Review

A Literature Review on the Development and Creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems

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Abstract: Digital Twins offer vast potential, yet many companies, particularly small and medium-sized enterprises, hesitate to implement them. This hesitation stems partly from the challenges posed by the interdisciplinary nature of creating Digital Twins. To address these challenges, this paper explores systematic approaches for the development and creation of Digital Twins, drawing on relevant methods and approaches presented in the literature. Conducting a systematic literature review, we delve into the development of Digital Twins while also considering analogous concepts, such as Cyber-Physical Systems and Product-Service Systems. The compiled literature is categorised into three main sections: holistic approaches, architecture, and models. Each category encompasses various subcategories, all of which are detailed in this paper. Through this comprehensive review, we discuss the findings and identify research gaps, shedding light on the current state of knowledge in the field of Digital Twin development. This paper aims to provide valuable insights for practitioners and researchers alike, guiding them in navigating the complexities associated with the implementation of Digital Twins.

Keywords: Digital Twin; Cyber-Physical System; development; review; methods

1. Introduction

Digital Twins have received a steadily growing degree of attention in recent years, both from industry and academia. One possible reason for this is a multitude of promising potentials and practical fields of application, such as real-time condition monitoring and the associated predictive maintenance, performance and usage analysis, or collection of information for product development. Extensive knowledge of the system is essential in order to calculate the remaining useful lifetime [1]. In addition to monetisation with existing business models, this concept can also be used to open up new digital business fields, such as pay per stress.

The creation of Digital Twins is a complex interdisciplinary project that requires know-how and experience as well as human and financial resources. For this reason, despite the promising potential, many companies, especially small and medium-sized enterprises (SME), have reservations about introducing Digital Twins. To mitigate this problem, systematic procedures in the form of guidelines and methods can be used to create Digital Twins. There are already a number of publications in the literature that systematically support the creation of Digital Twins. In addition, findings from the related fields of Cyber-Physical Systems and Product-Service Systems can be used to support the creation of Digital Twins.

At the moment, this literature is only available in an unsystematic form and with uneven granularity. This makes an identification or even connection of suitable publications

for the specific application difficult. For this reason, this contribution conducts a systematic literature review on the topic of developing and creating Digital Twins (DT), Cyber-Physical Systems (CPS), and Product-Service Systems (PSS). The results are then structured and compared. Although the three different systems—Digital Twins, Cyber-Physical Systems, and Product-Service Systems—are examined, the focus of this paper lies in the technical implementation of Digital Twins.

The goal of this paper is answering the following research questions:

- RQ1: How is the creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems considered in the literature and what research directions exist?
- RQ2: In what areas is further research needed to support direct utilisation for the creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems?

2. Materials and Methods

This section first introduces the fundamentals of Digital Twins. The concepts of Cyber-Physical Systems and Product-Service Systems are described as well. This is followed by a brief presentation of existing literature on the topic of creating Digital Twins, Cyber-Physical Systems, and Product-Service Systems. Finally, the study design for the research of this contribution is described.

### 2.1. Fundamentals and Definitions of Digital Twins

If a mechanical system is extended by electric or electronic components, and thus the range of functions is extended, it is called a mechatronic system. These components can be sensors, actuators, and microcontrollers and enable the system to be controlled on the basis of loops [2–4].

Mechatronic systems are the foundation for Cyber-Physical Systems (CPS). In this context, mechatronic systems are further developed by integrating embedded communication units that enable the system to connect or communicate with other systems and the Internet of Things and interact with its environment. For example, the behaviour of the system can be changed in response to the communication and interaction [2,4].

The communication capability of CPS is a necessary premise of the Digital Twin concept. The Digital Twin concept follows a more model-based approach. A Digital Twin is a digital representation of a product instance [4,5]. The product instance can be a physical product or a service and is then referred to as a physical twin. The Digital Twin is able to model the behaviour of the physical twin and thus enables conclusions and predictions through calculations and simulations. For this purpose, there is a bidirectional connection between the physical and Digital Twin for the exchange of information. Operational data from the physical twin is transferred to the Digital Twin, where it feeds the models. Operating data can be recorded using classic sensors which are integrated into the system or the environment. Alternatively, sensor-integrated machine elements [6,7], sensor-integrated design elements [8], or soft sensors [9] are also suitable for acquiring operating data. Sensors can either be taken into account during the development of the physical twins or retrofitted [10]. The results of the calculations and simulations are fed back into the physical space or directly to the Digital Twin. The fields of application for Digital Twins are very diverse. Some examples are predictive maintenance in manufacturing and stress identification in the context of agriculture, smart cities, supply chain optimisation, or healthcare diagnoses in humans [11].

Figure 1 demonstrates the Digital Twin concept using the example of a two-stage industrial gearbox. The physical twin is located in the physical space. Data are collected with sensors in or on the gearbox or in its environment. The data are then transferred from the physical space to the data space, where they feed behaviour-describing models of the gearbox. These can be, for example, RUL calculations of individual components. Here, the Wöhler curves of the components, such as bearings (L) and gears (G), can be used. The results are then transferred from the data space back to the physical space. There, they can be used to display results or recommendations for action. If the data flow does not end

on the physical space but instead flows directly into the physical twin, its operation can be adapted.
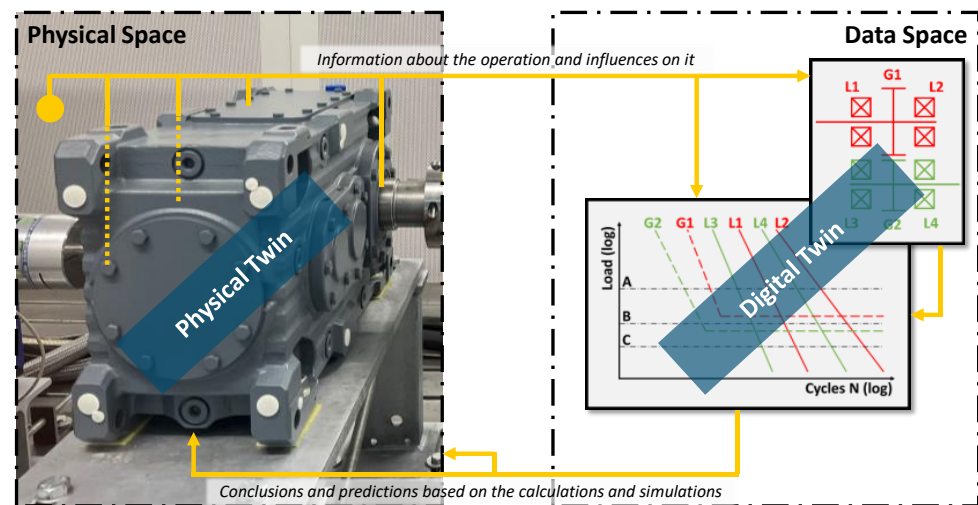
Figure 1. Schematic representation of the Digital Twin concept.

The ability to observe the physical twin and make conclusions and predictions about its behaviour opens up a range of new possibilities, such as predictive maintenance, performance analysis, adjustment of operating modes, or prevention of misuse. In this way, not only the product itself can be offered to a potential customer, but also further services. In this context, the term Product-Service System (PSS) is used. In addition to the product and the services, a PSS also requires a network of stakeholders and supporting infrastructure [12–14].

2.2. Existing Literature Reviews

There are several review and survey articles that analyse and categorise procedures for the development of DT, CPS, and PSS. These were identified and analysed as part of an initial literature search and are listed in Table 1. Most reviews are dedicated to the development of CPS. While Horvath et al. [15] provided a more general overview of the state-of-the-art, Korotunuv et al. [16], Liu et al. [17], and Quadri et al. [18] focused on modelling and design methodologies for CPS. The two reviews by Mohamed et al. [19,20] are particularly noteworthy due to the scope of the literature examined. They provided a broad overview of the CPS literature. Wu et al. conducted two literature reviews. One focused on design and implementation methods [21] and the other on concept and engineering development [22].

In comparison, there are only a few existing review papers for the creation of Digital Twins. Pater et al. [23] contrasted the topic of Digital Twins with the topics discussed in the literature. Adamenko et al. [24] compared modelling methods for Digital Twins.

Reviews also exist in the literature within the area of Product-Service Systems. Qu et al. [25] outlined the state-of-the-art with regard to design, evaluation, and operation methodologies for PSS, while the other reviews focus, in particular, on methodologies for creation. Mendes et al. [26] analysed PSS design processes, while Müller and Blessing [27] compared different approaches for product and service development. Gräßle et al. [28] analysed procedures in terms of characteristics related to the design process and results, PSS development goals, and PSS-specific and non-specific characteristics. Both Clayton et al. [29] and Haber and Fargnoli [30] contrasted the methods and methodologies from the literature with criteria from the creation phases of the PSS. Annamalai Vasantha et al. [31] created a maturity model to visualise the current state of development of PSS.

Table 1. Overview of existing literature reviews.

Source	Author	Title	System	Literature
[24]	Adamenko et al.	Review and Comparison of the Methods of Designing the Digital Twin	DT	3
[29]	Clayton et al.	Evaluating Existing Approaches to Product-Service System Design	PSS	12
[28]	Gräßle et al.	Vorgehensmodelle des Product-Service Systems Engineering	PSS	11
[30]	Haber and Fargnoli	Designing Product-Service Systems: A Review Towards a Unified Approach	PSS	20
[15]	Horvath et al.	Compositional Engineering Frameworks for Development of Smart Cyber-Physical Systems: A Critical Survey of the Current State of Progression	CPS	19
[16]	Korotunov et al.	Cyber-Physical Systems Architectures and Modelling Methods Analysis for Smart Grids	CPS	10
[17]	Liu et al.	Characteristic, Architecture, Technology, and Design Methodology of Cyber-Physical Systems	CPS	30
[26]	Mendes et al.	Product-Service System (PSS) Design Process Methodologies: A Systematic Literature Review	PSS	246
[19]	Mohamed et al.	A Systematic Literature Review on Model-Driven Engineering for Cyber-Physical Systems	CPS	187
[20]	Mohamed et al.	Model-Driven Engineering Tools and Languages for Cyber-Physical Systems—A Systematic Literature Review	CPS	187
[27]	Müller and Blessing	Development of Product-Service Systems—Comparison of Product and Service Development Process Models	PSS	7
[23]	Pater and Stadnicka	Towards Digital Twins Development and Implementation to Support Sustainability—Systematic Literature Review	DT	20
[25]	Qu et al.	State-of-the-Art of Design, Evaluation, and Operation Methodologies in Product-Service Systems	PSS	258
[18]	Quadri et al.	Modelling Methodologies for Cyber-Physical Systems: Research Field Study on Inherent and Future Challenges	CPS	58
[21]	Wu et al.	Cyber-Physical Production Systems: A Review of Design and Implementation Approaches	CPPS	25
[22]	Wu et al.	Concept and Engineering Development of Cyber-Physical Production Systems: A Systematic Literature Review	CPPS	100
[31]	Annamalai Vasantha et al.	A Review of Product-Service Systems Design Methodologies	PSS	22

3. Study Design

In this work, the similarities and connections between DT, CPS, and PSS were considered in order to create an overarching review of the corresponding procedures described in the literature. The review was conducted in accordance with the PRISMA approach for systematic literature research [32,33]. For this purpose, a search string was created that included the terms DT, CPS, and PSS, as well as corresponding synonyms. Building on the findings of the reviews examined in Section 2.2, the search string was further supplemented with synonyms for "procedure" and "development". The word search categories

were linked by use of the Boolean operators AND and OR. Since the literature found was screened for suitable titles as the first step, the search terms were deliberately limited to the title. Thus, the resulting search string was as follows:

TITLE ("digital twin" OR "virtual twin*" OR Avatar* OR "Digitale* Zwilling*" OR "Virtuelle* Zwilling*" OR "Cyber Physical System*" OR "Cyber-Physical-System*" OR CPS OR "Cyber Physical Production System*" OR "Cyber-Physical-Production-System*" OR CPPS OR "Cyber Physical Twin" OR "Cyber Physischer Zwilling" OR "Product Service System*" OR "Produkt Service System*" OR "Product-Service-System*" OR "Produkt-Service-System*") AND TITLE(*method* OR *approach* OR *framework* OR *strateg* OR "process model" OR *schema* OR *scheme* OR systema*) AND TITLE(creat* OR develop* OR implement* OR model* OR deploy* OR design*)*

This search string was used to identify suitable literature in five databases for scientific literature. These databases were Inspec, ProQuest, Scopus, TEMA, and Web of Science. After duplicates were eliminated from the totality of articles, the remaining articles were screened, first by title and then by abstract. The remaining articles were then screened for their suitability for the scope of this paper. The criteria applied were as follows:

- The article should describe the creation of the DT and not only its usage.
- The technical and technological aspects of the creation were in the focus. Articles that focused purely on organisational or economic aspects were discarded.
- The DT should also be in a technical context. DT of, e.g., humans, buildings, or agricultures, were neglected.

