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Toward Sustainable Development: Exploring the Value and Benefits of Digital Twins

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Abstract: The complexity and number of data streams generated by internal processes exceed the capabilities of most current simulation environments. Consequently, there is a need for the development of more advanced solutions that can handle any number of simultaneous simulations. One of the most promising ideas to address these and other challenges is the concept of a Digital Twin (DT), which refers to a digital representation or a virtual model designed to accurately reflect an intended or actual physical product, system, or process (i.e., a physical twin). As a Digital Twin spans the life-cycle of its physical twin, its development and application can bring considerable benefits to organizations seeking to improve existing processes as well as implement new ones. However, few studies have comprehensively examined the value and benefits of Digital Twins. To fill this gap, this study aims to provide a better understanding of this technology by reviewing the contemporary literature, with a particular focus on the documented case studies, as well as reported business and industrial deployments. The results obtained show that Digital Twins have proven beneficial for maintenance, cost reduction, optimization, simulation performance, monitoring, product life-cycle understanding, assessment validation, performance evaluation, product design, and safety and risk mitigation. In addition, when considering the human factor, DTs can facilitate education and training, team collaboration, and decision making. Undeniably, Digital Twins are a game changer for safer, faster, and more sustainable development.

Keywords: sustainable development; digital twin; virtual twin; value; benefit

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1. Introduction

Sustainable development is development that "meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [1]. In general, this issue has received considerable attention from businesses, governments, and researchers over the last decades [2–4]. Not surprisingly, due to global warming and its effects [5], there is a clear and growing interest in developing and implementing low-impact solutions [6]. Among many key drivers for sustainability, an innovation is one of today's most desired technological traits to create more efficient and more sustainable products and services [7,8]. According to Prudy et al. [9], Digital Twins are changing the face and pace of innovation, while the implications are profound, making an innovation faster, cheaper, and more radical.

According to Fortune Business Insights, the global Digital Twin market size reached a value of US$6.75 billion in 2021 and is projected to reach US$96.49 billion by 2029, exhibiting a compound annual growth rate (CAGR) of 40.6% during the forecast period [10]. The world's largest tech companies, including Alphabet [11], Amazon [12], and Microsoft [13], offer development tools that enable the creation of Digital Twins of real-world systems in areas such as construction [14], healthcare [15], manufacturing [16], supply chain [17], and retail [18], to name a few. Moreover, Digital Twins and closely related areas have piqued the interest of researchers from over 158 countries (The number of countries has been estimated based on the results from the query "digital twin" execution on the Scopus database (30 March 2023)), spanning a wide range of fields, including engineering, computer science, physics, energy, biochemistry, decision sciences, and business management. Despite the numerous research questions raised and answered, a fundamental question still remains: what value and benefits can a Digital Twin deployment bring to the organization?

In this paper, we aim to explore the value of a Digital Twin and identify its benefits, regardless of its domain of application. Thus, our study is qualitative in nature, providing an appropriate way to analyze a relatively under-examined topic. In other words, our study relies on exploring the state-of-the-art literature focused on Digital Twin development and implementation in any area of business or industry. In this sense, this paper contributes to the limited research in the Digital Twin landscape by identifying and articulating the story of its value and benefits, and informing interested parties of possible outcomes resulting from its adoption.

The rest of the paper is structured as follows. In Section 2, we outline the theoretical and technological background that underpins the Digital Twin concept and architecture. In Section 3, we present the research methodology we applied to achieve our research objectives. In Section 4, we provide the results we obtained, followed by a discussion of threats to validity, as well as contributions, limitations, and future research directions in Section 5.

2. Background

It is widely accepted that the concept of a "digital twin" originated from the National Aeronautics and Space Administration (NASA) in the 1960s, where it was referred to as a "living model" of the Apollo mission [19]. The term itself was first used by John Vickers in 2002 [20]. According to VanDerHorn and Mahadevan, a Digital Twin (DT) is defined as "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems" [21].

Lueth [22] classified Digital Twin use cases along three prevailing dimensions:

1. The hierarchical level at which the Digital Twin is deployed includes six levels (Informational, Component, Product, Process, System, and Multi-system).
2. The life-cycle phase in which the Digital Twin is deployed involves six phases (Design, Build, Operate, Maintain, Optimize, and Decommission).
3. The use of the Digital Twin refers to seven uses (Digitize, Visualize, Simulate, Emulate, Extract, Orchestrate, and Predict).

In total, 252 potential use cases are defined by combining the seven most common uses, six hierarchical levels, and six phases. It seems quite evident that researchers and practitioners have so far have documented and classified a plethora of use cases of the Digital Twin in many different sectors, introducing different sets of criteria, ranging from the general to the very technical [23].

In general, the architecture of a Digital Twin in terms of its modeling can be divided into three main layers [24,25]:

- The physical layer, which encompasses the physical entities of the system, environment, and processes;
- The virtual layer, which involves virtual models of the physical entities at different levels of abstraction;
- The interconnection layer, which serves as the bidirectional data proxy between the physical and virtual layers.

