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Sustainability Requirements of Digital Twin-Based Systems: A Meta Systematic Literature Review

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Abstract: Sustainable development was defined by the UN in 1987 as development that meets the needs of the present without compromising the ability of future generations to meet their own needs, and this is a core concept in this paper. This work acknowledges the three dimensions of sustainability, i.e., economic, social, and environmental, but its focus is on this last one. A digital twin (DT) is frequently described as a physical entity with a virtual counterpart, and the data, connections between the two, implying the existence of connectors and blocks for efficient and effective data communication. This paper provides a meta systematic literature review (SLR) (i.e., an SLR of SLRs) regarding the sustainability requirements of DT-based systems. Numerous papers on the subject of DT were also selected because they cited the analyzed SLRs and were considered relevant to the purposes of this research. From the selection and analysis of 29 papers, several limitations and challenges were identified: the perceived benefits of DTs are not clearly understood; DTs across the product life cycle or the DT life cycle are not sufficiently studied; it is not clear how DTs can contribute to reducing costs or supporting decision-making; technical implementation of DTs must be improved and better integrated in the context of the IoT; the level of fidelity of DTs is not entirely evaluated in terms of their parameters, accuracy, and level of abstraction; and the ownership of data stored within DTs should be better understood. Furthermore, from our research, it was not possible to find a paper discussing DTs only in regard to environmental sustainability.

Keywords: digital twins (DTs); Internet of Things (IoT); sustainability requirements; sustainable development; product design

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1. Introduction

A digital twin (DT) is often described as a digital or virtual entity with a physical counterpart, and with data connections between the two [1], implying the existence of connectors and blocks to allow efficient and effective data communication. A DT is a digital representation of some more complex physical system, and in spite of the fact there are distinct definitions of DT, this was the original, and the one we adopt [1]. Grieves and Vickers of NASA are considered the pioneers of this concept, presenting it in a lecture on product life-cycle management in 2003, as is acknowledged by Liu et al. [2]. They point out three components [2]: (i) a physical product, (ii) a virtual representation of that product, and (iii) the bi-directional data connections from the physical to the virtual representation, or vice versa. Among the main purposes of developing DTs are product design, modeling, simulation, and optimization of specific assets [3,4].

Today the usage of DTs is not yet generalized, but since 2015 there has been a clear increase of scientific studies toward a better understanding of their potentialities. Machine tools and consumer goods are common examples of DT usage. However, it is not in all cases that a DT has to be a high-fidelity digital model of a physical system or asset. For instance, a DT can also be used for representing a whole city (urban digital twin), geographic areas, buildings, or even human bodies and human organs. However, the focus of this paper is on DTs as they represent physical assets. Other reported usages of building DTs are for cybersecurity incident prediction [3], monitoring ergonomics in IoT contexts [5], online education [6], or optimization farming systems [7].

Product design is also a fundamental and related aspect of DTs and environmental sustainability because it is a discipline that deals with many complex decisions and cross-cutting concerns, such as safety, security, usability, or sustainability (including the choice of materials or the use of energy). Furthermore, product design may influence the planning of a production line, another frequent application of DTs [1,2,8]. This means that errors and failures can be predicted and managed with the help of DT approaches, using data analytics, artificial intelligence (AI), and machine-learning techniques.

Sustainable development is defined by the UN (1987), in the Brundtland Report ("Our Common Future") [9], as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This framework is very useful, as the concept of a circular economy (CE) [10], defined as an economic model to minimize the consumption of finite resources, is becoming more important and is closely related to the concept of the supply chain [11]. Industry 4.0 was introduced in 2011, and it has become synonymous with smart manufacturing/factory, corresponding to established concepts such as computer-integrated manufacturing, a flexible manufacturing system [10], CE, and all together, the management of a huge amount of data generated by DTs [12], allowing the integration of new tools such as those related to the Internet of Things (IoT).

Closely linked to product design optimization and CE is the concept of sustainable product design, defined by Massey [13] as the art of designing buildings, cities, and other artifacts so that they meet the objectives of sustainable development. Product design is not just art, it is also in the decision of what materials to use, choosing in such a way that a product is useful for society. A DT, as defined in this research, has a close connection with sustainable product design, but our focus will be on its IT characteristics and benefits.

This paper provides a meta systematic literature review (i.e., an SLR on SLRs) on the topic of the sustainability requirements of DT-based systems. In this context, sustainability requirements are defined as requirements that make sustainable development possible. Merten et al. [14] tried using the knowledge of generic requirements to assist automatically during requirement specification. Paech et al. [15] tried developing a systematic process for deriving the sustainability requirements for a specific system, i.e., a checklist of general and IT-specific details for each sustainability dimension (environmental, technical, social, economic, and individual), and the influences between them. Additionally, a new model and new concepts, such as needs and the effects between needs, whether negative, neutral, or positive, were created; this new mindset is used to develop a system respecting a due balance between different dimensions to achieve sustainability. In the context of IT, this means a controlled natural language [16] that helps the specification of requirements and tests systematically and rigorously [17,18], such as the ITLingo RSL language [19], does have a paramount role in defining software sustainability requirements [20] as it already supports risks, vulnerabilities and goals/solutions [21], for example. These tools belong to the spectrum of model-driven engineering, using textual specifications and conceptual models to improve the efficacy and efficiency of the analysis and design of these IT systems [22] and their usability [23].

To sum up, this paper is a meta-SRL plus an attempt to add new contributions to the environmental sustainability debate. Sustainable development implies a responsible consumption of resources today, and because DTs can allow optimization of the operations, they can be a tool for that purpose. When designers test a new product, they might use a DT to virtually test a new implementation without consuming raw materials and simulating the usage of environmentally friendly materials, also reducing working hours, and only produce it afterward if the simulation makes sense.

This paper is organized as follows: Section 2 introduces the SLR methodology followed; Section 3 presents the results of the meta-SLR; Section 4 presents a critical analysis to identify future work paths. Finally, Section 5 presents the main conclusions.

2. The Research Methodology

To develop this study, we considered the SLR methodology as proposed by Kitchenham et al. for software engineering [24], then we looked to the work by Escallón and Aldea because they presented a methodology that is valuable in the context of this research [25].

