made up and what its analytical capabilities should be. Similarly, several different ideas are presented of what comprises the maturity level of a Digital Twin. In addition to this vague vision of DT systems, there is also the lack of an explanatory model in which the flow of the lifecycle of a Digital Twin is presented.

For this reason, the objective of this thesis was to establish a *Digital Twin Lifecycle Management Framework* considering the whole lifecycle of a Digital Twin (viz. Design, engineering, and management stages), and addressing the technical and managerial requirements for its successful deployment, management and retirement across its lifecycle. After carrying out an iterative process, which began with the formation of a first theoretical framework through research in scientific and grey literature, later, it underwent an enrichment process through semi-structured interviews with 17 experts from the academy and industry, and finally, through a validation along peer-reviews focused on the same nominal group of DT experts, it was possible to elaborate a Digital Twin Lifecycle Management Framework that is robust and comprehensive enough for its application in the industry and the academy. Although this is a first effort to provide a general guide in the flow of the lifecycle of a Digital Twin, there is still a lot of work to be done to arrive at a framework that standardizes the development, implementation, management, and retirement of a Digital Twin.

5.1.1 Contribution to Theory (Academia)

First "conceptual" *Digital Twin Lifecycle Management Framework* in the scientific and grey literature (up to December 2021) considering the design, engineering, managerial, and decommissioning implications for the successful development, implementation, management, and retirement of a Digital Twin – considering its full lifecycle phases.

5.1.2 Contribution to Practice (Industry)

First "conceptual" guidelines (in the form of a Lifecycle Management Framework) in the scientific and grey literature (up to December 2021) for *Digital Twin developers and managers* for the successful development, implementation, management, and retirement of a Digital Twin, aimed at:

- Helping to shorten the time needed for a comprehensive *conceptualization* of a Digital Twin,
- Increasing the number of successful deployment cases of Digital Twin applications by closely supervising their *realization,*
- Ensuring the proper performance of a Digital Twin system within its threshold by using different (intelligent) maintenance strategies for each of its layers (i.e. physical product, digital thread, and digital product),
- Guaranteeing appropriate versioning management of a Digital Twin system throughout its evolution (i.e. modifications, upgrades, and new services development), and
- Providing strategic management of its historical data produced during its lifespan (e.g. for achieving for future usage, and for inheriting for immediate use).

5.2 Further Research

Although the enrichment and validation processes were carried out hand in hand with a nominal group made up of 17 experts in Digital Twins, of whom ten were academic experts and seven were industry experts, who provide an overview of the potential of the framework based on their experience in developed DT projects, it is necessary to create a third stage in the iterative enrichment and validation process in which the use of the framework is tested in a real use case. This means that although experts have given positive comments about its functionality in the lifecycle of a Digital Twin, as work and future research it is necessary to carry out the planning, development, management and retirement of a DT project employing the proposed framework, testing, in this case, the usability. This will show second indications about its functionality and will allow the framework to undergo a new process where new points to be considered will arise from the use of the framework. It is worth mentioning that this framework should not only be applied to a single-use case. To guarantee its comprehensive vision, it should be tested in different use cases. By carrying out these procedures, new comments and general recommendations will be added to the framework, bringing it closer and closer to a more standard framework for the correct management of the lifecycle of a Digital Twin.

In the same way, it must be considered that over time, as has been appreciated in recent years, new technologies emerge facilitating current DT tasks or simply enabling the creation of new values for the captured data. This means that the *Digital Twin Lifecycle Management Framework* will always be in constant change and new efforts will have to be done to keep it updated. Similarly, even though this framework is mainly focused on industrial applications, it can be adapted by making the pertinent modifications so that it complies with the characteristics of the sector where it is aimed to be implemented. Reference is made to this since, as seen in Section 1.2.4, the literature is, in turn, focusing on the application of Digital Twins in other areas such as sustainability, health, safety, etc. That is why the flexibility of the framework becomes important, setting aside the necessity to start from scratch since there is a solid base framework that has been proved in the industry.