The procedure, in accordance with the PRISMA approach, is schematically shown in Figure 2.
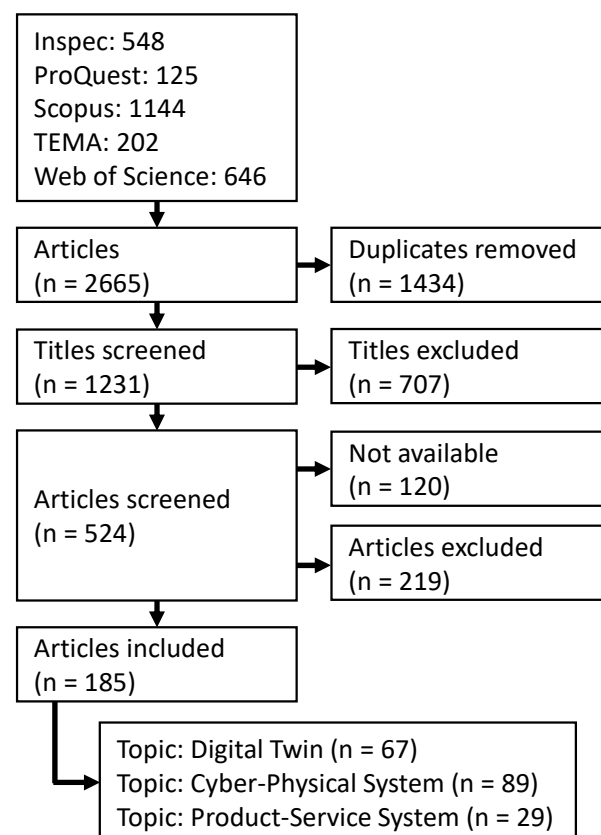

Figure 2. Schematic representation of the research approach.

A breakdown of the literature found by date of publication revealed clear trends. The first publication on the topic of DT examined in this contribution was published in 2018. Since then, however, the number of publications on this topic has risen sharply and continues to show an upward trend. Publications on the topic of CPS showed a less pronounced upward trend between 2008 and around 2016. Since then, the number of publications in this area has stagnated at a moderately high level. In the field of PSS, a slight increase can be observed between 2010 and 2018 and, since then, a slow decrease in the number of publications. The trends are shown in Figure 3.
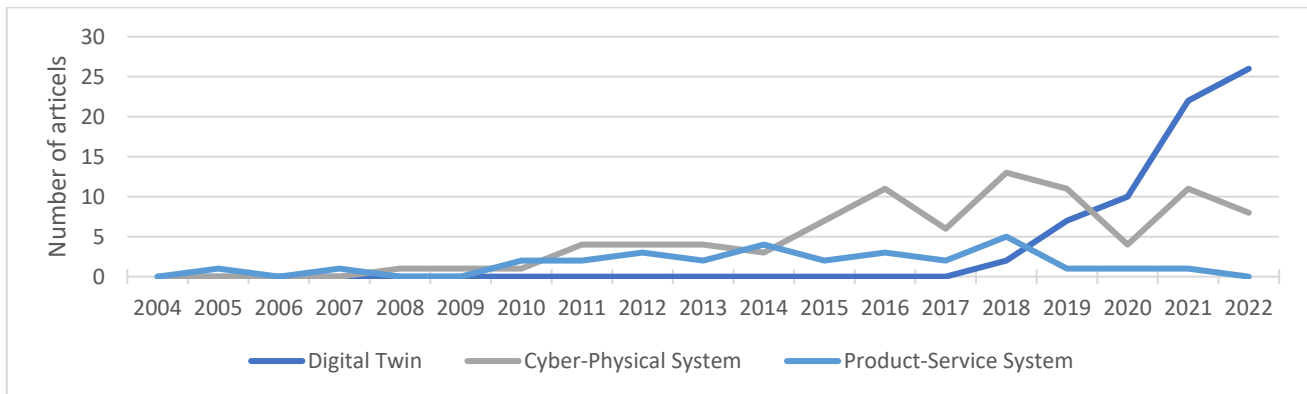
Figure 3. Number of literature articles found, sorted by systems and the years of publication.

When these trends were compared with the number of search queries on the Google search engine, large similarities became apparent. In the context of this article, this was performed using the "Google Trends" application [34] with the topics "Digital Twin", "Cyber-Physical System", and "Product-Service System". Figure 4 shows the results of the development of search queries worldwide over the last 20 years. The value 100 indicates the maximum number of search queries, and the absolute values were not determined.
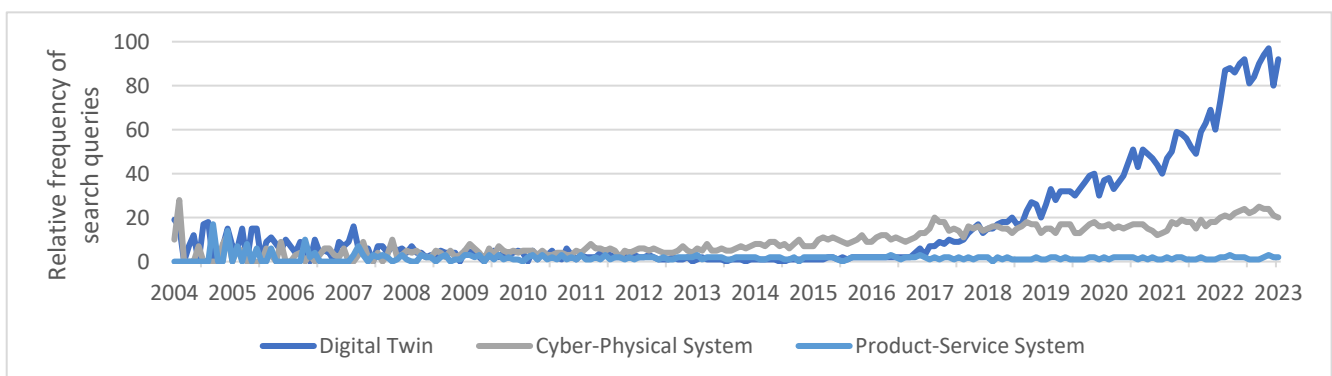
Figure 4. Development of search queries on Google.

While occasional peaks can be observed for all three search terms in the period from 2004 to 2008, the number of search queries for the topic "Digital Twin" has rapidly increased since 2017. The interest in this topic continues to increase every year. The topic "Cyber-Physical System" has also been searched more frequently since around 2010, although the growth observed here is nowhere near as rapid as that for Digital Twins. Finally, no growth beyond statistical noise can be observed for the search term "Product-Service System". Overall, the number of search queries here is very low compared to Digital Twins and Cyber-Physical Systems.

4. Results

The articles cover aspects that can be divided into three categories: "holistic approaches", "architecture", and "models". As described in the Introduction Section, the focus of this article is on the creation of Digital Twins. Even though the literature is spread over the three different systems—Digital Twins, Cyber-Physical Systems, and Product-Service Systems—in the following, the term Digital Twins will be used primarily.

The category "holistic approaches" includes procedures that describe the creation of Digital Twins across different domains. These are not limited to one domain, and often do not distinguish between them. Instead, they include aspects of modelling, the creation of an IT infrastructure, and/or the integration of appropriate sensors, simultaneously. Some publications also consider other domains, such as economic aspects.

The second category, "architecture", deals purely with aspects that are necessary for data transmission. Here, software and hardware aspects are considered, which enable data to be transferred from the physical space into the data space and processed there.

The third category, "models", includes literature that deals with the creation of models. It considers the necessary steps in the modelling process, but also the modelling scope and modelling types. Figure 5 shows how these categories interact in the context of the Digital Twin and refers to the corresponding sections in this contribution.
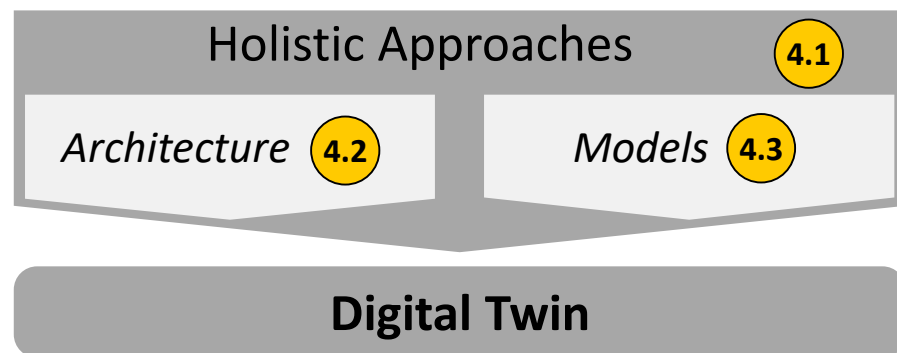

Figure 5. Context of the categories of this contribution.

If the number of publications classified into these three categories is considered over the year of publication, trends can be identified. For all categories, a steady increase in publications can be observed over the years. Publications on holistic approaches and models started as early as 2010, while publications on architecture were only published from 2014 onwards, with only a single exception in 2009. Furthermore, the number of publications on models started to increase more rapidly in 2017. This also corresponds to the year in which the number of publications and Google searches on the topic of Digital Twins began to significantly increase. Figure 6 shows the trends plotted over the years. The literature cannot always be clearly classified into one of these three categories, but it addresses several topics in some cases. For this reason, the sum of publications in Figure 6 differs from the sum of publications in Figure 3.