The method of SLR, as proposed by Kitchenham et al. [24], has three main stages: a phase for planning, to execute that plan, and to analyze the results. The execution phase has five tasks: (i) extract studies from databases, (ii) eliminate duplicates from the sample, (iii) apply inclusion and exclusion criteria, (iv) gather backward and forward citations, and (v) identify the final dataset of selected papers. If, at task iv, there are new papers found, then the researcher moves backward to task (ii) and repeats the process, from task (ii) to task (iv), as many times as are needed. Additionally, we included certain techniques described by Wolfswinkel et al., namely, the backward and forward citation steps of their selection phase [26]. If any work related to a research task is not present in the currently selected set of references, but it is considered relevant, it should be added to the selected ones. Since Google Scholar is a very popular tool and supports the backward and forward analysis of citations, this was the main tool adopted. The overall process is shown in Figure 1, inspired by the methodology used by Escallón and Aldea [25].

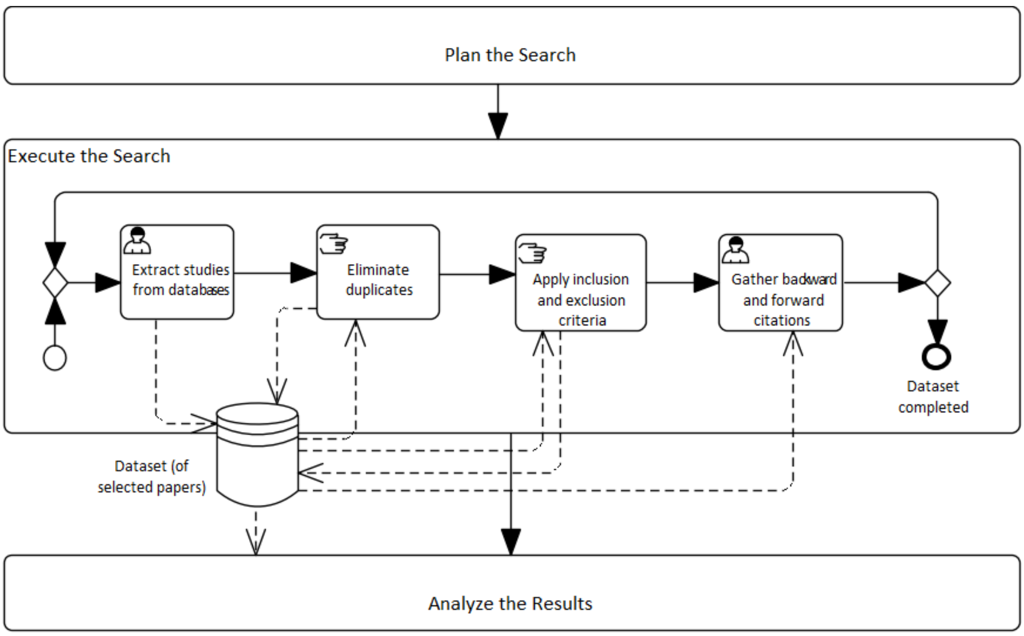

Figure 1. The overall process of SLR (in BPMN notation).

To allow for a more precise fine-tuning of our research, we also considered the work by Ahmad et al. [27]. They explicitly identified and categorized the different types of controlled or common vocabularies (CV) [27] available, and usage for the requirements specification of software development, which was an important output to us because we wished to focus on identifying sustainability requirements. A CV is an organized collection of terms that have well-known meanings, without the ambiguities or misunderstandings that synonyms could cause. Their purpose is to organize information in a structured manner with consistency, indicating semantic relationships, allowing the simple classification, querying, and retrieving of data [13,28–30]. Examples of the most frequent CVs are ontologies, taxonomies, thesauri, and folksonomies. Natural language processing and knowledge management techniques [31,32] often use CV support tools.

2.1. Planning Phase

The planning phase is the part where the design process is followed to perform the SLR according to the selected methodology. Firstly, the relationship between sustainability requirements and DTs-based systems is addressed, and then the relationship with product design is established. Section 2.1.1 defines the main questions that guided this research; Sections 2.1.2 and 2.1.3 refer to the scientific repositories and queries that were used in the search process, as well as the inclusion and exclusion criteria.

2.1.1. Research Question

We defined one research question (RQ1) with three sub-questions (SQ). These questions were used to address the main objectives of the research:

1. RQ1: What is the state of the art in the area of sustainability requirements of DT-based systems related to product design?
2. SQ1: What is the relationship between DTs and product design?
3. SQ2: What are the environmental sustainability requirements of DTs?
4. SQ3: What are the open issues and challenges in future research paths for DTs and sustainability?

The search process considers these questions and the technical definitions available in the existing literature and subsequent reading of the found works is also needed.

2.1.2. Search Process

The following were the databases or scientific repositories to search for relevant papers to answer the questions of this research. These databases were selected because they are very well known among the scientific community, and were also used in other SLR papers that we considered as models to follow in the IT domain:

1. ACM Digital Library (dl.acm.org (accessed on 4 June 2021))
2. Taylor & Francis (www.tandfonline.com (accessed on 4 June 2021))
3. Web of Science (www.webofknowledge.com (accessed on 4 June 2021))
4. ScienceDirect/Scopus (www.scopus.com (accessed on 4 June 2021))
5. IEEE Explore (ieeexplore.ieee.org/search/advanced (accessed on 4 June 2021))
6. Elsevier (www.elsevier.com (accessed on 4 June 2021))
7. Google Scholar (scholar.google.com (accessed on 4 June 2021))

These were the inclusion criteria: (i) articles published in the past 10 years; (ii) studies published in journals and conference proceedings or indexed books; (iii) studies written in English; (iv) articles referring to SLR that were selected in the first database searches. We also included high-quality studies, even when they were short or written in Portuguese. Conversely, these were the exclusion criteria: (i) very short papers (i.e., with fewer than 5 pages); and (ii) duplicated works, those unified by the database under various names.