Annex 1: Digital Twin Lifecycle Management Framework (Table Design View)

3 Digital Twin Lifecycle Management	3.1 Beginning of Life Phase	3.1.1 Conceptualization Stage	3.1.1.1 **Business Feasibility Assessment Activity**	3.1.1.1.1 **Problem(s)**	What is the business problem(s) I'm trying to solve? >> (One or more use cases or problem to solve)							
				3.1.1.1.2 **Customer Segments**	For whom am I designing for?							
				3.1.1.1.3 **Information Capabilities**	How much information we have access to and what kind?							
				3.1.1.1.4 **Technological Capabilities**	What type of technology does the product / machine / company has? Is it sufficient for a DT implementation?							
				3.1.1.1.5 **Digital Capabilities**	What type of digital assets are available?							
				3.1.1.1.6 **Value Proposition (Value Added)**	For (target customer) who (statement of the need or opportunity) this digital twin is (digital twin data value) that (statement of benefit).							
			3.1.1.2 **Business Case Activity**	3.1.1.2.1 **Solution / Strategic Case**	It should set out the background to the proposal and explain the objectives that are to be achieved.							
				3.1.1.2.2 **Risk Management**	Trustworthiness of the project or business red flags (internal and extrenal challenges).							
				3.1.1.2.3 **ROI Business Case / Economic Case**	Numbers for increased revenue, reduced costs, improved throughput or increased safety.							
				3.1.1.2.4 **Key Metrics**	Key activities to be measured to determine success.							
				3.1.1.2.5 **Systems Integration**	List integrations to other business information systems.							
				3.1.1.2.6 **Costing / Financial Case**	This section is concerned with issues of affordability, and sources of budget funding.							
				3.1.1.2.7 **Management Case**	Deliverability of the proposal >> (Work Breakdown Structure & Project Schedule - Critical Path)							
			3.1.1.3 **Verification Activity**	3.1.1.3.1 **Full Business Strategy**	Develop a detailed Digital Twin Framework and implementation strategy.							
				3.1.1.3.2 **Full Business Case**	Revisit the business case phase in more detail.							
		3.1.2 Realization Stage	3.1.2.1 **Design and Engineering Activity**	3.1.2.1.1 **Requirements Specifications**	3.1.2.1.1.1 Functional Requirements	3.1.2.1.1.2 Non-Functional Requirements						
				3.1.2.1.2 **Depth of System**	3.1.2.1.2.1 Entity (Product / Machine Tool / Worker)	3.1.2.1.2.2 Manufacturing Cell	3.1.2.1.2.3 Production Line	3.1.2.1.2.4 Factory	3.1.2.1.2.5 Supply Chain			
				3.1.2.1.3 **DT Classes and Instances**	3.1.2.1.3.1 Digital Twin Prototype	3.1.2.1.3.2 Digital Twin Instance	3.1.2.1.3.3 Digital Twin Aggregate					
				3.1.2.1.4 **Level of Cognition**	3.1.2.1.4.1 Reporting (Descriptive)	3.1.2.1.4.2 Analyzing & Diagnosing	3.1.2.1.4.3 Predicting	3.1.2.1.4.4 Integrating	3.1.2.1.4.5 Prescribing	3.1.2.1.4.6 Cognitive Analytics		
				3.1.2.1.5 **Level of Autonomy**	3.1.2.1.5.1 User Assistance	3.1.2.1.5.2 Partial Autonomy	3.1.2.1.5.3 Conditional Autonomy	3.1.2.1.5.4 Full Autonomy				
				3.1.2.1.6 **Data Synchronization**	3.1.2.1.6.1 Unidirectional Synchronization	3.1.2.1.6.2 Bidirectional Synchronization						