Figure 7 illustrates the sum of the literature articles in the three categories: "holistic approaches", "architecture", and "models". It is further divided by which system (DT, CPS, or PSS) is treated by the corresponding literature. Publications that deal exclusively with a literature review were not included here. The CPS literature treats the categories "holistic approaches" and "architectures" to a comparable extent. However, models are addressed here more than twice as often as architecture or holistic approaches. A similar relationship is seen in the DT literature between the architecture and the models categories. However, the holistic approaches are treated here more rarely. Literature dealing with the creation of PSS deals with holistic approaches, with only one exception.
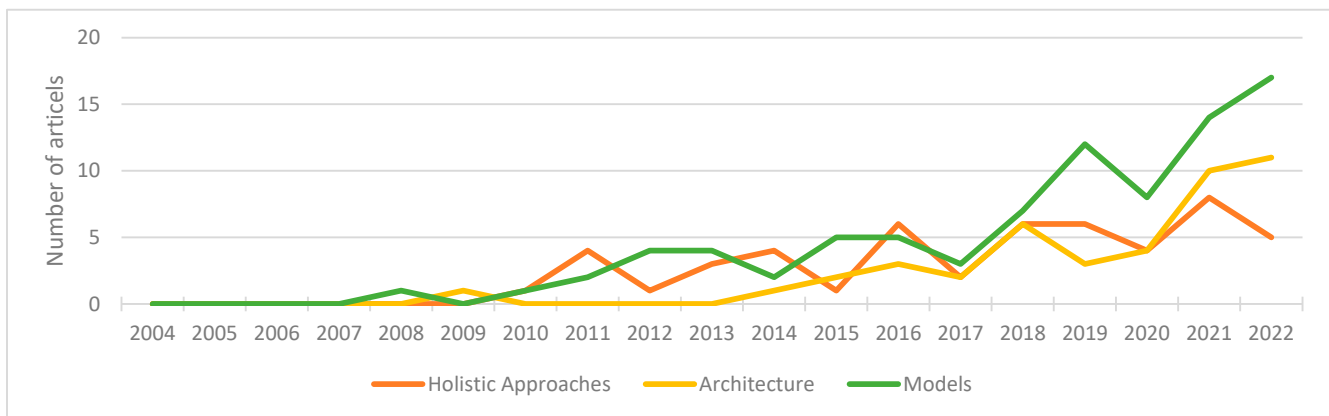
Figure 6. Number of literature articles found, sorted by domains and the years of publication.
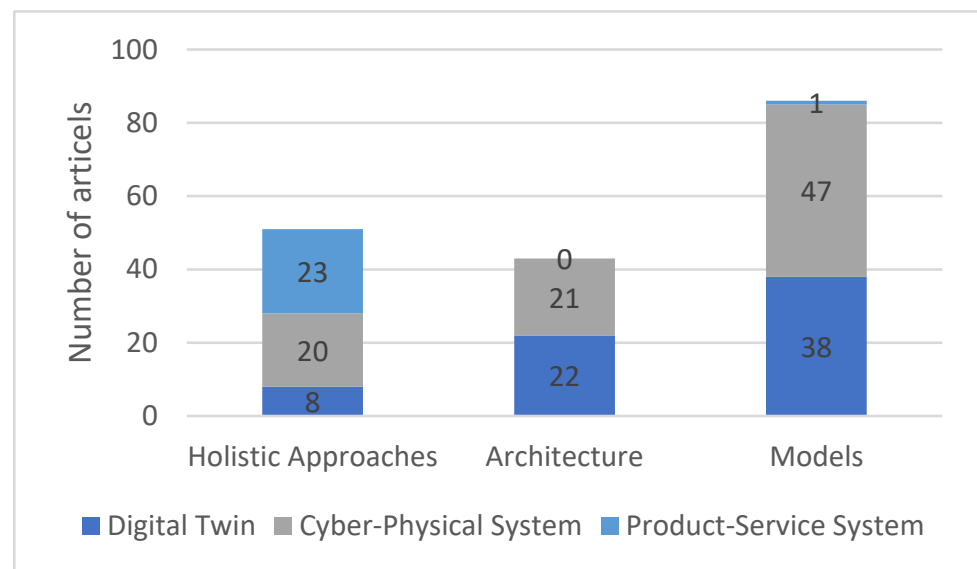

Figure 7. Categorisation of the studied literature into the three main categories.

4.1. Holistic Approaches

There are several publications that deal with the creation of Digital Twins and CPS. On the one hand, the publications in this direction can be divided into the formulation of criteria for appropriate approaches and analysis of existing methodologies. On the other hand, there is literature that presents specific approaches, either as a modification of existing approaches or entirely on its own.

Figure 8 shows the breakdown of the literature in the "holistic approaches" category into the two subcategories of "analysis" and "description". In the subcategory "analysis", existing and largely established development approaches were examined regarding their suitability for creating Digital Twins. Among other things, criteria were derived that the potentially suitable approaches must fulfil. The subcategory "description" includes literature that introduces and describes modified or completely new holistic approaches. This often builds on existing approaches.
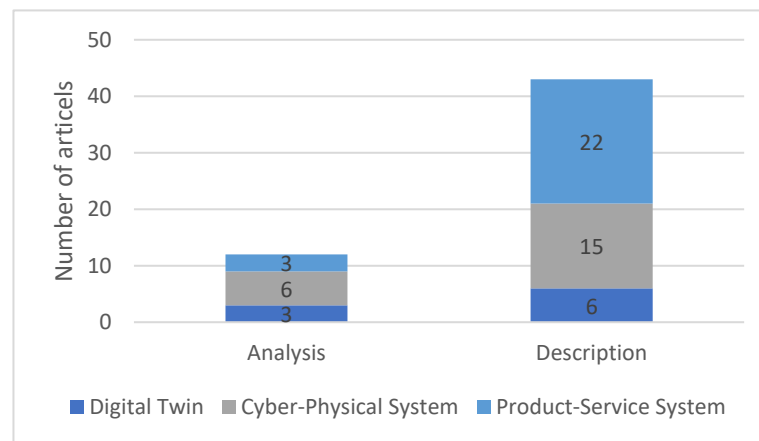
Figure 8. Breakdown of the literature on holistic approaches into subcategories.

The literature may address both subcategories and can, therefore, be sorted into both. For this reason, the sum of the literature in the subcategories is not equal to the corresponding quantity in Figure 7. For both DT and CPS, about twice as many publications described a (new) procedure compared to those that analysed existing ones. Publications dealing with PSS were almost exclusively devoted to the description of the procedure.

4.1.1. Literature with a Focus on the Analysis of Holistic Approaches

First, the literature on formulating criteria for appropriate approaches and analysing existing methodologies was considered.

Amrani et al. [35] examined two general paradigms for the development of systems: a formalism-oriented paradigm in the form of an object orientation and a workflow-oriented paradigm in the form of agile development. They transferred the findings into a metamodel for describing paradigms.

Perno and Hvam [36] developed a framework to help determine a suitable scope for a Digital Twin. They focused on the use cases and stakeholders of the Digital Twin.

Both Zheng et al. [37] and Aigner and Khelil [38] formulated various criteria that a procedure must fulfil in order to be suitable for the development of CPS. Zheng et al. [37] used the criteria to evaluate different methods from the areas of V-model-based design methods, MBSE, and agile methods. Aigner and Khelil [38] then compared these criteria with model-based methodologies and cyber-space domain concepts and created concepts for a methodology blueprint for the CPS architecture and an engineering process for CPSs. Chauhan et al. [39] identified the different aspects that need to be considered in the development of CPSs, namely, domain concerns, functional concerns, platform concerns, and deployment concerns. Comparable to this, Jeschke and Grassmann [40] elaborated the necessary requirements and development steps for the development of a Digital Twin in the context of German rail transport.

Riedelsheimer et al. [41] compared the suitability of different development approaches for the development of Digital Twins. In a similar way, Thammarak [42] investigated the suitability of agile development procedures for CPS. Agile procedures for the development of CPS were also examined by Schuh et al. [43], who furthermore compared three conventional and hybrid procedures with it. Schuh et al. presented a procedure that characterises the specific, individual use case and, based on this, proposes the most suitable development process.

In the context of PSS, existing approaches were also used and evaluated regarding their suitability. While Sadek and Köster [44] evaluated existing approaches of multidisciplinary development, Pezotta et al. [45] considered the waterfall model, V-model, and spiral model. Qu et al. [25] examined various modelling techniques, visualisation methods, modularity methods, and TRIZ.

4.1.2. Literature with a Focus on the Description of New Holistic Approaches

Several publications proposed integrated procedures for the creation of CPS or DT. Both Riedelsheimer et al. [41] and Lowenstein and Mueth [46] adapted the established V-model so that it could be used to create Digital Twins.

However, the majority of the procedures presented in the literature are described step-by-step without explicitly referring to existing approaches. Hehenberger et al. [47] considered three different disciplines of CPS (physical processes, computations, and integration of computations and physical processes) and related them to the early design process (consisting of the conceptual design phase and system modelling phase).

Slomka et al. [48] presented a generic design flow of CPS. This consists of five central steps. First, (1) the requirements are defined. Based on this, (2) the system is specified and designed. This is further specified during (3) the component specification. These are then (4) combined into a system architecture. Finally, (5) a comprehensive constraint analysis takes place.

Kofanov and Sotnikova [49] also presented a five-step procedure for creating a CPS with a digital counterpart using the example of a spacecraft. First, (1) the physical part of the CPS is developed and (2) the digital counterpart of the physical processes is created. Then, (3) the distribution of the physical variables is determined and (4) the installation position of the sensor is defined based on load cases. Finally, (5) a database is created with which future sensor values can be compared.

Jarvis et al. [50] presented a five-step procedure for the creation of CPS. Starting with specifying the (1) requirements, the (2) physical architecture, and the (3) agent team architecture. Then, (4) the two architectures are mapped and (5) the CPS is finalised.

Merlo et al. [51] presented a procedure consisting of a total of 16 steps, which were divided into 3 phases: exploration, user-centred, and development.

Wu et al. [21,22] categorised the results of a literature review on CPPS into two stages: the concept development stage and the engineering development stage. The former consists of three phases: the (1) needs analysis phase, (2) concept exploration phase, and (3) concept definition phase [22]. The engineering development stage, in turn, is based on the 5C Architecture [21,22].

Rogall et al. [52] and Francalanza et al. [53] also presented procedures for the systematic development of CPPS. Rogall et al. [52] start by (1) defining the system and identifying the relevant variables. Then, (2) the understanding of the system is developed and the relationships between the variables are considered. Next, (3) the specific objectives and stakeholders are considered, and a use case is derived. (4) The necessary data streams and IT elements are built and the CPPS setup is created before (5) the system is evaluated.

Francalanza et al. [53] also considered a modularisation of the CPPS. For this, the (1) requirements are clarified, followed by (2) the selection of technical solutions. Then, (3) module concepts are generated, (4) evaluated, and (5) improved.

Nogueira de Andrade et al. [54] presented a six-step methodology for the creation of Digital Twins. This consists of (1) obtaining data, (2) model creation, (3) communication establishment, (4) configuring real-time simulation, and (5) development of the control logic and (6) the graphical interface.

Psarommatis and May [55] presented a DT design methodology with seven steps. These steps (1) define the purpose of the DT and (2) identify the asset or process to be represented. Then, (3) the right technologies are chosen and (4) the input and output parameters of the DT are determined. This is used to (5) define the characteristics of each parameter. Finally, there is a (6) performance testing and (7) deployment of the DT.

Jensen et al. [56] presented a ten-step procedure for a model-based design (MBD) for CPS. First, (1) the problem is described and (2) the physical process is modelled. Then, (3) the problem is characterised and (4) a control algorithm is derived before (5) models of computation are selected. Further, (6) the hardware is specified and (7) the computation problem is solved by a simulation approach. Finally, (8) the device is constructed and (9) the software is synthesised. The system (10) is verified, validated, and tested.

Some authors described procedures that cannot easily be presented in lists of individual steps, such as Wu et al. [21,22]. Julien and Martin [57,58], as well as Ballarino et al. [59], followed the 5C model when creating the CPS or DT.

Based on the analysis of different approaches by science and industry described above, Aigner and Khelil [38] developed a methodological blueprint of the CPS architecture consisting of different layers, as well as an engineering process for CPSs.

Rivzi and Chew [60] looked at the state-of-the-art on the creation of CPSs and on CPPSs in general and derived a procedure for the creation of CPPSs. This procedure consists of a detailed description of numerous interconnected individual steps, so that the description of this procedure would go beyond the scope here.

Specific tools for the creation of CPS were presented by Rakov [61] and Larsen et al. [62]. Rakov [61] first identified 15 main attributes of a CPS. For each of these attributes, they presented some implementation emotions, resulting in a morphological box. Larsen et al. [62] presented a prototype of an online platform that includes a sandbox for creating CPS. Within the framework of model-based design (MBD), users can select components from the classes' models, tools, and operating systems.

The approaches for creating PSSs focus, to a large extent, on organisational and economic aspects. Since the focus of this contribution is primarily on technological aspects, many PSS approaches are, therefore, only relevant to a limited extent. However, a large area of intersection occurs in requirements' identification involving stakeholders [12,25,63–77]. Based on this, some authors created the functions and concept of the PSS [12,66,67,69,72–74], which also needs to be implemented from a technological point of view and is, therefore, also relevant to this contribution. In addition, Arioli et al. [63] considered conceptualisation of the infrastructure and network and, as part of a design step, data flow, adaptation of the product, IT architecture, and sensor technology. Nemoto et al. [70] transferred the customer needs into a PSS function model, from which required actors are derived. Apostolov et al. [78] developed services using the V-model and RFLP concept to model use cases. Marques et al. [79] presented approaches for product development and service development and put them into contrast. Sadek and Köster [44] created an integrated approach with micrologic and macro-logic based on their evaluation of existing approaches. Tran and Park [80,81] presented, in two publications, an approach to adapt PSS design methodologies with respect to appropriate criteria.

4.2. Architecture

The architecture of a DT describes the necessary structure for required key technological elements. The term architecture is often used synonymously with the terms framework or IT infrastructure. In order to create a uniform understanding, these terms are defined in Table 2. In the context of this article, only the term architecture is used, even if different articles have partly used other terms in a synonymous way.