2.1.3. Queries

In the first week of January 2021, we started from the query "systematic literature review" AND "digital twin" (all fields), and then tried other queries, considering not only the main aim of this paper but also the number of papers found, and the possibility of making the search deeper. The first step was to search for papers regarding a meta-SLR about DTs, and the second step was to search for sustainability requirements. The time period of the search was also considered, firstly the publication dates between 01/01/2011 and 31/12/2020, and secondly, the publication dates between 01/01/2019 and 31/12/2020. As a consequence, several additional queries were used:

- ACM: [All: "systematic literature review"] AND [All: "requirements"] AND [All: "digital twin*"] AND [Publication Date: (01/01/2019 TO 12/31/2020)];
- Elsevier: "digital twins" AND "systematic literature review" AND "product design" AND "requirement" AND "sustainability";

- IEEE: ((“Document Title”:”digital twin*”) AND (“All Metadata”:”systematic literature review”) AND (“All Metadata”:”design”)) and ((“Document Title”:”ontolo*”) AND (“All Metadata”:”systematic literature review”) AND (“All Metadata”:”design”));
- SCOPUS: TITLE-ABS-KEY (“systematic literature review” AND “digital twin*”) and TITLE-ABS-KEY (“systematic literature review” AND “ontolo*” AND “digital twin”);
- Web of Science: [All: “digital twin”] AND [All: “systematic literature review”] AND [All: “product design”] (Tailor); TITLE: (“systematic literature review” AND “digital twin*”) and TITLE: (“systematic literature review” AND “ontolo*”).

In different databases, we elicited distinct scientific outputs, and consequently, we had to use other queries. The search for the keyword “environmental sustainability” was fruitless.

2.2. Execution Phase

The execution phase is the step where both the results and the process to execute the SLR are explained. We followed the phases and criteria previously defined, and will now describe our experience during this process, followed by the useful information we were able to extract. The queries were presented in the already mentioned databases, and the results are presented in Table 1. After obtaining the results from these databases, we completed the following steps: first, eliminate all duplicates; second, based on the paper title, whether exclusion criteria apply; third, based on the title, select those articles where both inclusion criteria apply, and exclusion criteria do not apply; fourth, repeat the third step but read through the full text; fifth, for each remaining article, review the reference section and repeat steps 2 to 4; and sixth, for relevant references, for each remaining article, Google Scholar is used to review the forward citations and repeat steps 2 to 4.

Table 1. Search in Databases.

Database	First Search	With Google Scholar	Selected Papers	
			SLR	Non-SLR
ACM	6	15	3	7
ELSEVIER	19	10	1	2
IEEE Explore	13	34	1	4
SCOPUS	12	43	4	1
TAILOR	4	41	2	2
WEB SCIENCE	7	16	2	0
TOTAL	61	159	13	16

A first search (see column “First Search” in Table 1) allowed us to identify works related to SLR, and a second search identified citations using Google Scholar (see column “with Google Scholar”). It was also possible to identify relevant papers to analyze the context of DT usage even though they were not SLRs (see column “Non-SLR”). Finally, reading abstracts of the papers, it was possible to select 29 papers (column “Selected Papers”, with 13 SLR and 17 non-SLR papers). SLR papers are listed in Table 2, and non-SLR papers are listed in Table 3. The types of papers considered are C—Conference Paper; J—Journal Paper, T—Thesis, and B—Book.

Selected SLR papers are very recent: 2020 (10 papers); 2019 (2 papers) and 2018 (1 paper). The same holds true for selected non-SLR papers: 2020 (12 papers); 2019 (2 papers); 2016 (1 paper) and 2013 (1 paper). This situation is not surprising because the technologies and issues surveyed in this meta-SLR are very recent.

Table 2. Set of selected SLR papers.

ID	Reference	Title	Year	Type	Topics
S1	[1]	Characterising the Digital Twin: A systematic literature review	2020	J	DTs Definition
S2	[2]	Review of digital twin about concepts, technologies, and industrial applications	2020	J	DTs Definition
S3	[3]	Digital Twin for Cybersecurity Incident Prediction: A Multivocal Literature Review	2020	C	DTs Cybersecurity
S4	[4]	Reference Framework for Digital Twins within Cyber-Physical Systems	2019	C	DTs Cyber-Physical Systems
S5	[10]	Assessing relations between Circular Economy and Industry 4.0: a systematic literature review	2020	J	DTs, CE, I4.0
S6	[33]	Impact of Industry 4.0 on Sustainability—Bibliometric Literature Review	2020	J	DTs I4.0
S7	[34]	Industry 4.0 Model for circular economy and cleaner production	2020	J	DTs, CE I4.0
S8	[35]	Systematization of Digital Twins: Ontology and Conceptual Framework	2020	C	DTs Ontology
S9	[36]	A Review of the Literature on Smart Factory Implementation	2019	C	DTs, I4.0
S10	[37]	Digital Twins: Current problems in Smart City and Recommendations for future technology	2020	J	DTs Smart City
S11	[38]	Digital twin of stone sawing processes	2020	J	DTs, Example
S12	[39]	A Systematic Literature Review on the Application of Ontologies in Automatic Programming	2018	J	DTs Ontologies
S13	[40]	The Digital Twin Concept in Industry—A Review and Systematization	2020	J	DTs

Table 3. Set of selected non-SLR papers.

ID	Reference	Title	Year	Type	Topics
NS1	[8]	Enhancing Operational Performance and Productivity Benefits by Implementing Smart Manufacturing Technologies in Breweries	2019	J	I4.0
NS2	[41]	A review of industry 4.0 potential to accelerate the transition to a circular economy	2020	T	I4.0, CE
NS3	[42]	IoT-Based Digital Twin for Energy Cyber-Physical Systems: Design and Implementation	2020	J	DTs, Energy
NS4	[43]	A Framework for Quantifying Energy and Productivity Benefits of Smart Manufacturing Technologies	2019	C	I4.0, Energy
NS5	[44]	Data Resources to Create Digital Twins	2020	C	DTs, Data
NS6	[45]	On the Engineering of IoT-Intensive Digital Twin Software Systems	2020	C	DTs, IoT
NS7	[46]	Digital Twin Based Software Design in eHealth—A New Development Approach for Health/Medical Software Products	2020	C	DTs eHealth
NS8	[47]	A Taxonomy of Digital Twins	2020	C	DTs
NS9	[48]	Defining infrastructure requirements for the creation of Digital Twins	2020	T	DTs Requirements
NS10	[49]	Developing a Framework for Scoping Digital Twins in the Process Manufacturing Industry	2020	J	DTs Framework
NS11	[50]	A nova agenda da grande indústria: uma análise da indústria 4.0 com base em documentos e materiais de divulgação do projeto alemão plattform industrie 4.0	2020	T	I4.0
NS12	[51]	Modernização de Arquiteturas de Sistemas para suporte à Transformação Digital	2020	C	Systems
NS13	[52]	Toward to Operationalization of Socio-Technical Ontology Engineering Methodology	2020	J	Ontology
NS14	[53]	Applications of ontologies in requirements engineering: a systematic review of the literature	2016	J	Ontologies
NS15	[54]	Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case	2020	C	DTs, CE
NS16	[55]	Software requirements specification analysis using natural language processing technique	2013	J	Requirements

3. Literature Review and Results

This section presents the papers relevant to (i) the identification of DT sustainability requirements, and (ii) the identification of the relationship between DTs and product design. These two dimensions allowed the mapping of the answers we consider in this paper. Papers were sorted along the lines of these two dimensions being selected by the dominant work in each research.