				3.1.2.1.7 **Value Proposition**	3.1.2.1.7.1 New Product Introduction (Reduced Cost & Lead Time)	3.1.2.1.7.2 Record Retention and Serialization	3.1.2.1.7.3 Improved Quality	3.1.2.1.7.4 Reduced Operational Costs	3.1.2.1.7.5 Shortened Time-to-Market	3.1.2.1.7.6 Services Revenue	3.1.2.1.7.7 New Biz Models	3.1.2.1.7.8 Disruptive Biz Model
				3.1.2.1.8 **Data Analytics Sophistication**	3.1.2.1.8.1 Descriptive	3.1.2.1.8.2 Informative	3.1.2.1.8.3 Predictive	3.1.2.1.8.4 Comprehensive	3.1.2.1.8.5 Transformative			
				3.1.2.1.9 **Machine Learning Capability**	3.1.2.1.9.1 Pre-Digital Twin	3.1.2.1.9.2 Digital Twin	3.1.2.1.9.3 Adaptive Digital Twin	3.1.2.1.9.4 Intelligent Digital Twin				
				3.1.2.1.10 **Human-DT Interaction**	3.1.2.1.10.1 Document-based Intefaces	3.1.2.1.10.2 CAE Simulation-based Interfaces	3.1.2.1.10.3 AR-based Interfaces	3.1.2.1.10.4 VR-based Interfaces	3.1.2.1.10.5 MR-based Interfaces	3.1.2.1.10.6 Softbot-based Interface		
				3.1.2.1.11 **DT Virtual Representation**	3.1.2.1.11.1 Data Model (A Datum)	3.1.2.1.11.2 1D Model (A Graphic)	3.1.2.1.11.3 2D Model (A Design)	3.1.2.1.11.4 3D Model (A Design)				
				3.1.2.1.12 **ICT Architecture**	3.1.2.1.12.1 Centralized	3.1.2.1.12.2 Decentralized	3.1.2.1.12.3 Distributed					
				3.1.2.1.13 **Computing Environment**	3.1.2.1.13.1 Edge	3.1.2.1.13.2 Fog	3.1.2.1.13.3 Cloud					
				3.1.2.1.14 **IT Network**	3.1.2.1.14.1 TCP/IP	3.1.2.1.14.2 4G-Enabled	3.1.2.1.14.3 5G-Enabled					
				3.1.2.1.15 **OT Network**	3.1.2.1.15.1 Wired	3.1.2.1.15.2 4G-Enabled	3.1.2.1.15.3 5G-Enabled					
				3.1.2.1.16 **Cybersecurity Mechanisms**	3.1.2.1.16.1 Authentication	3.1.2.1.16.2 Authorization	3.1.2.1.16.3 Accounting					
			3.1.2.2 **Implementation Activity**	3.1.2.2.1 **Agile Development**	3.1.2.2.1.1 Plan	3.1.2.2.1.2 Iterative Design	3.1.2.2.1.3 Iterative Development	3.1.2.2.1.4 Iterative Testing	3.1.2.2.1.5 Iterative Deployment	3.1.2.2.1.6 Iterative Review	3.1.2.2.1.7 Launch	
	3.2 Middle of Life Phase	3.2.1 Management Stage	3.2.1.1 **Operation Activity (Maintenance)**	3.2.1.1.1 **Physical Product (Smart Connected Product)**	3.2.1.1.1.1 Autonomous Maintenance	3.2.1.1.1.2 Condition-based Maintenance	3.2.1.1.1.3 Predictive-based Maintenance					
				3.2.1.1.2 **Digital Thread (Connections & Interfaces)**	3.2.1.1.2.1 Cybersecure Connection Maintenance	3.2.1.1.2.2 IT/OT Networks Maintenance						
				3.2.1.1.3 **Virtual Product (Models, Algorithms, Database)**	3.2.1.1.3.1 1D/2D/3D Models Maintenance	3.2.1.1.3.2 Algorithms Maintenance	3.2.1.1.3.3 Database Maintenance					
			3.2.1.2 **Evolution Activity (Modifications, Upgrades, and New Services Development)**	3.2.1.2.1 **Physical Product (Smart Connected Product)**	3.2.1.2.1.1 Versioning Management							
				3.2.1.2.2 **Digital Thread (Connections & Interfaces)**	3.2.1.2.2.1 Versioning Management							
				3.2.1.2.3 **Virtual Product (Models, Algorithms, Database)**	3.2.1.2.3.1 Versioning Management							
	3.3 End of Life Phase	3.3.1 Retirement Stage	3.3.1.1 **Decommission Activity**	3.3.1.1.1 **Digital Twin Inheritance**	3.3.1.1.1.1 BoL Documentation	3.3.1.1.1 MoL Documentation (Maintenance Reports)						
				3.3.1.1.2 **Digital Twin Archiving**	3.3.1.1.2.1 Standards for Long-term Archiving of Digital Product Data	3.3.1.1.2.2 Standards for Long-term Archiving of Technical Data						

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