From the perspective of a solution vendor, the first physical reality layer is independent and is the object of observation, analysis, and understanding; while the remaining two dependent layers are the object of modeling, implementing, and testing. Four core technologies typically employed in modeling and developing a DT are Artificial Intelligence (AI), Big Data (BD), Internet-of-Things (IoT), and mobile/wireless networks [26].

AI aims to empower a Digital Twin with capabilities of perceiving, synthesizing, and inferring information to learn and adapt to new situations and circumstances [27]. Some researchers and practitioners argue that AI is an imperative component for some DT applications, such as autonomous driving systems [28] and additive manufacturing [29]. In particular, machine learning algorithms are commonly used to explore data for hidden patterns [30], detect anomalies [31], make predictions [32], or construct classifiers [33].

Big Data (BD) spans over the "high" seven Vs—namely, Volume, Velocity, Variety, Veracity, Variability, Visualization, and Value [34]. In short, Big Data refers to relatively larger, more complex data repositories [35], especially from new data sources [36]. For Perry [37], the concept Big Data really means "harvesting meaning from data", which "is coming in faster, from more sources, and in more varied formats than ever before" [38]. In a practical sense [39], Big Data technology refers to a software utility designed to "analyze process and extract information from extremely complex and large data sets which traditional data processing software could never handle" [40]. The modern big data solutions available in the market are [41] Apache Hadoop [42], Apache Spark [43], and Hortonworks Data Platform (HDP) [44].

The term Internet of Things (IoT) is understood as "the collective network of connected devices and the technology that facilitates communication between devices and the cloud, as well as between the devices themselves" [45]. In general, IoT capacitates the Digital Twin model to support new intelligent services to connect and interact with physical objects [46]. The realms of IoT and DTs overlap when it comes to describing, discovering, and accessing resources [47]. This is conceptualized on five layers, starting from physical space, communication network, virtual space, data analysis and virtualization, and ending with the application layer [48]. In the case of the first layer, the naming of objects is typically associated with the word "smart" when IoT comes into action; hence, numerous studies have already discussed smart buildings [49], smart enterprises [50], smart factories [51,52], smart farming [53], smart grid [54], smart health [55], and smart transportation [56], to name a few.

In recent years, significant advancements in mobile and wireless technologies have enabled many applications beyond traditional voice and video calls on mobile phones [57]. Digital Twin solutions are no exception to this trend. One of the main assumptions underlying the design of Digital Twins is reliability [58], which implies that twins are synchronized in real-time with their physical counterparts by receiving actual data with low latency. Data from physical entities are collected through Data Acquisition Systems (DAC) deployment [59] equipped with sensors, measurement devices, and computers [60].

The concept of a Digital Twin is not merely a passing trend from a business perspective. Even industries such as aviation and wind turbine manufacturing, which traditionally have little to do with digitization, have embraced the latest technological advancements and adapted their existing systems and procedures to incorporate Digital Twins. Recently, the term Digital Twin is often used to refer to the latest wave of computer modeling and simulation, which aim to develop digital representations of real-world objects, systems, or processes. Ultimately, the application of Digital Twins is expected to lead to significant time and cost savings [61].

3. Methodology

In our study, we put forward the following research question: what is the value and benefits of deploying Digital Twins across various applications? Given the nature of this research, it makes sense to adopt a qualitative approach using a literature review, which by definition is a structured, comprehensive review with an explicit methodology that is focused on finding the key evidence needed to answer the research question [62]. In general, according to Knopf [63], a literature review consists of two parts. First, it should be a concise summary of the findings or claims that are the result of previous research efforts on a topic. Second, it should provide a conclusion about how accurate and complete that knowledge is. In this sense, a literature review process "involves researching, reading, analyzing, evaluating, and summarizing scholarly literature (typically journals and articles) about a specific topic" [64].

Our research inquiry begins by specifying data sources. For the primary data source, we used Google Scholar (available at https://scholar.google.com/), which is the largest academic database with over 390 million indexed records [65]. As a secondary data source, we used Scopus (available at https://www.scopus.com/), an Elsevier abstract and citation multidisciplinary database of peer-reviewed literature, which includes scientific journals, books, and conference proceedings [66]. Note that both Google Scholar and Scopus are legitimate, reliable, and up-to-date sources of information used by most researchers around the world [67,68].

We developed search queries by combining keywords related to Digital Twin research, such as advantage, benefit, and value. Our objective was to analyze and summarize the existing literature comprehensively by discussing the background of the topic. We conducted a narrative literature review as the first step in our study [69]. Please note that for the Scopus database, we only searched for titles of reviewed articles and conference papers published solely in English.

The second step involved searching, analyzing, and documenting existing Digital Twin deployments across all areas of business or industry. We used a combination of keywords such as application, deployment, design, implementation, and solution. More specifically, we employed an exploratory approach to investigate the benefits reported after Digital Twin deployments. We excluded studies that only discussed promises or expectations. If insufficient information was found in the collected scholarly literature, we also used Google Search Engine (available at https://www.google.com/), as a supplementary data source.