3.1. Digital Twins and Sustainability Requirements

In our set of selected papers, there are 4 SLR papers and 4 non-SLR papers mainly related to DTs and sustainability.

Pokhrel, Katta, and Palacios [3] (S3) study the definition of DT and "state-of-the-art" on the development of DT, including reported work on the usability of a DT for cybersecurity using the SRL methodology. Regarding incident prediction, the cases of the reported use of DTs are: intrusion detection; anomaly detection; monitoring (remote and on-site); virtual commissioning; autonomy; predictive analytics; documentation; and communication. Security is a major dimension of sustainability; for example, if equipment is dangerous its daily usage is probably impossible; their paper is an example of relevant SLR application in the field.

Rosa et al. [10] (S5) assess the relationships between CE and I4.0 using the SLR methodology. They stress the hybrid categories like Circular I4.0 and Digital CE, but move forward to the identification of the main benefits of integrating CE and I4.0, such as production technologies, financial performance, market expansion, supply chain management, product life-cycle management, workforce empowerment, and business models.

Ejsmont, Gladysz, and Kluczek [33] (S6) use a bibliometric literature review to evaluate the impact of Industry 4.0 on sustainability. They find that authors who deal with CE usually also study sustainable supply chains; nevertheless, I4.0 concepts such as sustainability, big data, smart manufacturing, IoT, sustainable development, digital transformation, and industrial IoT are frequently addressed. Cyber-physical systems, sustainable manufacturing, the smart factory, and digitalization are also popular concepts. Possibly, the main conclusion of their paper is that the positive sustainability outcome of these technologies is not guaranteed, and so, success requires supportive measures and specific policies to ensure the competitiveness of local actors.

Rajput and Singh [34] (S7) present an Industry 4.0 model for CE and cleaner production. Their model is built with mixed-integer linear programming (MILP) to optimize product machine allocation, e.g., optimizing the trade-off between energy consumption and machine processing cost. In this model, sensors are also deployed to capture real-time information in the Industry 4.0 facility.

Iñigo [41] (NS2) stresses the complexity of the new I4.0 and the new tools associated with it, for example, 3D printing, to allow the optimization of manufacturing.

Because there is no production without energy (meaning electricity at the production factory level, non-renewable sources of energy still being the paramount contribution to electricity production), the next three papers (i.e., NS1, NS3, and NS4) look to the general requirement of the "responsible use of energy".

Nimbalkar et al. [8] (NS1) and Supekar et al. [43] (NS4) present a framework for quantifying the energy and productivity benefits of smart manufacturing technologies. Breweries are the example used to demonstrate this framework and the implementation of smart manufacturing technologies. To determine the feasibility of a set of smart manufacturing interventions, the framework uses the cost of conserving energy (CCE) as a complementary measure. The quantification and analysis of energy productivity is its focus, and a strategic analysis framework to estimate cost-effective improvements in energy efficiency and productivity, using smart manufacturing, has been developed.

Saad, Faddel, and Mohammed [42] (NS3) study the effective and efficient implementation and design of DTs for energy cyber-physical systems. With the emergence of distributed energy resources (DERs), with communication and control complexities, it is fundamental to guarantee an efficient platform that can digest all the incoming data and ensure the reliable operation of the power system. To build this support technology, two DT types are introduced: one to cover the high-bandwidth applications, and another to the low-bandwidth applications that need centric oversight decision-making. The validation and test of this approach were performed using Amazon Web Services (AWS) as a cloud host that incorporates physical and data models, and additionally can receive live measurements.

3.2. Digital Twins and Product Design

The following papers are important to establish a bridge between DTs and product design. These papers introduce and analyze aspects that should be considered in real scenarios when designing or building DTs. In our set of selected papers, there are 9 SLR papers and 12 non-SLR papers mainly related to DTs and product design:

Jones et al. [1] (S1) try to characterize the DT concept using an SLR. The authors acknowledge that there are a variety of definitions employed across industry and academia. They identified 13 characteristics of DTs to clarify the definition, namely: physical entity/twin; virtual entity/twin; physical environment; virtual environment; state; realization; metrology; twinning; twinning rate; physical-to-virtual connection/twinning; virtual-to-physical connection/twinning; physical processes; and virtual processes and a complete framework and operation process of the DT.

Liu et al. [2] (S2) provide a literature review on DTs based on concepts, technologies, and industrial applications. They evaluate the current state of the art, discuss the concept of the DT, and analyze certain key enabling technologies of DTs. Additionally, they discuss fifteen industrial applications with their respective life cycles, and also present valuable observations and future work recommendations for DT research.

Josifovska, Yigitbas, and Engels [4] (S4) develop a reference framework for DTs within cyber-physical systems (CPSs). The authors define CPSs as system representations that integrate physical units and processes with computational entities over the internet, allowing ubiquitous access to information and services. The framework establishes a relationship between the 5-level CPS architecture and the DT framework, to answer open questions and challenges on how to design and realize CPSs.

Barth et al. [35] (S8) systematize DTs, creating an ontological and conceptual framework. Furthermore, these authors try to answer three research questions: (i) Which dimensions are used to classify and structure DTs in academic literature? (ii) What are the fundamental differences or specifications within these dimensions? and (iii) How do these different specifications relate to each other?

Rub and Bahemia [36] (S9) try to understand the current reality of smart factory implementation using an SLR. They identify a research gap related to the make-or-buy decision around DTs and other core components of the smart factory. This is significant because it is assumed that the smart factory leads to the creation of value, but that creation depends upon the way the factory is implemented—whether the implementation project is executed in-house or using an external supplier.

Dave et al. [37] (S10) discuss the new possible reality of smart cities where concepts such as IoT, big data, AI, robotics, and DTs are paramount, and stress the role of the latter. Smart cities, manufacturing, and healthcare are considered the main fields of application for DTs. An example of the application of DT is their usage in traffic management systems, using traffic cameras that are merely recording, but their recordings can be used to create traffic management models to reduce traffic congestion; they certainly provide more data to export and update a road network with real-time decisions. The authors conclude that there is a need for demonstration sites to test the new technologies with real data, and a need for extensive professional panels of experts in diverse research fields, for example, urban development, IT, transportation, and environmental policies.Polini and Corrado [38] (S11) present an example of DT for the stone-sawing process. The authors describe the DT, but have concerns regarding the accuracy of the equipment and its efficiency and efficacy.