Table 2. Definitions of the terms: architecture, framework, and IT infrastructure.

Term	Definition	Source
Architecture	"Architecture is a unified structure for the purpose of implementing a technology. It can be used to decompose technology into key elements and help to integrate them into existing or new ecosystems with minimal efforts".	[82]
Framework	"A framework is a semi-complete application. A framework provides a reusable, common structure to share among applications. Developers incorporate the framework into their own application and extend it to meet their specific needs. Frameworks differ from toolkits by providing a coherent structure, rather than a simple set of utility classes".	[83]
IT Infrastructure	"IT infrastructure is the system of hardware, software, facilities and service components that support the delivery of business systems and IT-enabled processes".	[84]

Different types of architectures for a Digital Twin are available. For example, Diaz et al. [85] drew a comparison between a monolithic architecture (consisting of data, business logic, and web) and a microservice architecture. Dumitrache et al. [86] presented a generic architecture of an enterprise in the context of CPS, also considering business aspects, for example.

The most common classification is the general classification into physical space and cyber space (also called virtual or cloud space/layer) [87–97]. Some authors explicitly mention the communication between these two spaces [89,91,94,95,97]. Several authors present a more fine-grained classification of infrastructure. These finer granular considerations are compatible with the general classification into physical and cyber space and complement it in many places or substitute it with more detailed considerations. The publications that do not explicitly mention the general classification are nevertheless fully compatible with it. In the following, the finer granular considerations are integrated into the general classification and assigned to the literature.

Figure 9 shows the division between physical space, data space, and the communication in between. Further, the more detailed subdivision, which is proposed by some authors in the literature, is sorted here.
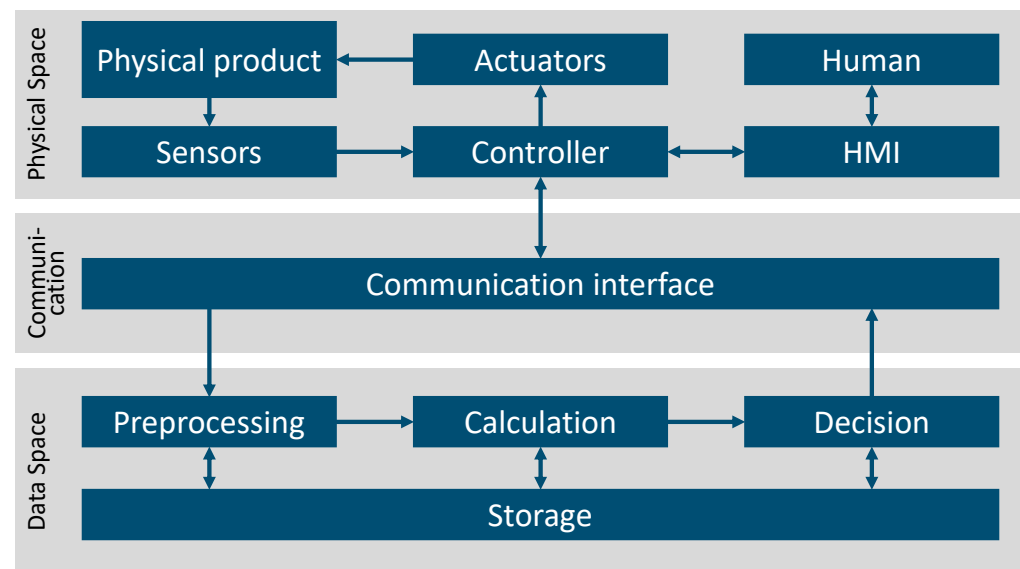
Figure 9. Structure of the overall architecture into physical space, communication, and data space.

Figure 10 shows the breakdown of literature in the "architecture" category into the three subcategories: "physical space", "communication", and "data space". The subcategory "physical space" deals with hardware components that are located on, in, or around the physical twin. The "communication" subcategory includes aspects that serve the transmission of data between the physical space and the data space. Finally, the subcategory "data space" deals with aspects of data processing in the Digital Twin itself.

The literature may address more than one subcategory and can, therefore, be sorted into multiple categories. For this reason, the sum of the literature in the subcategories is not equal to the corresponding quantity in Figure 7. Literature on CPS addresses all three categories equally often. In the context of DT, physical space and data space are addressed about equally as often, but the communication in between is addressed only around half as often.
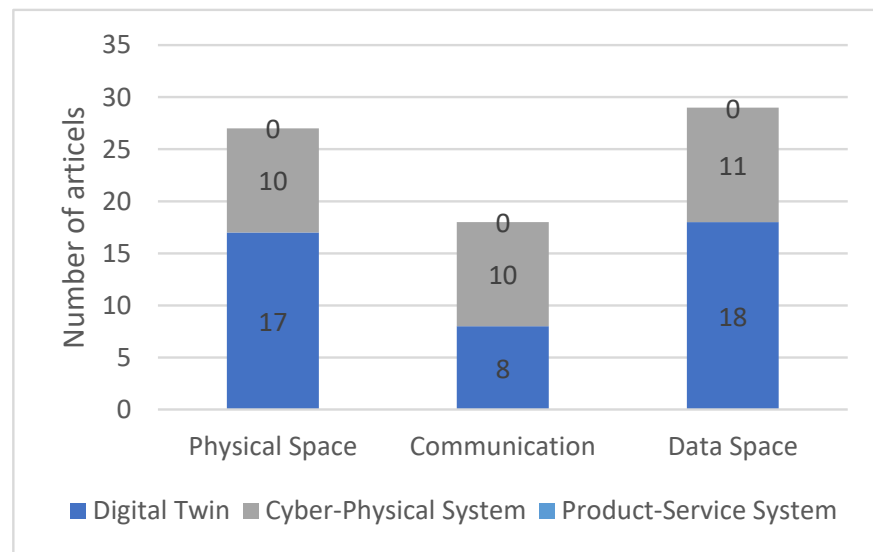
Figure 10. Breakdown of the literature on architectures into subcategories.

4.2.1. Physical Space

On the physical side, only a few details are discussed in the publications, and the focus is often on cyber space. For this reason, many authors only mention the physical device and/or the data collection, for example, through sensors. Only a few publications go beyond these core components.

One "component" in physical space is humans, who can act as users or operators [87,88,95]. The users are interconnected with the technical system via a user interface [86,95]. The second, and at the same time, the key component in the physical space is the physical product itself [87,88,90,92,93,95,98–109]. The physical product is equipped with components for data acquisition, primarily integrated sensors [86–90,92,93,95,98–103,110–112]. However, external data sources or operational data can also be used [102]. In general, the data can come from the entire product life cycle [113,114]. Babiceanu and Seker [115] explored the use of a Big Data approach, where the information sources can take different forms. To control the physical product, some authors mentioned the use of actuators [87,89,92,95,98,112]. The sensors and actuators are connected on the physical side to a control unit such as a PLC (Programmable Logic Controller) [87,89,90,103,112,116].

4.2.2. Communication

In order to be able to exchange data between the physical space and the cyber space, a corresponding network is necessary, which establishes a bidirectional connection between the physical and virtual aspects [87,88,90,92,95,97,101,108,109]. The communication takes place via interfaces that connect the physical space and the cyber space [89,91]. Francalanza et al. [53] mentioned a bus module with an IoT gateway and the OPC/UA communication standard. The OPC/UA communication standard was examined in more detail by Liu et al. [117], who compared it with MTConnect. Another standard that is frequently mentioned in the literature is MQTT [116,118]. Mishra and Ray [90] listed a sum of other communication possibilities. Shin et al. [119] presented an approach for creating a low-cost communication system for CPS. They built on an existing commercial communication infrastructure and used a middleware gateway to connect it to the physical system. Both Li et al. [120] and Bernady et al. [121] analysed further necessary sub-aspects and components and developed the necessary requirements.

4.2.3. Data Space

Often, the data cannot be processed directly but must be pre-processed [110,122]. This is also referred to as the use of a conditioner [98]. Pre-processing involves a preliminary analysis of the data [95,110]. On the one hand, the data are converted and/or compressed [99,102] and, on the other hand, useful information and features of the data are extracted [99,102,111].

The selected data or the information and features are then used for the calculations and/or simulation [86,90–93,98,99,102,103,110,112]. For this purpose, models are used that represent the physical product [88,95,100,104,108,109,111]. These models can be, for example, analytical simulations [89,95,105,122], statistical models [105], mathematical functions [107], or machine learning models [90,105,110,111]. A more detailed consideration of the models follows in the next section of this contribution.

The evaluation and utilisation of the results of the previous calculations and simulations are highly scenario-specific [90,107,122]. Various authors speak in this context of service [103,104,108,109] or application [87,88,90,92,101–103,106]. Chen et al. [88] and Jia et al. [101] provided a number of examples for this. In the following, the services are considered, which are also mentioned by the other contributions. It is possible to recognise and react to events based on the simulation and calculation results [99]. For this purpose, it is possible for the system to make decisions within a spectrum [88,95,99,100]. This allows an intelligent operation of the system [88]. Furthermore, a real-time monitoring of the system and the performance is possible [93,95,102,103,106], which can be used for health management [88,101,106]. It is also possible to make predictions about the system [93,102]. The models are to be connected via a suitable architecture, as considered by Lektauers et al. [123] and Wang and Jin [103].

The data are stored in a database and can be retrieved from it [91,95,99,102,111,124,125]. Li et al. [102] and Eyre et al. [116] mentioned an SQL database as a possible implementation. The database is connected to all positions in the data processing chain [108,109]. The stored data can be put in physical space [93], the fog [98,99], or the cloud [87,98,101,103,104].

4.3. Models

The models describe the behaviour of the physical product and are a key element of the Digital Twin. In the context of Digital Twins, the models are so present that the two terms are used synonymously by some authors. The literature can be further divided into three subcategories: "procedure steps", "modelling scope", and "model type". The subcategory "procedure steps" describes the individual steps that must be carried out to create the models. In the "modelling scope" subcategory, the modelling scope and, thus, what is to be represented within the framework of the models, is described. The third subcategory "model type" contains different types of models. Furthermore, modelling languages or simulation software, for example, are discussed.
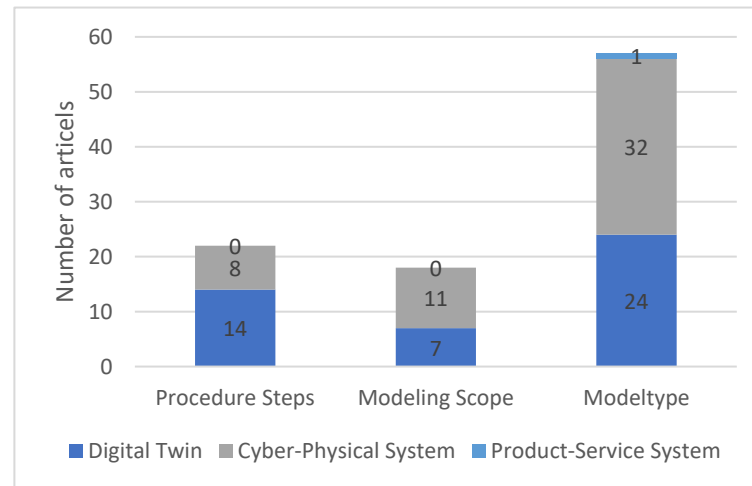
Figure 11 shows the breakdown of the literature in the "models" category into the three subcategories. The literature can address more than one subcategory and can, therefore, be sorted into multiple categories. For this reason, the sum of the literature in the subcategories is not equal to the corresponding quantity in Figure 7. Both the procedure steps as well as the modelling scope are equally covered by the literature on CPS and DT. In comparison, the literature on model type is much more represented.

4.3.1. Procedure Steps

The creation of models can be carried out by applying existing engineering approaches. Lopez and Akundi [126] used model-based system engineering (MBSE) approaches, while Michael and Wortmann [127] followed model-driven software engineering (MDSE) techniques. In contrast to this, various authors presented the necessary steps to create appropriate models. Existing differences can be explained with different granularities and/or scopes. Figure 12 shows the sub-steps described in the literature, which are explained in the following.

The modelling process begins with preparation [128] and **requirements'** identification [129–132]. For this, the problem to be solved is described and analysed. This results in requirements and necessary specifications for the models [100,133].