Eventually, having collected necessary data, we performed manual coding, following the instructions authored by Hacking [70]. By definition, in qualitative research, a code is usually a word or short phrase that semantically assigns a summative attribute for a portion of language-based data. Therefore, the application of manual coding involves detailed reading and manually developing and assigning codes.

In this study, we adopted the inductive coding approach, which means building a list of codes from scratch based on the collected data. In this extent, the following four steps were undertaken. Firstly, one of the researchers read all the papers and extracted all the text fragments related to the research question. Secondly, by making use of the keywords and their synonyms, the contextualized meaning was individually classified to one word, or alternatively to a string, consisting of two or three words. Thirdly, the second researcher manually verified the coding and, if necessary, extended the list of codes. In the last step, the list was the subject of shared processing with the aim of consensual understanding and final refinement. The outcome of the manual coding is provided in Appendix A.

4. Benefits of Digital Twin Deployments

To summarize our results, we used the cloud of words technique, which is a free and online tool (worditout.com). This technique generates a visual representation of word frequency by extracting words from the source text and emphasizing those that appear more frequently. While there were 103 codes found in the original source, we set up the minimum frequency on two. Next, after careful analysis, we excluded four words (commissioning, failure, problem, and risk) due to their negative connotation, as well eight common words (analysis, cost, costs, data, interaction, model, sales, and time). Thus, the remaining set, as an input for visualization, includes 40 words. Figure 1 depicts the cloud of codes assigned, expected, and reported from Digital Twin deployment that were anticipated from our quantitative analysis.

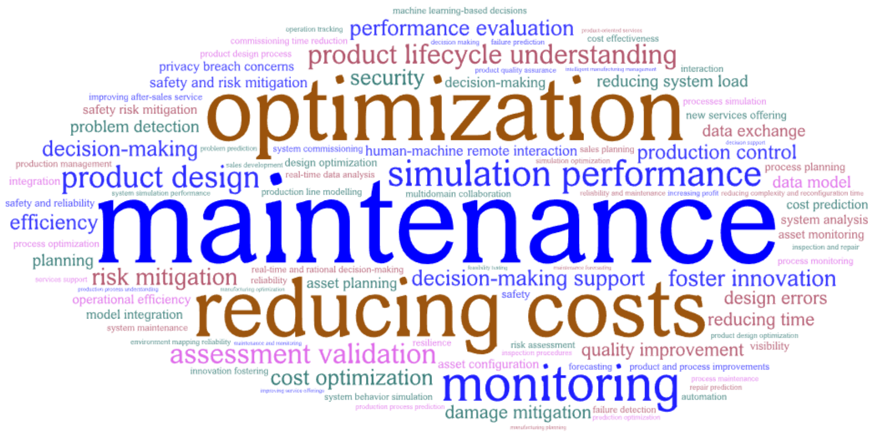

Figure 1. The cloud of codes with regard to the benefits expected and documented from Digital Twin deployment.

As one can notice, the benefits of deploying a Digital Twin are multifaceted (see Figure 2). The most frequent and common benefits include the following:

- Maintenance (22.4%)—related to both operational and predictive analysis, enabling stakeholders to better understand the physical systems and actual processes;
- Cost reduction (16.3%)—refers to the better understanding of the product life-cycle loop, thus recognizing the points of materials and work overhead;
- Optimization (12.2%)—due to the discovery of the best solutions, incorporating the cost-effective resources while maximizing business value;
- Simulation performance (10.2%)—having the capability of handling multiple simultaneous and heterogeneous simulations and aims to model the processes' evolution by testing different settings of their key behaviors, characteristics, or relationships;
- Monitoring (8.2%)—refers to the regular surveillance over digitized assets, processes, and services over a period of time;
- Product life-cycle understanding (6.1%)—refers to the handling of a good as it moves through the various stages of its lifespan, bringing tangible effects of reducing system load, configuring and planning assets, and checking product feasibility;
- Assessment validation (6.1%)—concerns the quality review of the assessment process, including checking that the assessment tool produces consistent results;
- Performance evaluation (6.1%)—through analyzing, developing, and categorizing a set of alternative scenarios and models before their implementation within the physical system;
- Product design (6.1%)—enabling designers to develop and test more product variations with fewer resources engaged;
- Safety and risk mitigation (6.1%)—relates to the detection, assessment, understanding, and prevention of adverse events, side effects, or any other health-related issues.

Last but not least, other benefits of a Digital Twin deployment pertained to innovation fostering [71], system security [72], and multidomain collaboration [73]. However, it seems that the most intriguing side of the Digital Twin implementations currently relates to the healthcare pathway involving human organs [74], such as the heart [75], liver [76], or lung [77]. In addition, Digital Twins can provide a realistic and safe environment for healthcare professionals to improve their skills by practicing complex medical procedures [78,79]. Thus, the implementation of Digital Twin technology in healthcare has the potential to greatly improve patient outcomes and support patient safety [80].