Strmecki et al. [39] (S12) use an SLR to study the possible application of ontologies in automatic programming. Ontologies, which are typically considered as a technique or an artifact used in one or more software life-cycle phases, may be used to help achieve the goal of finding higher abstraction levels, and ways to reuse software to increase its productivity and quality, within the discipline of software engineering.

Sjarov et al. [40] (S3) study the DT concept in the industry in a systematic way. The authors acknowledge a significant growth in the number of scientific studies since 2015 (industry-related publications per year carrying "Digital Twin" in their title). Studies show a variety of applications of DTs ranging from products and processes to whole production systems. Explicit definitions were found to be partly conflicting, and similar notions like "Product Avatar" and "Digital Shadow" are also identified. Their paper extends the theoretical foundation, setting a basis for future, improved DT modeling.

Schweiger, Barth, and Meierhofer [44] (NS5) focus their work on the data resources needed to create DTs. DTs are considered one of the key technologies for organizations moving from producing goods to offering services. The main hypothesis is that a large part of the new data produced, or resources, are already generated during the beginning of life (BOL) phase of the product life cycle, but are not used in the middle of life (MOL) phase. The new framework allows a better understanding of how to use data resources from BOL phases in MOL phases, and permits the creation of an ontology of product data, making the creation and maintenance of DTs easier.

Rivera et al. [45] (NS6) look closely at the engineering of IoT-intensive DT software systems. The authors assume the real DT to be a product that is equipped with several sensors or computing devices that generate, consume, and transfer data for different purposes. Due to this reality, they consider DTs, to a large extent, IoT-intensive systems.

Lutze [46] (NS7) studies the DT-based software design in eHealth as a new development approach for health/medical software products. The author's DT concept builds on (i) a personal digital twin as a Gemini of the patient, (ii) a group digital twin modeling the designated user group of the software, and (iii) a system digital twin for the software product itself. Agile development techniques in comparison to the V-model-based classic software development are considered as offering better support possibilities.

Valk et al. [47] (NS8) present a taxonomy of DTs using an SLR. To accomplish this task several dimensions of DTs are pointed out: data link, purpose, conceptual elements, accuracy, interface, synchronization, data input, and creation time.

Jay [48] (NS9) identifies the infrastructure requirements for the creation of DTs. In addition, the author assumes that after 2015, simulation is a core functionality of systems using seamless assistance along their entire life cycle, i.e., supporting operation and service with a direct link to operation data.

Perno and Hvam [49] (NS10) investigate the processes of the manufacturing industry and develop a framework for scoping DTs in that context. Due to the novelty of the concept and the broad range of technologies upon which it is built, the process of scoping Digital Twin projects can prove to be daunting for process-manufacturing companies.

Arias [50] (NS11) entitles the new project "Plattform Industrie 4.0", and, after briefly describing its technologies, considers its implications.

Leon and Horita [51] (NS12) try to overcome two challenges: (i) how to decentralize existing legacy systems to provide a technology solution that meets the new needs of users in this more digital society; and (ii) how to create a systems architecture that addresses the characteristics inherent in digital transformation.

Sensuse et al. [52] (NS13) use SLR to identify qualitative research in ontology engineering. The main purpose of these authors is an operationalization of socio-technical ontology engineering methodology. This methodology consists of five main phases, namely: (i) planning, (ii) analysis, (iii) design, (iv) implementation, and (v) evaluation.

Dermeval [53] (NS14) uses SLR to identify the applications of ontologies in RE (requirements engineering). The main findings of this research are that: (i) there is empirical evidence of the benefits of using ontologies in RE activities, especially for reducing ambiguity, inconsistency, and the incompleteness of requirements; (ii) the RE process is usually only partially addressed, for example, only considering functional requirements; (iii) ontologies support a great diversity of RE modeling styles; (iv) several studies describe the use/development of tools to support different types of ontology-driven RE approaches; (v) about half of the studies followed W3C recommendations on ontology-related languages; (vi) a great variety of RE ontologies were identified; nevertheless, none of them has been broadly adopted; and (vii) several promising research opportunities were identified. Other authors also have some valuable inputs to this discussion [3,13,37].

Rocca et al. [54] (NS15) try to put into the same basket VR, DTs and CE practices, and present a laboratory application case: virtually testing waste from electrical and electronic equipment (WEEE) disassembly plant configuration, using a set of dedicated simulation tools. The authors stress the importance of their work due to the increasing awareness of customers toward climate change effects, the high demand instability affecting several industrial sectors, and the fast automation and digitalization of production systems.

Fatwanto [55] (NS16) proposes a software requirements specification analysis using natural-language processing techniques. The author tries to improve the software product production process.

4. Discussion

The study of DTs is recent, mainly after 2015 [33,40], and there is an unclear definition of DT. However, regardless of the growing complexity of their applications, it is agreed that there are several benefits to using DTs, such as optimization of Industry 4.0, and the sustainability of the product design process. In addition, the lack of studies with technical details can be a difficulty when adopting this technology. A closer look into possible environmental sustainability benefits and at the product design level can help a clear understanding of this reality.

The analysis of the available literature allows us to identify several aspects of the relationship between DTs, product design and sustainability, and hence, to answer the original research question, we preliminary discuss the involved sub-questions (SQi):

SQ1: What is the relationship between DTs and product design?

Concerning SQ1, from the set of selected papers we verify that there are primarily two relationships between DTs and product design: (i) DTs are digital models of physical products fed with real-time data, having an important role in understanding real behaviors and needed adaptations, and (ii) tests using DTs are less expensive and easier than building new physical prototypes.

SQ2: What are the environmental sustainability requirements of DTs?

Concerning SQ2, and based on the selected literature, the main environmental classes of sustainability requirements are: (i) control of energy consumption and (ii) use of environmentally friendly materials. When CE at the I4.0 level is considered, there is a clear need for a tradeoff between complexity and energy consumption versus the results of the new technology implementation. Possibly, making DT tests and creating less complex products is a main topic of research.

SQ3: What are the open issues and challenges in future research paths for DTs and sustainability?