Figure 11. Breakdown of the literature on models into subcategories.
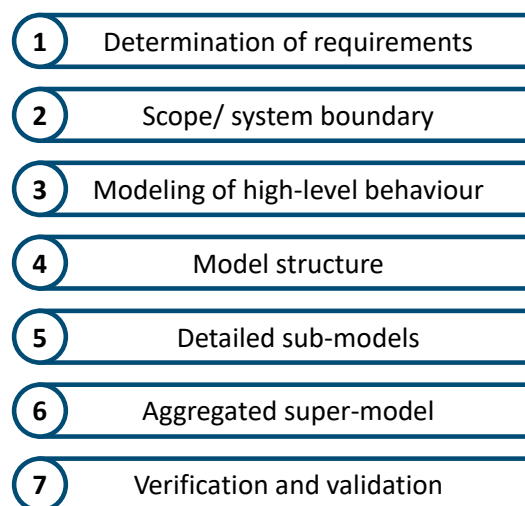
Figure 12. Overview of the procedure steps in the creation of models.

The intended use of the Digital Twin determines the **scope** of the Digital Twin and the modelling scope [134,135]. This can be supported by identifying suitable observable objects [136] and is separated from the environment by defining a system boundary [137].

Based on the modelling scope, the **higher-level behaviour** of the physical product can be modelled [129,137–140]. In the understanding of Gao et al. [141], this corresponds to the representation in the problem domain. Alternatively, or complementing the modelling of the higher-level physical behaviour, a macroscopic **model structure** or architecture can be created for the subsequent detailed models [133,140,142–144].

Based on the created macroscopic structure or architecture, or in order to describe the higher-level behaviour of the physical product on a detailed level, more **detailed sub-models** have been created to represent individual aspects of the behaviour. These are specific models for calculation and simulation [129,143] and can be achieved in different ways depending on the model. The subdivision into sub-models can be performed via individual domains [133,141] or via the component and subsystems [137,139]. These represent the individual characteristics, detailed features, and parameters of the system [134,138,145]

and can be linked to real operating data [134,146]. This corresponds to the description in a solution domain. Furthermore, the addition of semantic annotations is possible [136,144]. The detailed modelling requires a choice of computing models and a determination of the hardware to be used [129].

The detailed sub-models are then deployed and **aggregated into a super-model** [129,133,134,136,138–141,144,145]. In the software context, this can be described as software synthesis or code generation [129,141].

In the final step, **verification**, **validation**, and/or testing takes place [128–130,140]. Documentation is also necessary [146].

4.3.2. Modelling Scope

Wan et al. [147] combined model-driven engineering (MDE) with component-based design (CBD) for the design of CPPS. They used one model (type) that can be used for different domains. Apart from this, however, several different model types were used in the rest of the considered literature, which are linked with each other. As described in the previous section on cyber space, one possible breakdown is into a descriptive model and a decision-making model [88,95,99,100]. This division was also used by Luo et al. [148,149] and Alessandro Pinto [150]. A large number of alternative model scopes can also be found in the literature. The most mentioned are as follows:

- System model [100,151,152]
- Components, such as the physic and cyber components [152–154]
- Process model [100,152,155]
- Behaviour model [156–158]
- Simulation model [100,155]
- Rule model [153,157]
- Data transfer model [153,154]
- Environment model [159,160].

In addition to these model types, others are mentioned in some of the reviewed literature. However, due to the fact that these are only mentioned once in the literature, they are not all listed, and instead, reference is only made to the named sources.

4.3.3. Model Type

As already described in the section on cyber space and modelling scope, Digital Twins can include a variety of different models. Adamenko et al. [24] differentiated between two key modelling approaches, which resulted in two different types of models: data- and system-based models. Data-based models are created on the basis of extensive datasets, for example, using machine learning approaches. In contrast, system-based (or physics-based) models use known relationships to describe behaviour. The relationships can be represented in the form of simulation models, mathematical and statistical models, or logical models. Furthermore, defined modelling languages can be used. This requires a high degree of system knowledge. There are already a large number of commercial and industrially used software solutions for modelling simulation models, which may be a possible explanation for why these are not the focus of the literature. Instead, the focus is on modelling via modelling languages, mathematical, and logical modelling, but also model creation via machine learning.

In the literature on modelling languages, Lichen Zhang is particularly noteworthy, with a large number of publications. In several papers [161–163], he has presented various modelling languages (such as Modelica, Simulink, AADL, MARTE, and SysML) and compared them with different views of the CPS. Furthermore, in several publications, he considered the interactions with Big Data [164,165] and how the different languages can be used together [166,167]. Babris et al. [129] also examined a number of modelling languages for designing CPS and compared them against several criteria. Similar collections of modelling languages and tools can be found in the works of Buffoni et al. [168], Attaerzadeh-Niaki and Sander [169], as well as Staroletov et al. [170].

One of the most frequently considered modelling languages is UML (Unified Modelling Language), or modifications of it. Woo et al. [171] used the UML modification xUML (eXecutable Unified Modelling Language) for modelling CPS as early as 2008. Lichen Zhang used UML for modelling [172] and, in a follow-up work, extended the successor UML2.0 to a Cloud-Based Hybrid UML metamodel (CHUML) [173]. More recent publications increasingly rely on UML2.0 and corresponding modifications. For example, Zhai et al. and Zhou et al. used Hybrid UML, which is a profile of UML 2.0 [174,175]. Sadwovykh et al. and Tannoury et al. both used SysML, which is a graphical standardised modelling language based on UML 2.0 [176,177]. Tannoury et al. further linked SysML with MARTE and OCL (Object Constraint Language), as well as Reo for additional constraints [176]. Wilking et al. [178] utilised SysML to design and operate Digital Twins. Wang et al. [179] described a bidirectional mapping structure between Simulink and UML.

Another modelling language used in the literature is the Architecture Analysis and Design Language (AADL). While Wu et al. [180] used it to model the behaviour from different domains for a CPS, Renya et al. [181] combined AADL with the modelling language Modelica. Sales et al. [135] transferred the results of an ontology analysis into an AADL model. Modelica was also used by Wawrzik et al. [182] in combination with other languages. They presented a simulation framework called SICYPHOS (SImulation of CYber PHysical Systems), which integrates SysML, Modelica, SystemC, and C/C++. Junjie et al. [183], on the other hand, used Modelica alone to model CPS. They contrasted the Modelica features (object-oriented modelling, equation-based modelling, connect-based modelling, and hybrid modelling) with the CPS system modelling approaches (physical system modelling, information system modelling, and interface modelling). Schroeder et al. [138] used the modelling language AutomationML (Automation Modelling Language) for modelling. Centomo et al. [184] linked models of different levels of abstraction of a manufacturing plant. Lehner et al. [185] introduced the AML4DT (Automation Modelling Language for Digital Twin) framework for this purpose. Fitzgerald et al. [186,187] used the Unifying Theories of Programming (UTP) approach and its large-scale application in the form of the definition of the COMPASS Modelling Language (CML) [187].

In addition to the dedicated modelling languages, there are methods in the literature using mathematical modelling approaches. Lee et al. [188] examined various mathematical models for describing discrete event systems (DES) in the context of CPS. One mathematical model considered is Petri Nets, which is used by several other authors. He et al. first used this to model CPS [139], and then extended it to Predicate Transitions Nets (PrTNs) in another publication [189]. Quian and Yu, in particular, used time-constrained aspect-oriented Petri nets (TAOPN) [190].

Several authors used (interconnected) flow and decision diagrams to model the behaviour of the product [191,192]. Christofi and Pucel [193] described the behaviour of a product using fault trees and behaviour trees, while Negri et al. [194] used the identified states (idle, working, error, emergency button, and energy-saving mode) of the product to model it. Doka and Horak [195] created block diagrams of a gearbox to represent and simulate its behaviour. Steinmetz et al. [136] used the application Node-Red to create knowledge graphs of an asset. Meryem Afendi [151] used Event-B to model a CPS. Tou et al. [196] extended the traditional hybrid system description language HYSDEL to E-HYSDEL. This can be used to describe the behaviour of CPS. Janda et al. [197] utilised the methods Virtual Numerical Controller Kernel (VNCK) and Mechatronic Concept Designer (MCD) on a case study and compared the results. Erkoyuncu et al. [198] presented an ontology concept that is used to describe an asset and model the behaviour of the Digital Twin. The focus is on the adaptivity of the Digital Twin. Eyre et al. [116] used CAD data to map the geometric properties of the product in the Digital Twin. Lai et al. [199] also used CAD models to derive a mesh, which was then used to calculate the power flow (Optimal Power Flow—OPF).

There are approaches that make use of special libraries for the model creation. Zhao et al. [200] used a component-based reduced order modelling (ROM) technique

to create a Digital Twin of a wind turbine. The components are stored in a library and can be selected and combined from there. Zou et al. [201] presented a process model for a Digital Twin to make statements about the quality of machined parts. They considered key features, which they stored in a library.

Apart from these system-based modelling approaches, there are data-based approaches, which find specific application in the examined literature in the context of machine learning [146]. Lou et al. [148,149], Dashkina et al. [202], as well as Tarkhov and Malykhina [203] used neural networks as behavioural models of a Digital Twin. Liu et al. and Yang et al. further used transfer learning approaches to adapt the models to changing conditions, for example, and thus increase robustness [204,205]. Zheng and Ni [142] also used real data to retrain the parameters of their model, creating a hybrid model.

5. Discussion and Need for Research

Finally, here, the results are compared and discussed with the research questions formulated at the beginning. The first research question (RQ1) deals with the topic of how the creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems is considered in the literature and what research directions exist. The discussion is visualised in Figure 13. This shows the overarching holistic approaches with the three domains: architecture, models, and modification of physical twins, as well as their respective sub-topics. The individual elements are coloured according to the usability of the literature. Topics that allow direct utilisation of the literature are coloured green, while indirect utilisation is coloured yellow. Topics that are not covered in the literature, or only to a limited extent, are coloured grey. The size of the individual elements has no significance in this illustration.
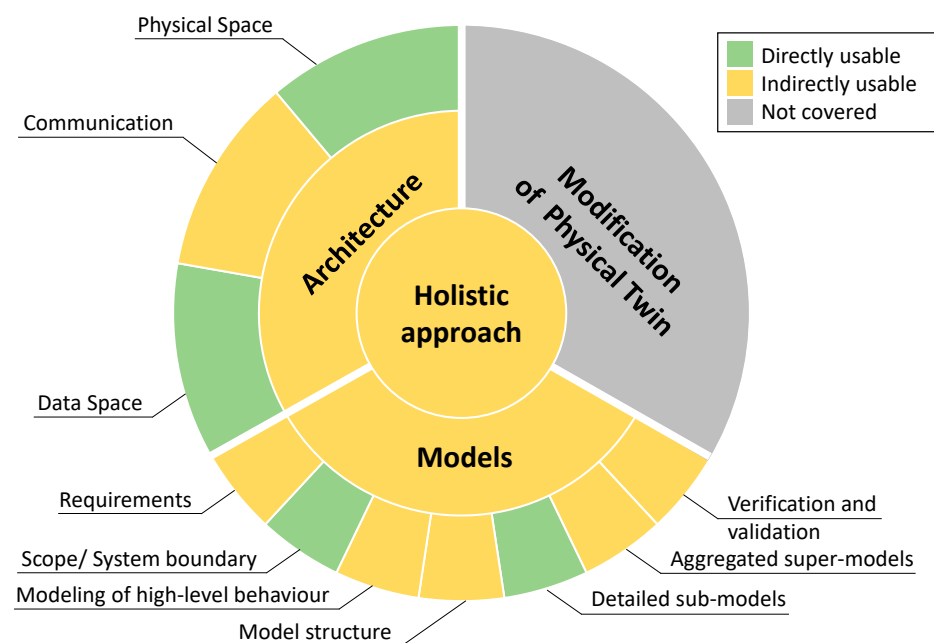
Figure 13. Overview of the usability of the literature on various topics (size of the individual elements has no significance).