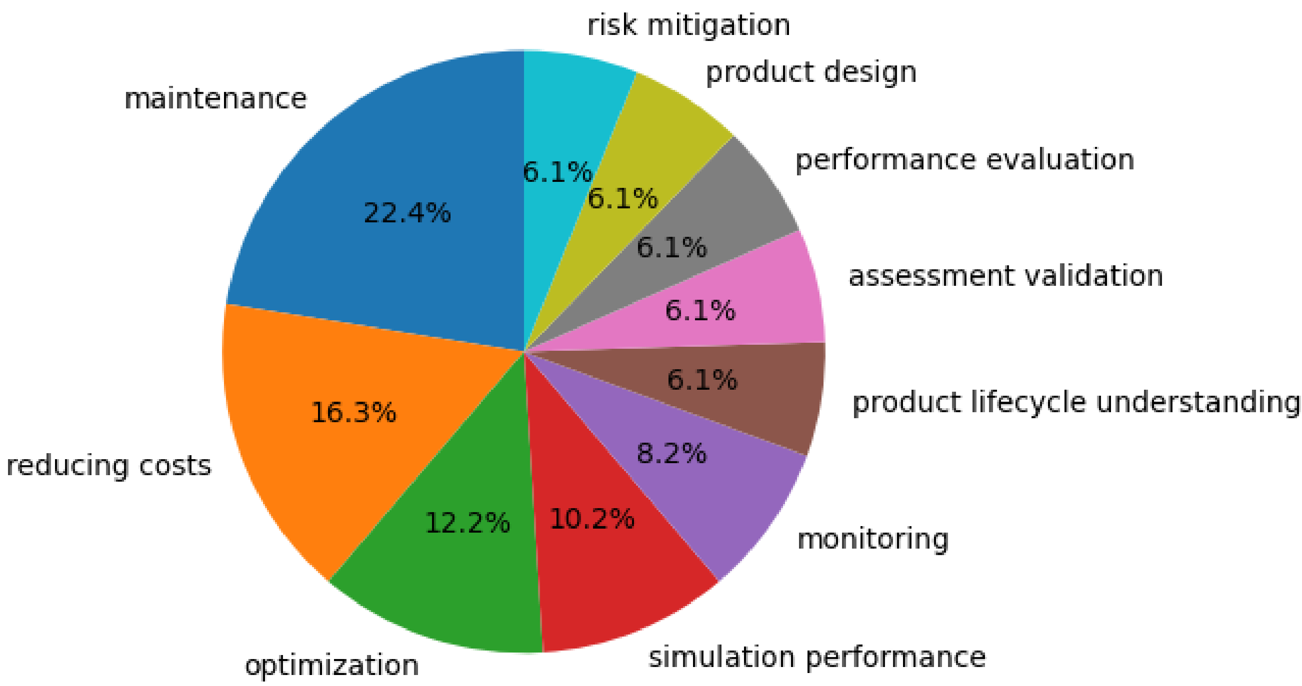

Figure 2. The top 10 benefits of Digital Twin deployment.

Note that while there are many adopters of digital life models, there is not yet a widely accepted consensus on the value and benefits of the Digital Twin as its first solutions are deployed and are still expanding across many industries on a global scale. Therefore, the calculated percentages should be treated with considerable caution. Nevertheless, we believe that the results obtained can provide a valuable foothold for both the academic and business communities by providing a broad view of the value and benefits of implementing Digital Twins.

5. Discussion

At present, we are witnessing the Fourth Industrial Revolution [81], and time is driven by digital transformation in the service and manufacturing sectors. Almost every industry, if not all, is currently subject to these changes—which are characterized by interconnectivity via digital tools [82,83]—that promise to deliver affordable, smart, scalable, and reliable capabilities beyond physical limitations [84]. Future generations of computer systems (FGCs), particularly Digital Twins solutions, are expected to provide support not only to their users but also to their physical counterparts in economic, operational, and strategic domains. Clearly, the FGCs are not off-the-shelf technological products; as such, a variety of unprecedented challenges and issues have already been identified [85–87], both in terms of their development and deployment. This makes them one of the most complex and demanding endeavors to undertake. Therefore, the expected benefits should be treated with caution and considered over the long term.

Collected information suggests that different technologies used to design and develop Digital Twin solutions have been implemented and integrated over time. There is an obvious role for hardware infrastructure, which is a major requirement for efficient data processing units as well as for the system as a whole. Another key component underpinning Digital Twin solutions is a digital definition of its counterpart, along with an attached information model. The last but not least component is a middleware that links physical and digital entities and exchanges data between them. However, combining all these components into one fully operational system is a complex and challenging process that carries additional risks to a deployment effort [88–90]. Thus, in addition to considering the expected benefits of a DT deployment, it is also important to identify and assess potential threats and vulnerabilities to which the system may be exposed.