Concerning SQ3, at a first look and as already mentioned, the complexity reduction to build and set up DTs is only one future research path. The impact of complexity and energy consumption is paramount when the decision to introduce DTs at the factory level is considered. This has an overall impact on sustainability in its dimensions of security, environmental and financial sustainability. The discussed meta-SLR allowed us to identify several possible open issues and challenges for research.

First, methods and processes to design and implement DTs are needed. Since there are several specific application domains with their characteristics, this should be considered. Although there are detailed descriptions of DTs [38,56], it is unclear how to realize them, especially if there is no previous experience on how to do it.

Second, SLR studies point out gaps such as: (i) perceived benefits have not been identified; (ii) DT across the product life cycle or the DT life cycle is not sufficiently studied (whole life cycle, evolving digital profile, historical data); (iii) DTs have not been created, thus, it is not clear how DTs contribute to reducing cost or improving service or supporting decision making; (iv) technical implementations must be improved and detailed in the context of IoT; (v) the level of fidelity is not evaluated in terms of the number of parameters, their accuracy and levels of abstraction; (vi) data ownership of data stored within the DT must be determined; and (vii) integration between virtual entities must be improved, because better methods are needed for communication [1]. As already mentioned, DTs are a recent technology, and this fact partially explains these gaps or diversified future research paths.

At the same time, there is an attempt to clearly define the DT concept, for example, to classify existing standards such as the "Plattform Industry 4.0", which describes a standardized DT in I4.0 [47]. If there are several approaches and contexts to define DTs, how can we identify the most important gaps in the study of sustainability in DT usage? We start with the assumption that a DT consists of three parts: (i) a physical product, (ii) a virtual product, and (iii) connections and data flowing between them [47]. Then, we assume that at the technical implementation and at a particular level of fidelity, it is possible to identify its main contributions to sustainability.

RQ1: What is the state of the art in the area of sustainability requirements of DT-based systems related to product design?

Finally and trying to answer our original research question RQ1, we must address it carefully. Despite the existing gaps, the literature identifies several sustainability requirements for DT-based systems related to product design, namely: (i) fidelity; (ii) energy control; (iii) complexity control; (iv) identification of environmentally friendly and cost-efficient materials, and (v) easy reproduction of new product designs. Different studies investigate distinct sustainability requirements, and there is no integrated approach to understanding how DTs can create environmental sustainability. An integrated approach would imply additional complexity, for example, a fully rigorous fidelity implies additional time and further energy consumption, and this output might create a tradeoff, leading to fuzzy fidelity. This fuzzy fidelity means that environmental costs continue to be external to the production because their evaluation would also imply further work and costs. Easy reproduction of new product designs might imply a reduction of costs at the production stage, but the costs of the first steps of DT implementation might explain why this requirement is such a demanding one.

5. Conclusions

In this work, it has been possible to identify relevant research work regarding the study of DT-based systems and technologies, using the SLR methodology as the main tool for a meta-analysis on the subject of SLR. Special attention was put on the choice of vocabulary used to perform the research in several databases. Based on that analysis, it was possible to answer the RQ1 as well as the sub-questions SQ1, SQ2, and SQ3.

There are five main concerns to address in the development of a sustainable DT: (i) fidelity; (ii) energy control; (iii) complexity control; (iv) identification of environmentally and cost-efficient materials; and (v) easy reproduction of new product designs. It is also possible to identify areas of research related to DTs, namely: (i) the study of its concept and definition [1,4,35,36,40,47]; (ii) the presentation of examples [38,56]; and (iii) the use of SLR to understand the current research and to identify future research paths [2,10,33,37].

This analysis allows us to identify two main gaps that correspond to two future research paths. The first gap is the absence of a detailed paper explaining exactly what a DT is, with an extensive and rich example that stresses even the hardware characteristics, and how the connections between the physical and digital dimensions can be designed, developed, and maintained. This reality might be explained by the unwillingness of the industry to disclose sensitive information, this gap to be fulfilled by the academy.

Secondly, we identify papers that present sustainability in DT applications, and, additionally, we identify studies that distinguish between several types of sustainability, including environmental sustainability. Furthermore, we identify papers where the connection between CE and the usage of DTs, in the context of Industry 4.0, is clearly stated. However, it was not possible to find a paper that only discusses an SLR of DTs regarding environmental sustainability. Is this merely a vocabulary issue, CE being equal to environmental sustainability? We believe the answer is no, because CE, at the factory level, is still a concept at the laboratory stage, and the complexity implied by its implementation might be paramount. In other words, for the question of whether CE is environmentally sustainable if the management and technical complexity to achieve it is so noteworthy, to evaluate this hypothesis, a future research path might be the study of a scenario where a zero environmental impact product as a control is the design objective, with the help of a DT.

In summary, this paper presents a meta-SLR on DT-based systems that allow us to identify and discuss the main classes of requirements to consider in the development of a sustainable DT, but also allow us to identify gaps and limitations in both research and practice aspects.

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Abbreviations

Concept	Acronym
Artificial Intelligence	AI
Circular Economy	CE
Controlled Vocabularies	CV
Digital Twins	DT
Flexible Manufacturing System	FMS
Industry 4.0	I4.0
Information Technology	IT
Internet of Things	IoT
Requirements Engineering	RE
Research Question	RQ
Sub-questions	SQ
Systematic Literature Review	SLR

References

1. Jones, D.; Snider, C.; Nassehi, A.; Yon, J.; Hicks, B. Characterising the Digital Twin: A systematic literature review. *CIRP J. Manuf. Sci. Technol.* **2020**, *29*, 36–52. [CrossRef]
2. Liu, M.; Fang, S.; Donga, H.; Xu, C. Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **2020**, 346–361. [CrossRef]
3. Pokhrel, A.; Katta, V.; Colomo-Palacios, R. Digital Twin for Cybersecurity Incident Prediction: A Multivocal Literature Review. In Proceedings of the 2020 IEEE/ACM 42nd International Conference on Software Engineering Workshops (ICSEW), Seoul, Korea, 27 June–19 July 2020; pp. 671–678.