Several holistic approaches for the creation of Digital Twins and Cyber-Physical Systems can be found in the literature. Existing development approaches were analysed regarding their suitability for the creation of Digital Twins and criteria for this were formulated. Furthermore, approaches were described, which were either a suitable modification of the existing approaches or completely new approaches for the creation of Digital Twins. However, the described procedures were either on a rather superficial and general level or considered only selected sub-steps or even domains in the creation of Digital Twins. The

individual steps described in the holistic approaches overlapped or complemented each other to a certain extent. However, it was not possible to adequately cover the domains described in more detail below. One reason for this is that the scope of the holistic approaches greatly differs.

The review of the literature has shown that several domains need to be mastered in order to effectively create Digital Twins. The two most dominant domains in the literature were clearly the models and the architecture. In addition, other domains were also mentioned, although they received less focused attention in the literature. For example, it is necessary to modify the physical product to make it usable with Digital Twins.

Within these three domains, the focus of the literature is on the models, which are a key aspect of Digital Twins. A large number of publications presented individual steps for creating product-describing models. Since these individual steps have a great degree of overlap, they can be combined into a comprehensive sequence of steps. Two individual steps received special attention in the literature. One step was the model scopes, which help in the identification of the scopes. Here, the authors described which aspects of the physical twin are represented within the context of the Digital Twin. The other step that received special attention in the literature was the specific model types for the creation of detailed sub-models. Various modelling approaches were presented here. Due to this particular focus, these two steps are directly feasible, and the literature is directly usable. The literature on the other steps focused primarily on theory and is only indirectly applicable in a practical sense. Since only some of the steps in context of the models are directly applicable, the literature in this domain can only be classified as indirectly usable, as well.

The second domain, which was also dealt with extensively in the literature, was architecture. This was divided in the literature into physical space, data space, and the communication in between. Most of the literature was limited to the description of this architecture and less to tools, methods, or guidelines to create this architecture. The detailed description of the physical space and the data space nevertheless allow a direct use of the corresponding literature. Users can use the detailed architectures described to help them overcome their own challenges. Nevertheless, specific guidance would be more desirable. The communication between the two spaces mentioned is only treated superficially in the literature and can only be used to a limited extent. Since the subcategories in the field of architecture can only be used partially directly, the literature in this domain can only be classified as indirectly usable.

The last domain mentioned, the modification of the physical twins, was only marginally dealt with in the literature. In particular, there were no systematic procedures for the selection and integration of sensors. This is marked by the grey colour in Figure 13. For this reason, a systematic literature search for sensors in the context of Digital Twins and CPS was carried out in parallel to this contribution; however, the results were not discussed here, and instead reference is made to the corresponding contribution [206]. There is a need for further research on actuators in the physical twin.

For a holistic approach, all three domains must be interconnected and the interactions between them must be considered. This was only partially covered in the literature on holistic approaches. The indirect usability of the literature in all three domains does not allow a direct link to a holistic approach.

The second research question (RQ2) addresses the question of in which domains and to what extent further research is necessary. An answer to this question can also be derived from the previous discussion of the research results.

There is a need for further research in the domain of architecture. In particular, the description of communication cannot be directly applied in practice. Further research and documentation of the results is necessary here. Furthermore, there are no recommendations for action or lists of necessary procedure steps for the creation of a suitable architecture for a Digital Twin in the literature. This is a key need for future research.

The domain of modelling is described in the literature as specific action steps. As described in Section 4.3.1, these can be grouped into a unified procedure. However, there

is still a need for further research. The literature that describes the individual steps can often only be used indirectly. More research is needed, especially in the areas of requirements, modelling of high-level behaviour, model structure, aggregated super-models, and verification and validation.

The modification of the physical twin was hardly covered in the literature. This includes, for example, the selection and integration of sensors and actuators in the product, and it represents a significant need for research. For this reason, as already mentioned above, a systematic literature search on the topic of the selection and integration of sensors for Digital Twins was carried out parallel to this contribution [206]. The results are rooted in the work of Hausmann et al. [207,208] on sensor integration. Comparable research in the field of actuators is still needed.

Finally, further research is also needed in the area of holistic approaches. In the literature, only a few aspects of a few domains are currently considered. Based on the results of the discussed domains, the consideration of all domains and, in particular, the linkage and interactions between them, is a subject for future research. Furthermore, the presented procedures are all at a moderate level of abstraction. This degree of abstraction can be varied during further research. An increase in the degree of abstraction would lead to a consideration of the partial model level or the RFLP model, which would enable a holistic view and allow the identification of systematic errors or blind spots. Reducing the level of abstraction would transform the results into specific guidelines.

6. Conclusions and Outlook

In this contribution, a systematic literature review on the development and creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems was conducted. A total of 185 articles were identified and examined. With this, the first research question (RQ1), formulated in the Introduction Section, of how the creation of Digital Twins, Cyber-Physical Systems, and Product-Service Systems is considered in the literature, was answered. Furthermore, the contents of the articles were clustered and divided into three categories: "holistic approaches", "architecture", and "models", and their corresponding subcategories. From this, two domains were identified that are necessary for the Digital Twin: models and architecture. A more detailed analysis showed that sensors and actuators are also necessary, which is a third necessary domain. However, this was not sufficiently covered in the literature, as found during the research in this contribution. In the domain of models, there is a large number of literature articles describing procedures at different levels of granularity. There are specific procedure steps described for modelling. Furthermore, abstract model scopes or models are described, but also specific model types for specific use cases. In the domain of architecture, the literature is limited to the description of the physical space, the data space, and the network. Specific components or necessary development steps are not mentioned. The dependencies and interactions between the domains are also not considered in the literature. These aspects represent clear research gaps and require further research (RQ2).

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References

1. Bienefeld, C.; Kirchner, E.; Vogt, A.; Kacmar, M. On the Importance of Temporal Information for Remaining Useful Life Prediction of Rolling Bearings Using a Random Forest Regressor. *Lubricants* **2022**, *10*, 67. [CrossRef]
2. Abramovici, M. Smart Products. In *CIRP Encyclopedia of Production Engineering*; Chatti, S., Laperrière, L., Reinhart, G., Tolio, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2019; pp. 1574–1578, ISBN 978-3-662-53119-8.
3. Tomiyama, T.; Lutters, E.; Stark, R.; Abramovici, M. Development capabilities for smart products. *CIRP Ann.* **2019**, *68*, 727–750. [CrossRef]
4. *VDI/VDE 2206:2021-11*; Development of Mechatronic and Cyber-Physical Systems. VDI: Düsseldorf, Germany, 2021.
5. Stark, R.; Anderl, R.; Thoben, K.-D.; Wartzack, S. WiGeP-Positionspapier: "Digitaler Zwilling". *Z. Wirtsch. Fabr.* **2020**, *115*, 47–50. [CrossRef]
6. Czwick, C.; Martin, G.; Anderl, R.; Kirchner, E. Cyber-Physische Zwillinge. *Z. Wirtsch. Fabr.* **2020**, *115*, 90–93. [CrossRef]
7. Hausmann, M.; Koch, Y.; Kirchner, E. Managing the uncertainty in data-acquisition by in situ measurements: A review and evaluation of sensing machine element-approaches in the context of digital twins. *Int. J. Prod. Lifecycle Manag.* **2021**, *13*, 48. [CrossRef]
8. Harder, A.; Hausmann, M.; Kraus, B.; Kirchner, E.; Hasse, A. Sensory Utilizable Design Elements: Classifications, Applications and Challenges. *Appl. Mech.* **2022**, *3*, 160–173. [CrossRef]
9. Fett, M.; Turner, E.; Breimann, R.; Kirchner, E. Extension of the system boundary of the Digital Twin onto the sensors of the Physical Twin through the introduction of redundant soft sensors. *Forsch Ingenieurwes* **2023**, *87*, 479–488. [CrossRef]
10. Vorwerk-Handing, G.; Martin, G.; Kirchner, E. Integration of Measurement Functions in Existing Systems—Retrofitting as Basis for Digitalization. In Proceedings of the NordDesign 2018, Linköping, Sweden, 14–17 August 2018.
11. Attaran, M.; Celik, B.G. Digital Twin: Benefits, use cases, challenges, and opportunities. *Decis. Anal. J.* **2023**, *6*, 100165. [CrossRef]
12. Song, W.; Sakao, T. A customization-oriented framework for design of sustainable product/service system. *J. Clean. Prod.* **2017**, *140*, 1672–1685. [CrossRef]
13. Mont, O. Clarifying the concept of product-service system. *J. Clean. Prod.* **2002**, *10*, 237–245. [CrossRef]
14. Tukker, A. Eight types of product-service system: Eight ways to sustainability? Experiences from SusProNet. *Bus. Strat. Environ.* **2004**, *13*, 246–260. [CrossRef]
15. Horváth, I.; Tepjit, S.; Rusák, Z. Compositional Engineering Frameworks for Development of Smart Cyber-Physical Systems: A Critical Survey of the Current State of Progression. In Proceedings of the 38th ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2018, Quebec, QC, Canada, 26–29 August 2018; American Society of Mechanical Engineers: New York, NY, USA, 2018, ISBN 978-0-7918-5172-2.
16. Korotunov, S.; Tabunshchyk, G.; Wolff, C. Cyber-Physical Systems Architectures and Modeling Methods Analysis for Smart Grids. In Proceedings of the 2018 IEEE 13th International Scientific and Technical Conference on Computer Sciences and Information Technologies (CSIT), Lviv, Ukraine, 11–14 September 2018; pp. 181–186, ISBN 978-1-5386-6464-3.
17. Liu, C.; Chen, F.; Zhu, J.; Zhang, Z.; Zhang, C.; Zhao, C.; Wang, T. Characteristic, Architecture, Technology, and Design Methodology of Cyber-Physical Systems. In *Industrial IoT Technologies and Applications*; Chen, F., Luo, Y., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 230–246, ISBN 978-3-319-60752-8.
18. Quadri, I.; Bagnato, A.; Brosse, E.; Sadovykh, A. Modeling Methodologies for Cyber-Physical Systems: Research Field Study on Inherent and Future Challenges. *Ada User J.* **2015**, *36*, 1666–1671.
19. Mohamed, M.A.; Kardas, G.; Challenger, M. A Systematic Literature Review on Model-driven Engineering for Cyber-Physical Systems. *arXiv* **2021**, arXiv:2103.08644. [CrossRef]

20. Mohamed, M.A.; Kardas, G.; Challenger, M. Model-Driven Engineering Tools and Languages for Cyber-Physical Systems–A Systematic Literature Review. *IEEE Access* **2021**, *9*, 48605–48630. [CrossRef]

21. Wu, X.; Goepp, V.; Siadat, A. Cyber Physical Production Systems: A Review of Design and Implementation Approaches. In Proceedings of the 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Macao, China, 15–18 December 2019; pp. 1588–1592, ISBN 978-1-7281-3804-6.

22. Wu, X.; Goepp, V.; Siadat, A. Concept and engineering development of cyber physical production systems: A systematic literature review. *Int. J. Adv. Manuf. Technol.* **2020**, *111*, 243–261. [CrossRef]

23. Pater, J.; Stadnicka, D. Towards Digital Twins Development and Implementation to Support Sustainability—Systematic Literature Review. *Manag. Prod. Eng. Rev.* **2021**, *13*, 63–73.

24. Adamenko, D.; Kunnen, S.; Pluhnau, R.; Loibl, A.; Nagarajah, A. Review and comparison of the methods of designing the Digital Twin. *Procedia CIRP* **2020**, *91*, 27–32. [CrossRef]

25. Qu, M.; Yu, S.; Chen, D.; Chu, J.; Tian, B. State-of-the-art of design, evaluation, and operation methodologies in product service systems. *Comput. Ind.* **2016**, *77*, 1–14. [CrossRef]

26. Mendes, G.H.S.; Oliveira, M.G.; Rozenfeld, H.; Marques, C.A.N.; Costa, J.M.H. Product-service system (PSS) design process methodologies: A systematic literature review. In Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 7: Product Modularisation, Product Architecture, Systems Engineering, Product Service Systems, Milan, Italy, 27–30 July 2015.

27. Müller, P.; Blessing, L. Development of product-service-systems—Comparison of product and service development process models. In Proceedings of the 16th International Conference on Engineering Design, ICED 2007, Paris, France, 28–31 July 2007.