Our findings are consistent with previous research that has explored the topic of Digital Twins. More generally, the domain of its applications spans many industries, including automotive, aerospace, construction, agriculture, mining, utilities, retail, healthcare, military, natural resources, and public safety sectors [91]. Secondly, since a DT is a theoretical notion and does not exist as such, and takes advantage of four technology pillars—Internet-of-Things [92], Cloud Computing [93], Artificial Intelligence [94], and Extended Reality (XR) [95]—it is able to deliver an added value, originating from the integration of the above pillars and their real-time collaboration.

While the adoption of Digital Twin technology has grown significantly in recent years, with many successful application scenarios reported to date, several challenges and issues remain to be addressed. Tahmasebinia et al. [96] identified such challenges as cost control, data processing, security, and privacy, along with seamless integration of the physical and digital worlds, and integration with intelligent solutions. In the construction domain, Madubuike et al. [97] claim that the process of deploying effective DT involves highly technical and complex steps. Digital Twin technology requires collecting and utilizing large amounts of data from multiple endpoints, each a potential vulnerability. In addition, employees may show a lack of interest due to concerns about job security, which can hinder adoption. Another significant challenge is the difficulty of integrating the various stakeholders in the construction industry to work as one team.

While Tao et al. [98] indicate that Digital Twin (DT) modeling involves physical modeling, virtual modeling, connection modeling, data modeling, and service modeling, on the other hand, such an approach implies several challenges. First, the digital model requires managing a large volume of data, including physical data, virtual data, and their integrated fusion data. As a result, data preprocessing is essential, providing data cleaning, data conversion, and data filtering. Second, all components of the digital twin must interact and collaborate to solve complex tasks. DTs have three types of interaction and collaboration: physical–physical, virtual–virtual, and virtual–physical. Note that physical–physical interaction and collaboration allows multiple physical entities to communicate, coordinate, and work together to accomplish complex tasks that a single entity cannot accomplish alone. Finally, the remaining issues relate to service encapsulation [99], service matching [100] and discovery [101], quality of service (QoS) modeling and evaluation [102,103], service optimization and integration [104,105], and fault tolerance management.

Having said that, the question that naturally arises is as follows: how do you address all these challenges and issues? Obviously, there is no single valid answer. However, considering Deponti's view that "Digital Twin is not about technology, it's about people. People and processes to be exact." [106], there are many proven and well-documented methods and solutions for modeling interactions between people and processes as well as among them. Nevertheless, there is no one-size-fits-all approach that works best in all cases. Therefore, each case should be considered individually, taking into account the skills and resources [107,108] available on the one hand and the requirements and constraints [109,110] on the other.

This study was set up to investigate the benefits of Digital Twin deployments. A qualitative exploratory approach was undertaken to address this research inquiry. In our opinion, the obtained results present some interesting findings that are of value to both researchers and practitioners. Nevertheless, further research is needed to determine not only the benefits but also the challenges and limitations associated with DT deployments. One limitation of the study is that the targeted literature review only included title keyword searches of the Scopus database and only included articles and conference proceedings published in English. Therefore, future research should also incorporate more case studies and technical reports that document the deployment of DTs in real-world settings.

6. Conclusions

The deployment of Digital Twins is able to create added value by providing the capacity to analyze and evaluate both existing and under-development physical products and systems. Depending on the particular industry in question, DT models bring considerable benefits in any number of ways. However, deploying a DT also means understanding the physical products and systems and discovering their simultaneous and varied uses. Thus, one should carefully balance out the expectations and deliverables, followed by a comprehensive cost–benefit analysis. Nevertheless, while there are a number of different approaches that are possible to be used to identify and quantify the costs in an accurate and reliable way, we are not yet able to fully monetize the effects. In other words, the reported pieces of evidence so far mostly rely on qualitative judgment instead of solid numbers. Moreover, some prior studies have some drawbacks due to the lack of supporting evidence, or issues related to sampling and its representativeness, affecting the generalizability of the findings.

Despite the aforementioned weaknesses, Digital Twins could take many forms and pick up many uses, delivering value to users every single day. For instance, Google Maps, a free web mapping service with over 1 billion monthly active users [111], spanning across 220 countries and covering 24 thousand cities and towns, provides detailed information about geographical regions and sites. Here, a question arises: what will come next? Since the democratization of artificial intelligence (AI) has put advanced technologies such as ChatGPT [112] into the hands of users without specialized or even technical knowledge, the road towards Intelligent Digital Twins (IDTs) has become a reality. We believe that this shift will further empower innovators, researchers, and industry leaders from various domains to accelerate the adoption and implementation of IDTs in a wide range of everyday applications, making a significant contribution to sustainable development goals.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
DT	Digital Twin
IoT	Internet-of-Things
ML	Machine Learning
XR	Extended Reality

Appendix A. An Input for Manual Coding along with the Codes Assigned

Table A1. Overview of the identified literature items and assigned codes.