4. Josifovska, K.; Yigitbas, E.; Engels, G. Reference Framework for Digital Twins within Cyber-Physical Systems. In Proceedings of the IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS), Montreal, QC, Canada, 28 May 2019; pp. 25–31.
5. Minerva, G.; Lee, M.; Crespi, N. Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models. *Proc. IEEE* **2020**, *108*, 1785–1824. [CrossRef]
6. Sepasgozar, S. Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering. *Appl. Sci.* **2020**, *10*, 4678. [CrossRef]
7. Verdouw, C.; Tekinerdogan, B.; Beulens, A.; Wolfert, S. Digital twins in farming systems. *Agric. Syst.* **2021**, *189*, 103046. [CrossRef]
8. Nimbalkar, S.; Supekar, S.; Meadows, W.; Wenning, T.; Guo, W.; Cresko, J. *Enhancing Operational Performance and Productivity Benefits by Implementing Smart Manufacturing Technologies in Breweries*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2019; pp. 93–107.
9. UN. Our Common Future. The Brundtland Report, Oslo. 1987. Available online: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf (accessed on 2 January 2021).
10. Rosa, P.; Sassanelli, C.; Urbinati, A.; Chiaroni, D.; Terzi, S. Assessing relations between Circular Economy and Industry 4.0: A systematic literature review. *Int. J. Prod. Res.* **2020**, *58*, 1662–1687. [CrossRef]
11. Samadi, E.; Kassou, I. The Relationship between IT and Supply Chain Performance: A Systematic Review and Future Research. *Am. J. Ind. Bus. Manag.* **2007**, *6*, 480–495. [CrossRef]
12. Gereco, A.; Caterino, M.; Fera, M.; Gerbino, S. Digital Twin for Monitoring Ergonomics during Manufacturing Production. *Appl. Sci.* **2020**, *10*, 7758. [CrossRef]
13. Massey, J. The Sumptuary Ecology of Buckminster Fuller's Designs. In *A Keener Perception, Ecocritical Studies in American Art History*; University Alabama Press: Tuscaloosa, AL, USA, 2009; pp. 189–212.
14. Merten, T.; Schäfer, T.; Bürsner, S. Using RE knowledge to assist automatically during requirement specification. In Proceedings of the 2012 Seventh IEEE International Workshop on Requirements Engineering Education and Training (REET), Chicago, IL, USA, 24 September 2012; pp. 9–13.
15. Paech, B.; Moreira, A.; Araujo, J.; Kaiser, P. Towards a Systematic Process for the Elicitation of Sustainability Requirement. In Proceedings of the CEUR Workshop Proceedings, 8th International Workshop on Requirements Engineering for Sustainable Systems, RE4SuSy 2019, Jeju, Korea, 24 September 2019.
16. Maciel, D.; Paiva, A.; Rodrigues da Silva, A. From Requirements to Automated Acceptance Tests of Interactive Apps: An Integrated Model-based Testing Approach. In Proceedings of the ENASE'2019, SCITEPRESS, Heraklion, Crete, Greece, 3–5 May 2019.
17. Paiva, A.; Maciel, D.; Silva, A. From Requirements to Automated Acceptance Tests with the RSL Language. In *Evaluation of Novel Approaches to Software Engineering (ENASE 2019)*; Communications in Computer and Information Science; Springer: Cham, Switzerland, 2020; Volume 1172.
18. Caramujo, J.; Silva, A.; Monfared, S.; Ribeiro, A.; Calado, P.; Breaux, T. RSL-IL4Privacy: A Domain-Specific Language for the Specification of Privacy-Aware Requirements. In *Requirements Engineering*; Springer: Cham, Switzerland, 2019; Volume 24. [CrossRef]
19. Silva, A. Rigorous Specification of Use Cases with the RSL Language. In Proceedings of the International Conference on Information Systems Development'2019, AIS, Toulon, France, 28–30 August 2019.
20. Carvalho, R.; Silva, A. Discussion Towards a Library of Software Sustainability Requirements. In Proceedings of the 9th International Workshop on Requirements Engineering for Sustainable Systems (RE4SuSy) at RE'2020, Online, 20–21 September 2020.
21. Gonçalves, L.; Silva, A. Towards a Catalogue of Reusable Security Requirements, Risks and Vulnerabilities. In Proceedings of the International Conference on Information Systems Development'2018, AIS, Lund University, Sweden, 22–24 August 2018.
22. Silva, A. Model-Driven Engineering: A Survey Supported by a Unified Conceptual Model. In *Computer Languages, Systems and Structures, 43(C)*; Elsevier: New York, NY, USA, 2015; pp. 139–155. [CrossRef]
23. Silva, A.; Sequeira, C. Towards a Library of Usability Requirements. In Proceedings of the ACM SAC'2020 Conference, ACM, Brno Czech Republic, 30 March–3 April 2020.
24. Kitchenham, B.; Brereton, P.; Budgen, D.; Turner, M.; Bailey, J.; Linkman, S. Systematic literature reviews in software engineering—A systematic literature review. *Inf. Softw. Technol.* **2009**, *51*, 7–15. [CrossRef]
25. Escallón, R.; Aldea, A. On Enterprise Architecture Patterns: A Systematic Literature Review. In Proceedings of the 22nd International Conference on Enterprise Information Systems (ICEIS 2020), Online, 5–7 May 2020; pp. 666–678.
26. Wolfswinkel, J.; Furtmueller, E.; Wilderom, C. Using Grounded Theory as a Method for Rigorously Reviewing Literature. *Eur. J. Inf. Syst.* **2013**, *22*, 45–55. [CrossRef]
27. Ahmad, A.; Justo, J.; Feng, C.; Khan, A. The Impact of Controlled Vocabularies on Requirements Engineering Activities: A Systematic Mapping Study. *Appl. Sci.* **2020**, *10*, 7749. [CrossRef]
28. Leise, F. Controlled vocabularies: An introduction. *Indexer* **2008**, *26*, 121–126. [CrossRef]
29. Silva, A.; Savić, D. Linguistic Patterns and Linguistic Styles for Requirements Specification: Focus on Data Entities. *Appl. Sci.* **2021**, *11*, 4119. [CrossRef]