28. Gräßle, M.; Thomas, O.; Dollmann, T. Vorgehensmodelle des Product-Service Systems Engineering. In *Hybride Wertschöpfung*; Thomas, O., Loos, P., Nüttgens, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; pp. 82–129, ISBN 978-3-642-11854-8.

29. Clayton, R.J.; Backhouse, C.J.; Dani, S. Evaluating existing approaches to product-service system design. *J. Manuf. Technol. Manag.* **2012**, *23*, 272–298. [CrossRef]

30. Haber, N.; Fargnoli, M. Designing Product-Service Systems: A Review Towards a Unified Approach. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Rabat, Morocco, 11–13 April 2017.

31. Annamalai Vasantha, G.V.; Roy, R.; Lelah, A.; Brissaud, D. A review of product-service systems design methodologies. *J. Eng. Des.* **2012**, *23*, 635–659. [CrossRef]

32. Liberati, A.; Altman, D.G.; Tetzlaff, J.; Mulrow, C.; Gøtzsche, P.C.; Ioannidis, J.P.A.; Clarke, M.; Devereaux, P.J.; Kleijnen, J.; Moher, D. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: Explanation and elaboration. *Ann. Intern. Med.* **2009**, *339*, b2700. [CrossRef]

33. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ* **2021**, *372*, n160. [CrossRef] [PubMed]

34. Google Trends. Available online: https://trends.google.de/trends/ (accessed on 6 September 2023).

35. Amrani, M.; Blouin, D.; Heinrich, R.; Rensink, A.; Vangheluwe, H.; Wortmann, A. Multi-paradigm modelling for cyber-physical systems: A descriptive framework. *Softw. Syst. Model.* **2021**, *20*, 611–639. [CrossRef]

36. Perno, M.; Hvam, L. Developing a Framework for Scoping Digital Twins in the Process Manufacturing Industry. In *SPS2020*; Säfsten, K., Elgh, F., Eds.; IOS Press: Amsterdam, The Netherlands, 2020; ISBN 9781643681467.

37. Zheng, C.; Le Duigou, J.; Hehenberger, P.; Bricogne, M.; Eynard, B. Multidisciplinary integration during conceptual design process: A survey on design methods of cyber-physical systems. In Proceedings of the 14th International Design Conference, Dubrovnik, Croatia, 16–19 May 2016; pp. 1625–1634.

38. Aigner, A.; Khelil, A. Assessment of Model-based Methodologies to Architect Cyber-Physical Systems. In Proceedings of the International Conference on Omni-Layer Intelligent Systems, Crete, Greece, 5–7 May 2019; pp. 146–151, ISBN 9781450366403.

39. Chauhan, S.; Patel, P.; Delicato, F.C.; Chaudhary, S. A development framework for programming cyber-physical systems. In Proceedings of the 2nd International Workshop on Software Engineering for Smart Cyber-Physical Systems, Austin, TX, USA, 14–22 May 2016; pp. 47–53, ISBN 9781450341714.

40. Jeschke, S.; Grassmann, R. Development of a Generic Implementation Strategy of Digital Twins in Logistics Systems under Consideration of the German Rail Transport. *Appl. Sci.* **2021**, *11*, 10289. [CrossRef]

41. Riedelsheimer, T.; Gogineni, S.; Stark, R. Methodology to develop Digital Twins for energy efficient customizable IoT-Products. *Procedia CIRP* **2021**, *98*, 258–263. [CrossRef]

42. Thammarak, K. Agile Approach for Cyber-Physical Systems (CPS) Development using Cloud Computing. In Proceedings of the 2019 23rd International Computer Science and Engineering Conference (ICSEC), Phuket, Thailand, 30 October–1 November 2019; pp. 43–47, ISBN 978-1-7281-2544-2.

43. Schuh, G.; Zeller, V.; Stroh, M.-F.; Harder, P. Finding the Right Way Towards a CPS—A Methodology for Individually Selecting Development Processes for Cyber-Physical Systems. In *Collaborative Networks and Digital Transformation*; Camarinha-Matos, L.M., Afsarmanesh, H., Antonelli, D., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 81–90, ISBN 978-3-030-28463-3.

44. Sadek, T.; Köster, M. Conceptual Development of Industrial Product-Service Systems—A model-based Approach. *Enterp. Model. Inf. Syst. Archit.* **2015**, *6*, 35–53. [CrossRef]

45. Pezzotta, G.; Cavalieri, S.; Gaiardelli, P. A spiral process model to engineer a product service system: An explorative analysis through case studies. *CIRP J. Manuf. Sci. Technol.* **2012**, *5*, 214–225. [CrossRef]

46. Lowenstein, D.; Mueth, C. Implementing a Digital Twin, Design and Test, Test and Measurement Strategy. In Proceedings of the 2022 IEEE AUTOTESTCON, National Harbor, MD, USA, 29 August–1 September 2022; pp. 1–6, ISBN 978-1-7281-5400-8.

47. Hehenberger, P.; Vogel-Heuser, B.; Bradley, D.; Eynard, B.; Tomiyama, T.; Achiche, S. Design, modelling, simulation and integration of cyber physical systems: Methods and applications. *Comput. Ind.* **2016**, *82*, 273–289. [CrossRef]

48. Slomka, F.; Kollmann, S.; Moser, S.; Kempf, K. A Multidisciplinary Design Methodology for Cyber-physical Systems. In Proceedings of the 7th International Wireless Communications and Mobile Computing Conference, Istanbul, Turkey, 4–8 July 2011.

49. Kofanov, Y.N.; Sotnikova, S.Y. Method of Digital Counterpart Creation of Physical Processes at Productive Foresight Modeling of Cyber-Physical Systems. In Proceedings of the 2020 Moscow Workshop on Electronic and Networking Technologies (MWENT), Moscow, Russia, 11–13 March 2020; pp. 1–5, ISBN 978-1-7281-2572-5.

50. Jarvis, D.; Jarvis, J.; Yang, C.-W.; Sinha, R.; Vyatkin, V. Janus: A Systems Engineering Approach to the Design of Industrial Cyber-Physical Systems. In Proceedings of the 2019 IEEE 17th International Conference on Industrial Informatics (INDIN), Helsinki, Finland, 22–25 July 2019; pp. 87–92, ISBN 978-1-7281-2927-3.

51. Merlo, C.; Akle, A.A.; Llaria, A.; Terrasson, G.; Villeneuve, E.; Pilnière, V. Proposal of a user-centred approach for CPS design: Pillbox case study. *IFAC-Pap.* **2019**, *51*, 196–201. [CrossRef]

52. Rogall, C.; Mennenga, M.; Herrmann, C.; Thiede, S. Systematic Development of Sustainability-Oriented Cyber-Physical Production Systems. *Sustainability* **2022**, *14*, 2080. [CrossRef]

53. Francalanza, E.; Mercieca, M.; Fenech, A. Modular System Design Approach for Cyber Physical Production Systems. *Procedia CIRP* **2018**, *72*, 486–491. [CrossRef]

54. Nogueira de Andrade, M.; Lepikson, H.A.; Machado, C.A.T. A New Framework and Methodology for Digital Twin Development. In Proceedings of the 2021 14th IEEE International Conference on Industry Applications (INDUSCON), São Paulo, Brazil, 15–18 August 2021; pp. 134–138, ISBN 978-1-6654-4118-6.

55. Psarommatis, F.; May, G. A literature review and design methodology for digital twins in the era of zero defect manufacturing. *Int. J. Prod. Res.* **2023**, *61*, 5723–5743. [CrossRef]

56. Jensen, J.C.; Chang, D.H.; Lee, E.A. A model-based design methodology for cyber-physical systems. In Proceedings of the 2011 7th International Wireless Communications and Mobile Computing Conference (IWCMC 2011), Istanbul, Turkey, 4–8 July 2011; pp. 1666–1671, ISBN 978-1-4244-9539-9.

57. Julien, N.; Martin, E. A Usage-Driven Approach to Characterize and Implement Industrial Digital Twins. In Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021), Angers, France, 19–23 September 2021; Castanier, B., Cepin, M., Bigaud, D., Berenguer, C., Eds.; Research Publishing Services: Singapore, 2021; pp. 1721–1728, ISBN 978-981-18-2016-8.

58. Julien, N.; Martin, E. Typology of Manufacturing Digital Twins: A First Step Towards a Deployment Methodology. In *Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future*; Borangiu, T., Trentesaux, D., Leitão, P., Cardin, O., Joblot, L., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 161–172, ISBN 978-3-030-99107-4.

59. Ballarino, A.; Brondi, C.; Brusaferri, A.; Chizzoli, G. The CPS and LCA Modelling: An Integrated Approach in the Environmental Sustainability Perspective. In *Collaboration in a Data-Rich World*; Camarinha-Matos, L.M., Afsarmanesh, H., Fornasiero, R., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 543–552, ISBN 978-3-319-65150-7.

60. Rizvi, M.A.K.; Chew, E. Towards systematic design of cyber-physical product-service systems. In Proceedings of the 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018; pp. 2961–2974.

61. Rakov, D.L. Modelling and presentation of cyber-physical systems on the morphological approach basis. *J. Phys. Conf. Ser.* **2021**, *1901*, 12044. [CrossRef]

62. Larsen, P.G.; Macedo, H.D.; Fitzgerald, J.; Pfeifer, H.; Benedikt, M.; Tonetta, S.; Marguglio, A.; Veneziano, G.; Sutton, L.; Gusmeroli, S.; et al. HUBCAP: A Novel Collaborative Approach to Model-Based Design of Cyber-Physical Systems. In *Simulation and Modeling Methodologies, Technologies and Applications*; Obaidat, M.S., Oren, T., de Rango, F., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 90–110, ISBN 978-3-030-84810-1.

63. Arioli, V.; Ruggeri, G.; Sala, R.; Pirola, F.; Pezzotta, G. A Methodology for the Design and Engineering of Smart Product Service Systems: An Application in the Manufacturing Sector. *Sustainability* **2023**, *15*, 64. [CrossRef]

64. Asmar, L.; Rabe, M.; Low, C.Y.; Yee, J.; Kühn, A.; Dumitrescu, R. Framework for the agile development of innovative Product-Service-Systems for existing physical rehabilitation systems. *Procedia Manuf.* **2018**, *24*, 147–152. [CrossRef]

65. Chen, D.; Chu, X.; Su, Y.; Chu, D. A new conceptual design approach for context-aware product service system. In Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Selangor, Malaysia, 9–12 December 2014; pp. 1389–1393, ISBN 978-1-4799-6410-9.

66. Cerri, D.; Terzi, S. How to Design Product Service Systems? Proposal of a framework. In Proceedings of the 2016 International Conference on Engineering, Technology and Innovation/IEEE lnternational Technology Management Conference (ICE/ITMC), Trondheim, Norway, 13–15 June 2016; pp. 1–3, ISBN 978-1-5090-2935-8.

67. Kim, Y.S.; Maeng, J.W.; Lee, S.W. Product-Service Systems Design with Functions and Activities: Methodological Framework and Case Studies. In Proceedings of the International Conference on Design and Emotion, Chicago, IL, USA, 4–7 October 2010.

68. Minato, S.; Idei, Y.; Mitake, Y.; Shimomura, Y. A Design process management method for product-service systems. In Proceedings of the 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018; pp. 2913–2924.

69. González Chávez, C.A.; Romero, D.; Rossi, M.; Luglietti, R.; Johansson, B. Circular Lean Product-Service Systems Design: A Literature Review, Framework Proposal and Case Studies. *Procedia CIRP* **2019**, *83*, 419–424. [CrossRef]

70. Nemoto, Y.; Akasaka, F.; Shimomura, Y. A Knowledge Management Method for Supporting Conceptual Design of Product-Service Systems. In Proceedings of the 2013 ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications, Portland, OR, USA, 4–7 August 2013; ISBN 978-0-7918-5591-1.

71. Niemöller, C.; Özcan, D.; Metzger, D.; Thomas, O. Towards a Design Science-Driven Product-Service System Engineering Methodology. In *Advancing the Impact of Design Science: Moving from Theory to Practice*; Hutchison, D., Kanade, T., Kittler, J., Kleinberg, J.M., Kobsa, A., Mattern, F., Mitchell, J.C., Naor, M., Nierstrasz, O., Pandu Rangan, C., et al., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 180–193, ISBN 978-3-319-06700-1.