Statements	Assigned Codes
"The Digital Twin can move from an interesting and potentially useful concept that aids in understanding the relationship between a physical product and its underlying information to a critical component of an enterprise-wide closed loop product lifecycle. These tasks will both reduce costs and foster innovation in the manufacture of quality products" [71].	enhance analysis; reducing costs; foster innovation; product life-cycle understanding; quality improvement
"In order to gain a better understanding of the impact of external factors on the validity of products throughout their lifecycle, we are proposing to expand the digital thread through a digital framework capable of delivering a rapid impact assessment of product validation. The proposed digital framework can help reduce costs by capitalizing on the knowledge inherent to the product families while recognizing and reusing common association patterns" [113].	reducing costs; assessment validation; product life-cycle understanding
"(...) digital twins are often the best solutions that support remote interaction of humans with physical machines and overcome the challenge of geographical distance" [114].	human–machine remote interaction
"(...) the cloud-based digital twins successfully reduce the system's overhead and provide an effective CPCM application" [114].	reducing costs; reducing system load
DT "is used to detect privacy concerns and minimize breaches and associated risks to which smart car drivers can be exposed trough connected infotainment applications and services" [115].	problem detection; privacy breach concerns; safety risk mitigation
"The real-time insight into operational driving states provided by the Digital Twin, enables operational efficiency and automated feedback to drivers. (...) The overall outcome should be quicker and more informed decisions on possible privacy vulnerabilities related to operational driving lifecycle" [115].	real-time and rational decision-making; operational efficiency
"(...) Digital Twin is designed with the aim to improve real-world products and processes based on simulated data and ML supported decisions" [115].	product and process improvements; machine learning-based decisions
Digital Twin "can be used to reduce the complexity and time of reconfiguration by early detection of design or process sequence errors of the system with a cross-domain simulation" [73].	reducing complexity and reconfiguration time; design errors
"The Digital Twin is enriched with the developed multi-domain models, which are integrated and semantically referenced together. References between models are achieved by using software tools that allow model integration and data exchange across different domains. This enables a cross-domain simulation of different aspects and the system behavior" [73].	data exchange; model integration; system behavior simulation
"A cross-domain simulation during engineering supports a rising tendency for parallelizing the engineering process, therefore reducing engineering time and supporting multidomain collaboration" [73].	reducing time; multidomain collaboration
"Using this virtual model, sometimes called the "digital twin," producers can improve their after-sales service, offer a range of new services, and generate insights that can be used to optimize the design of future cars" [116].	improving after-sales service; new services offering; design optimization
"(...) emulation software has become a key tool to create Digital Twins and carry out virtual commissioning of new manufacturing systems, reducing the commissioning time and increasing its final quality" [117].	efficiency; quality improvement; commissioning time reduction
"We envision cognitive digital twins will impact all the stages of the manufacturing systems", and (...) "we have particularly highlighted the impact of the cognitive digital twin in the product design stage" [117].	product design process
"(...) the asset-related decision-making process can be supported by Digital Twin modeling", in particular: "Asset configuration – The DT is used for modelling and simulating a production line, to evaluate its systemic Reliability, Availability, Maintainability performance (RAM performance), to finally predict its Total Cost of Ownership (TCO). It allows to assess the choice of the best design solution for the production line" [118].	maintenance; decision-making; cost optimization; asset configuration; production line modeling; performance evaluation

Table A1. *Cont.*

Statements	Assigned Codes
"Asset reconfiguration, (. . .) the DT is used for modelling and simulating a complex process production plant, to evaluate its systemic RAM performance, to finally predict its TCO. It allows to assess the choice of the best reconfiguration alternative to increase the availability of the plant" [118].	processes simulation; performance evaluation; decision-making; cost prediction
"Asset reconfiguration and planning – The DT is used as semantic data model within a web service-based control system for manufacturing systems. It forms the ground for an open, knowledge-driven Manufacturing Execution System architecture, which allows quick reconfigurations of the system" [118].	asset planning; production control; production management; system maintenance
"Asset commissioning – The DT is used as semantic data model, data analytics and advanced simulation, to make the virtual commissioning of the manufacturing system. Simulation of the system is based on a semantic data model and of a software structure that is able to analyse data in runtime. It allows a quick time to commission the system" [118].	data model; system analysis; real-time data analysis; system simulation performance; system commissioning
"Asset condition monitoring and health assessment – The DT is used for the asset diagnosis, helping to assess its health status based on the monitored condition. The DT provides the data analytics in order to extract the features required for the diagnosis. It allows to limit unreliability situations" [118].	reliability and maintenance; asset monitoring
The primary benefit of using a digital twin, as opposed to a testbed, is that it reliably represents the real industrial environment. In other words, the results of a pen-test conducted on the digital twin genuinely reflect the expected results of conducting the same test in the real environment. [72].	security; environment mapping reliability
"To secure good geometrical quality in the final product, tolerances, locator positions, clamping strategies, welding sequence etc. are optimized during design and pre-production. Faster optimization algorithms, increased computer power and amount of available data, can leverage the area of simulation toward real-time control and optimization of products and production systems—a concept often referred to as a Digital Twin" [119].	product quality assurance; safety and reliability; product design optimization
"The Digital Twin can use data from individuals to perform real-time in-line individual adjustments or data from batches of parts to make adjustment batch wise" [119].	production control
"(. . .) the digital twin driven smart manufacturing will be made more responsive and predictive and will be beneficial to more reasonable and precise manufacturing management in many aspects. Together they complement each other nicely to help the development of smart manufacturing" [120].	intelligent manufacturing management
"The digital twin is tweeted to be stored, refined and propagated to the process planning for an optimized machining solution" [121].	process planning; process optimization
"A digital twin collects data and monitors the process, has access to past data, and, overall, allows for a better understanding of the production process and better prediction of the behavior and results" [121].	production process understanding; process monitoring; maintenance; production process prediction
The digital twin model allows a shared conceptualization that can be visualized in exactly the same way by an unlimited amount of individuals and by individuals who do not need to share the same location [71].	innovation fostering
"A key ingredient of the DT model is to simulate the inspection and repair of cracked structures in order to plan and implement cost effective inspection and repair procedures. A typical scenario is to determine the time and type of inspections to conduct that minimize cost (. . .)" [90].	planning; maintenance; reducing costs; inspection procedures; cost effectiveness
"A present-day version of the risk assessment computations for fatigue critical locations was presented that contained the essential components of a probabilistic descriptions of loads, geometry, material properties, probabilistic methods, efficient fracture mechanics, and inspection and repair procedures" [90].	risk assessment; inspection and repair
"The utilisation of in-service data: The implementation of the Digital Twins involves the collection and utilisation of in-service data, such as the pressure of the valves, the amount of fuel consumed by the engines. (. . .) While some companies use the data for monitoring only, others use it for simulation, prediction and operation optimization" [122].	monitoring; simulation optimization; process maintenance; prediction optimization
"The integration of planning tools: It is possible to connect the data collected and stored in the Digital Twins with planning tools. Before production, it allows the optimization of the manufacturing strategy. During the manufacturing phase, the data stored in the Digital Twin helps to keep track of the operations and optimize planning" [122].	manufacturing planning; operation tracking; manufacturing optimization