30. Polpinij, J.; Ghose, A. An automatic elaborate requirement specification by using hierarchical text classification. In Proceedings of the 2008 International Conference on Computer Science and Software Engineering, Hubei, China, 12–14 December 2008; pp. 706–709.
31. Pizard, S.; Vallespir, D. Towards a controlled vocabulary on software engineering education. *Eur. J. Eng. Educ.* **2017**, *42*, 927–943. [CrossRef]
32. NISO. ANSI/NISO Z39.19-2005 (2010): Guidelines for the Construction, Format, and Management of Monolingual Controlled Vocabularies, NISO. Available online: https://www.niso.org/publications/ansiniso-z3919-2005-r2010 (accessed on 30 July 2019).
33. Ejsmont, K.; Gladysz, B.; Kluczek, A. Impact of Industry 4.0 on Sustainability—Bibliometric Literature Re-view. *Sustainability* **2020**, *12*, 5650. [CrossRef]
34. Iñigo, I. A Review of Industry 4.0 Potential to Accelerate to Accelerate the Transition to a Circular Economy. Master's Thesis, Industrial Engineering, Universidad de Pais Vasco, Escuela de Ingeniería de Bilbao, Bilbao, Spain, 2020; pp. 1–122.
35. Saad, A.; Faddel, S.; Mohammed, O. IoT-Based Digital Twin for Energy Cyber-Physical Systems: Design and Implementation. *Energies* **2020**, *13*, 4762. [CrossRef]
36. Rajput, S.; Singh, S. Industry 4.0 Model for circular economy and cleaner production. *J. Clean. Prod.* **2020**, *277*, 123853. [CrossRef]
37. Supekar, S.; Graziano, D.; Riddle, M.; Nimbalkar, S.; Das, S.; Shehabi, A.; Cresko, A. A Framework for Quantifying Energy and Productivity Benefits of Smart Manufacturing Technologies. In Proceedings of the 26th CIRP Life Cycle Engineering (LCE) Conference, Purdue University, West Lafayette, IN, USA, 7–9 May 2019; pp. 699–704.
38. Barth, L.; Ehrat, M.; Fuchs, R.; Haarmann, J. Systematization of Digital Twins: Ontology and Conceptual Framework. In Proceedings of the ICISS 2020, Cambridge, UK, 19–22 March 2020; pp. 13–23.
39. Schweiger, L.; Barth, L.; Meierhofer, J. Data Resources to Create Digital Twins. In Proceedings of the 2020 7th Swiss Conference on Data Science (SDS), KKL Luzern, Switzerland, 26 June 2020; pp. 55–56.
40. Rivera, L.; Müller, H.; Villegas, N.; Tamura, G.; Jiménez, M. On the Engineering of IoT-Intensive Digital Twin Software Systems. In Proceedings of the 2020 IEEE/ACM 42nd International Conference on Software Engineering Workshops (ICSEW), Seoul, Korea, 27 June–19 July 2020; pp. 631–638.
41. Lutze, R. Digital Twin Based Software Design in eHealth—A New Development Approach for Health/Medical Software Products. In Proceedings of the 2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Cardiff, UK, 15–17 June 2020; pp. 1–9.
42. Valk, H.; Haße, H.; Möller, F.; Arbter, M.; Henning, J.; Otto, B. A Taxonomy of Digital Twins. In Proceedings of the Americas Conference on Information Systems, Online, 10–14 August 2020; pp. 1–10.
43. Jay, M. Defining Infrastructure Requirements for the Creation of Digital Twins. Master's Thesis, School of Innovation, Design and Engineering, RISE Research Institutes of Sweden, Malarden University Sweden, Västerås, Sweden, 2020; pp. 1–47.
44. Perno, M.; Hvam, L. Developing a Framework for Scoping Digital Twins in the Process Manufacturing Industry. 2020, pp. 1–12. Available online: Media.sps2020.se (accessed on 2 January 2021).
45. Rüb, J.; Bahemia, H. A Review of the Literature on Smart Factory Implementation. In Proceedings of the 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Valbonne Sophia-Antipolis, France, 17–19 June 2019; pp. 1–9.
46. Arias, A. A Nova Agenda da Grande Indústria: Uma Análise da Indústria 4.0 com Base em Documentos e Materiais de Divulgação do Projeto Alemão Plattform Industrie 4.0. Ph.D. Thesis, Universidade Tecnológica Federal do Paraná Programa de Pós-Graduação em Tecnologia e Sociedade, Curitiba, Brazil, 2020; pp. 1–163.
47. Leon, P.; Horita, F. Modernização de Arquiteturas de Sistemas para suporte à Transformação Digital. In Proceedings of the Anais Estendidos do XVI Simpósio Brasileiro de Sistemas de Informação, SBC, Online, 3–6 November 2020; pp. 61–66.
48. Sensusea, D.; Sucahyoa, Y.; Silalahia, M.; Wulandaria, I.; Akmaliaha, F.; Noprisson, H. Toward to Opera-tionalization of Socio-Technical Ontology Engineering Methodology. In Proceedings of the 2017 5th International Conference on Cyber and IT Service Management (CITSM), Denpasar, Indonesia, 8–10 August 2020; pp. 1–7.
49. Dermeval, D.; Vilela, J.; Bittencourt, I.; Castro, J.; Isotani, S.; Brito, P.; Silva, A. Applications of ontologies in re-quirements engineering: A systematic review of the literature. *Requir. Eng.* **2016**, *21*, 405–437. [CrossRef]
50. Dave, R.; Dave, S.; Thakkar, H. Digital Twins: Current problems in Smart City and Recommendations for future technology. *Int. Res. J. Eng. Technol. (IRJET)* **2020**, *7*, 1–11.
51. Polini, W.; Corrado, A. Digital twin of stone sawing processes. *Int. J. Adv. Manuf. Technol.* **2020**, *112*, 121–131. [CrossRef]
52. Strmečki, D.; Magdalenić, I.; Radosević, D. A Systematic Literature Review on the Application of Ontologies in Automatic Programming. *Int. J. Softw. Eng. Knowl. Eng.* **2018**, *28*, 559–591. [CrossRef]
53. Rocca, R.; Rosa, P.; Sassanelli, C.; Fumagalli, L.; Terzi, S. Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case. *Sustainability* **2019**, *12*, 2286. [CrossRef]
54. Sjarov, M.; Lechler, T.; Fuchs, J.; Brossog, M.; Selmaier, A.; Faltus, F.; Donhauser, T.; Franke, J. The Digital Twin Concept in Industry—A Review and Systematization. *IEEE Explor.* **2020**, *1*, 1789–1796.
55. Fatwanto, A. Software requirements specification analysis using natural language processing technique. In Proceedings of the 2013 International Conference on QiR, Yogyakarta, Indonesia, 25–28 June 2013; pp. 105–110.
56. Pang, T.; Restrepo, J.; Cheng, C.-T.; Yasin, A.; Lim, H.; Miletic, M. Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0' Shipyard. *Appl. Sci.* **2021**, *11*, 1097. [CrossRef]