Table A1. *Cont.*

Statements	Assigned Codes
"During the utilization phase, some failures or breakdowns can be predicted through the analysis of the data stored in the Digital Twin and affect task scheduling both for the operator and the manufacturer that might have to do some repair" [122].	repair prediction; maintenance forecasting
"The integration of simulation tools: To push the analytics further, it is possible to integrate simulation tools into the Digital Twins. (. . .) The comparison between in-service data and theoretical data obtained through modelling and simulation allows the assessment of the performance of the physical asset, the detection of failures, the prediction of potential problems and the determination of the next best actions" [122].	performance evaluation; failure detection; problem prediction
"The integration of the product lifecycle steps: A very important characteristic is the level of integration of the different lifecycle steps of the product into the Digital Twin" [122].	product design; product lifecycle understanding
"The creation of simple services: Using Tukker's service classification, the "simple services" refer to "product-oriented services" (. . .). These services consist essentially in advice and consultancy using the data stored in the Digital Twin. It can also be some basic real time monitoring features such as asset localization, fuel consumption, etc." [122].	maintenance and monitoring; product-oriented services
"The creation of advanced services. (. . .) By using the in-service data of the assets, these services aim at optimizing the operations and predicting failures" [122].	optimization; failure prediction
"The creation of services, enabled by the Digital Twins, allows the manufacturers to develop new selling paradigms. They can build subscription systems for the services, pay per use systems for the product and also base their revenues on the result obtained with the services they provide" [122].	sales planning; sales development
"In particular, the digital twin lends itself to contribute to the value propositions by supporting all of the actors around the product service system, in particular by relieving the pains and increasing the gains of the actors" [123].	improving service offerings; increasing profit
The DT "can be considered a data-driven enabler and support for providing services" [123].	services support
"(. . .) embedded digital twins are involved in all activities that imply their physical twins—e.g., service set up and optimized configuring, delivery monitoring and update. The main benefits brought by the digital twin concept are: (a) visibility: DTs allow visibility in the operations of resources; (b) prediction: using various modelling techniques (DES—based), the DT model can be used to predict the future state of a service process or resource; (c) interaction with the DES model: simulate conditions that are impractical to create in real life through "what if" analysis; (d) documenting: mechanisms to understand and explain behaviours of individual or interconnected resources; (e) integration: the DT model can be used to connect with backend business applications to co-create value" [124].	optimization; monitoring; maintenance; visibility; integration; interaction
"The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc." [125].	reliability
"(. . .) the Digital Twin continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success. The Digital Twin can also predict system response to safety critical events and uncover previously unknown issues before they become critical by comparing predicted and actual responses. Finally, the systems on board the Digital Twin are capable of mitigating damage or degradation by activating self-healing mechanisms or by recommending changes in mission profile to decrease loadings thereby increasing both the life span and the probability of mission success" [125].	forecasting; safety; risk mitigation; damage mitigation
(. . .) a digital twin that fuses the information gained from probabilistic damage diagnosis and prognosis. The digital twin thus supports intelligent decision making (mission planning) using up-to-date information, and quantified uncertainty" [126].	decision making; resilience
"The U. S. Air Force has been investigating the extension of IAT to realize the digital twin concept (. . .) to fuse multiple heterogeneous sources of information from models and data to support proactive fleet sustainment decisions" [127].	decision support
"The U.S. Air Force is currently investigating this methodology within the Airframe Digital Twin program for demonstration with Air Force legacy aircraft, using full scale experimental tests. The demonstrated P2IAT methodology is expected to be used for both legacy and new aircraft to reduce maintenance cost" [127].	feasibility testing; reducing costs

Table A1. *Cont.*

Statements	Assigned Codes
"With the rapid technological developments of the last several years, it is now possible to simulate complex industrial systems and develop and run digital twins in real-time settings. Digital twins offer an ability to complete off-line "what-if" analysis in a close-to-reality virtual environment before implementing tested actions in actual operations" [128].	decision-making; simulation performance
"(...) considerable benefits of creating digital twin of a building are as follows: (1) gathering, generating and visualizing the environment of the building, (2) analyzing data irregularities, and (3) optimizing building services" [129].	simulation performance; optimization; risk mitigation
"The digitization of production systems offers the possibility of automated data acquisition". (...) "Benefits of the proposed new approach for the analysis and modification of production systems can be experienced by participants in practical training sessions, especially continuous data acquisition, automated derivation of optimization measures and capturing of motion data" [130].	monitoring; optimization
"The benefits of DT technology include cost cutting, reduced time-to-market, and predictive maintenance". (...) "Digital tools and DT technology can increase study motivation, students' own responsibility for learning, as well as improve learning" [131].	reducing costs; maintenance; cost optimization
"The digital twin is an emerging technology used in intelligent manufacturing that can grasp the state of intelligent manufacturing systems in real-time and predict system failures" (...). "Manufacturing systems can monitor physical processes, create a digital twin in the physical world [132], receive real-time information from the physical world for simulation analysis, and make informed decisions through real-time communication and collaboration with humans" (...). "Using the built-in flexible digital twin helps designers quickly evaluate different designs and find design flaws" [133].	monitoring; risk mitigation; damage mitigation; simulation performance; assessment validation
"The digital twin extends the use of virtual simulation models developed in the design phase of a production system to operations for real-time control, dynamic skill-based tasks allocation between human and robot, sequencing of tasks and developing robot program accordingly." (...) "Results show that the approach supports the notion of automation while maintaining assembly flexibility" [134].	maintenance; optimization; automation
"The approach proposed prevent complex reverse-engineering processes in setting up a usable digital environment which grow in importance to support and evaluate the impact of increasing engineering and decision-making processes. Stakeholders are being informed about the current machine configuration, status or behaviour or get general information on what machines are present and connected at the moment" [135].	maintenance; decision-making support; assessment validation
"By establishing cyberphysical connection via decentralized digital twin models, various manufacturing resources can be formed as dynamic autonomous system to co-create personalized products" (...). "It addresses a bi-level online intelligence in proactive decision making for the organization and operation of manufacturing resources". (...) "Digital twin defines the use of performance metrics to support a manufacturing operation and provides a systems engineering-based approach that enables continuous improvement and strategic adaptability to change. The complexities of mass individualization in the dynamic production flows management are reduced, and the flexibility of WIP for individualized manufacturing demands is improved. Evidenced by a successful case study in board-type product manufacturing system, the proposed prototype can provide manufacturing system with an intelligent optimization engine" [136].	optimization; product design; decision-making support; maintenance
"The dynamic fusion process of digital twin data not only reflects the running conditions of physical elements and virtual models, but also keeps driving and affecting the iterative running processes of both physical production and virtual simulation respectively as well as the co-evolution between these two parts" [137].	maintenance; simulation performance; product design
"Based on the digital twin model, probabilistic roadmap method (PRM) is performed to generate a collision-free path and control the robot to accomplish the assembly mission". (...) "The experiment results show that the proposed method can quickly plan a collision-free assembly path, and then control the industrial robot to automatically, safely and efficiently complete large-scale components installation" [138].	simulation performance; safety and risk mitigation; reducing costs

Table A1. *Cont.*

Statements	Assigned Codes
"The production plan under the digital twin model is a dynamic model with stronger disturbance resistance. It not only makes the processes (i.e., coking, sintering, iron making, steel making, and steel rolling) and other processes more coordinated and orderly, but also makes energy, power, logistics, equipment maintenance and all kinds of raw materials more balanced. Through capacity requirement planning model and material requirement planning model, the requirements of equipment and material are determined, and the production is arranged according to the scheduling model, and the coordination of man, machines and materials is ensured in time" [139].	maintenance; reducing costs; decision-making support
"This digital twin will have high impact in terms of developing HRI techniques for example facilitating human-robot trust in high stakes scenarios such as emergency response. It will also allow testing of task planning algorithms for cooperative inspection and long-term autonomy, and humanguided supervision and control of the robotic assets from remotely located control stations" [140].	maintenance; safety and risk mitigation

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