72. Pezzotta, G.; Sassanelli, C.; Pirola, F.; Sala, R.; Rossi, M.; Fotia, S.; Koutoupes, A.; Terzi, S.; Mourtzis, D. The Product Service System Lean Design Methodology (PSSLDM). *J. Manuf. Technol. Manag.* **2018**, *29*, 1270–1295. [CrossRef]

73. Rennpferdt, C.; Krause, D. Towards a framework for the design of variety-oriented product-service systems. *Proc. Des. Soc. Des. Conf.* **2020**, *1*, 1345–1354. [CrossRef]

74. Rosen, D.; Choi, Y.M. Extending product family design methods to product-service-system family design. *Proc. Des. Soc.* **2021**, *1*, 1557–1566. [CrossRef]

75. Tran, T.A.; Park, J.Y. Development of integrated design methodology for various types of product-service systems. *J. Comput. Des. Eng.* **2014**, *1*, 37–47. [CrossRef]

76. Annamalai Vasantha, G.V.; Hitoshi, K.; Romana, H.; Rajkumar, R.; Tetsuo, T.; Steve, E.; Ashutosh, T.; Stewart, W. A manufacturing framework for capability-based product-service systems design. *J. Remanufacturing* **2013**, *3*, 8. [CrossRef]

77. Annamalai Vasantha, G.V.; Hussain, R.; Roy, R.; Tiwari, A.; Evans, S. A Framework for designing product-service systems. In Proceedings of the 18th International Conference on Engineering Design (ICED 11), Lyngby/Copenhagen, Denmark, 15–19 August 2011.

78. Apostolov, H.; Fischer, M.; Olivotti, D.; Dreyer, S.; Breitner, M.H.; Eigner, M. Modeling Framework for Integrated, Model-based Development of Product-Service Systems. *Procedia CIRP* **2018**, *73*, 9–14. [CrossRef]

79. Marques, P.; Cunha, P.F.; Valente, F.; Leitão, A. A Methodology for Product-service Systems Development. *Procedia CIRP* **2013**, *7*, 371–376. [CrossRef]

80. Tran, T.; Park, J. Development of a framework to customize design methodologies for product service systems. In Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management (IEOM), Dubai, United Arab Emirates, 3–5 March 2015; pp. 1–9, ISBN 978-1-4799-6065-1.

81. Tran, T.; Park, J.Y. Development of a novel set of criteria to select methodology for designing product service systems. *J. Comput. Des. Eng.* **2016**, *3*, 112–120. [CrossRef]

82. Wang, K.; Wang, Y.; Li, Y.; Fan, X.; Xiao, S.; Hu, L. A review of the technology standards for enabling digital twin. *Digit. Twin* **2022**, *2*, 4. [CrossRef]

83. Johnson, R.; Foote, B. Designing Reusable Classes. *J. Object-Oriented Program.* **1988**, *1*, 22–35.

84. Gartner Glossary. Available online: https://www.gartner.com/en/information-technology/glossary/it-infrastructure (accessed on 9 August 2023).

85. Díaz, J.; Pérez, J.; Pérez, J.; Garbajosa, J. Conceptualizing a framework for cyber-physical systems of systems development and deployment. In Proceedings of the 10th European Conference on Software Architecture Workshops, Copenhagen, Denmark, 28 November–2 December 2016; pp. 1–7, ISBN 9781450347815.

86. Dumitrache, I.; Sacala, I.S.; Moisescu, M.A.; Caramihai, S.I. A Conceptual Framework for Modeling and Design of Cyber-Physical Systems. *Stud. Inform. Control.* **2017**, *26*, 325–334. [CrossRef]

87. Castro, H.; Pinto, N.; Pereira, F.; Ferreira, L.; Ávila, P.; Bastos, J.; Putnik, G.D.; Cruz-Cunha, M. Cyber-Physical Systems using Open Design: An approach towards an Open Science Lab for Manufacturing. *Procedia Comput. Sci.* **2022**, *196*, 381–388. [CrossRef]

88. Chen, J.; Yang, J.; Zhou, H.; Xiang, H.; Zhu, Z.; Li, Y.; Lee, C.-H.; Xu, G. CPS Modeling of CNC Machine Tool Work Processes Using an Instruction-Domain Based Approach. *Engineering* **2015**, *1*, 247–260. [CrossRef]

89. Dittmann, S.; Zhang, P.; Glodde, A.; Dietrich, F. Towards a scalable implementation of digital twins—A generic method to acquire shopfloor data. *Procedia CIRP* **2021**, *96*, 157–162. [CrossRef]

90. Mishra, A.; Ray, A.K. A Novel Layered Architecture and Modular Design Framework for Next-gen Cyber Physical System. In Proceedings of the 2022 International Conference on Computer Communication and Informatics (ICCCI), Coimbatore, India, 25–27 January 2022; pp. 1–8, ISBN 978-1-6654-8035-2.

91. Rajhans, A.; Cheng, S.-W.; Schmerl, B.; Garlan, D.; Krogh, B.H.; Agbi, C.; Bhave, A. An Architectural Approach to the Design and Analysis of Cyber-Physical Systems. In Proceedings of the Models in Software Engineering, Workshops and Symposia at Models 2009, Denver, CO, USA, 4–9 October 2009. [CrossRef]

92. Shangguan, D.; Chen, L.; Ding, J. A Hierarchical Digital Twin Model Framework for Dynamic Cyber-Physical System Design. In Proceedings of the 5th International Conference on Mechatronics and Robotics Engineering, Rome, Italy, 16–19 February 2019; pp. 123–129, ISBN 9781450360951.

93. Zhang, C.; Sun, Q.; Sun, W.; Mu, X.; Wang, Y. A construction method of digital twin model for contact characteristics of assembly interface. *Int. J. Adv. Manuf. Technol.* **2021**, *113*, 2685–2699. [CrossRef]

94. Cao, R.; Hao, L.; Gao, Q.; Deng, J.; Chen, J. Modeling and Decision-Making Methods for a Class of Cyber–Physical Systems Based on Modified Hybrid Stochastic Timed Petri Net. *IEEE Syst. J.* **2020**, *14*, 4684–4693. [CrossRef]

95. Darwish, A.; Hassanien, A.E. Cyber physical systems design, methodology, and integration: The current status and future outlook. *J. Ambient. Intell. Humaniz. Comput.* **2018**, *9*, 1541–1556. [CrossRef]

96. Casola, V.; de Benedictis, A.; Mazzocca, C.; Montanari, R. Designing Secure and Resilient Cyber-Physical Systems: A Model-based Moving Target Defense Approach. *IEEE Trans. Emerg. Topics Comput.* **2022**, 1–12. [CrossRef]

97. Farhadi, A.; Lee, S.K.H.; Hinchy, E.P.; O'Dowd, N.P.; McCarthy, C.T. The Development of a Digital Twin Framework for an Industrial Robotic Drilling Process. *Sensors* **2022**, *22*, 7232. [CrossRef]

98. Azeri, N.; Hioual, O.; Hioual, O. Towards an Approach for Modeling and Architecting of Self-Adaptive Cyber-Physical Systems. In Proceedings of the 2022 4th International Conference on Pattern Analysis and Intelligent Systems (PAIS), Oum El Bouaghi, Algeria, 12–13 October 2022; pp. 1–7, ISBN 978-1-6654-6161-0.

99. Benzadri, Z.; Bouheroum, T.; Cheloufi, Y.O.; Hassani, M.N.; Belala, F. A Modelling Framework for CPS-Based Industry 4.0: Application to Manufacturing Systems. In *Modern Industrial IoT, Big Data and Supply Chain*; Chang, V., Ramachandran, M., Méndez Muñoz, V., Eds.; Springer: Singapore, 2021; pp. 3–10, ISBN 978-981-33-6140-9.

100. Gao, Y.; Lv, H.; Hou, Y.; Liu, J.; Xu, W. Real-time Modeling and Simulation Method of Digital Twin Production Line. In Proceedings of the 2019 IEEE 8th Joint International Information Technology and Artificial Intelligence Conference (ITAIC), Chongqing, China, 24–26 May 2019; pp. 1639–1642, ISBN 978-1-5386-8178-7.

101. Jia, G.; Jinghai, X.; Mi, S.; Dongyu, S.; Tao, W.; Youhang, Y.; Shaorong, W. Substation Digital Twin Framework Design and Key Technology Research. In Proceedings of the 2022 IEEE 3rd China International Youth Conference on Electrical Engineering (CIYCEE), Wuhan, China, 3–5 November 2022; pp. 1–8, ISBN 978-1-6654-7732-1.

102. Li, Z.; Kong, Y.; Ren, L. A Multi-level Heterogeneous Model data Framework for Intelligent Factory Digital-Twin Systems. In Proceedings of the 33rd European Modeling & Simulation Symposium, Online, 15–17 September 2021; pp. 152–157, ISBN 9788885741577.

103. Wang, H.; Jin, G. Digital Twin Model Construction and Management Method of Workshop Based on Cloud Platform. In Proceedings of the 2022 11th International Conference of Information and Communication Technology (ICTech), Wuhan, China, 4–6 February 2022; pp. 28–32, ISBN 978-1-6654-9694-0.

104. Hung, M.-H.; Lin, Y.-C.; Hsiao, H.-C.; Chen, C.-C.; Lai, K.-C.; Hsieh, Y.-M.; Tieng, H.; Tsai, T.-H.; Huang, H.-C.; Yang, H.-C.; et al. A Novel Implementation Framework of Digital Twins for Intelligent Manufacturing Based on Container Technology and Cloud Manufacturing Services. *IEEE Trans. Automat. Sci. Eng.* **2022**, *19*, 1614–1630. [CrossRef]

105. Kovalyov, S.P. Design and Development of a Power System Digital Twin: A Model-based Approach. In Proceedings of the 2021 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA), Lipetsk, Russia, 10–12 November 2021; pp. 843–848, ISBN 978-1-6654-3981-7.

106. Peng, H.; Zhang, Z.; Chen, G.; Xu, Z.; Wang, Y. Construction Method of Digital Twin Model for Distribution Automation Terminal. In Proceedings of the 2022 China International Conference on Electricity Distribution (CICED), Changsha, China, 7–8 September 2022; pp. 718–722, ISBN 978-1-6654-5268-7.

107. Silva, G.; Araujo, A. Framework for the Development of a Digital Twin for Solar Water Heating Systems. In Proceedings of the 2022 International Conference on Control, Automation and Diagnosis (ICCAD), Lisbon, Portugal, 13–15 July 2022; pp. 1–5, ISBN 978-1-6654-9794-7.

108. Xie, J.; Guo, J.; Sun, M.; Su, D.; Li, W.; Chen, S.; Wang, S. A digital twin five-dimensional structural model construction method suitable for active distribution network. In Proceedings of the 2022 2nd International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT), Hangzhou, China, 1–3 July 2022; pp. 418–426, ISBN 978-1-6654-5928-0.

109. Zheng, X.; Psarommatis, F.; Petrali, P.; Turrin, C.; Lu, J.; Kiritsis, D. A Quality-Oriented Digital Twin Modelling Method for Manufacturing Processes Based on A Multi-Agent Architecture. *Procedia Manuf.* **2020**, *51*, 309–315. [CrossRef]

110. Du, W.; Zhang, T.; Zhang, G.; Wang, J. A Digital Twin Framework and an Implementation Method for Urban Rail Transit. In Proceedings of the 2021 Global Reliability and Prognostics and Health Management (PHM-Nanjing), Nanjing, China, 15–17 October 2021; pp. 1–4, ISBN 978-1-6654-0131-9.

111. Upadhyay, R.; Borzacchiello, D.; Aguado, J.; Garg, U.; Arona, V. Generic Framework for Developing Process Digital Twin Applicable to High Value-Added Manufacturing. In Proceedings of the SAMPE Nexus 2021, Online, 29 June–1 July 2021; ISBN 978-1-934551-39-4.

112. Veljovic, A.; Matijevic, M.; Nedeljkovic, M.; Cantrak, D. An approach to design of the cyber-physical systems for engineering-education. In Proceedings of the 2018 IEEE Global Engineering Education Conference (EDUCON), Santa Cruz, Spain, 17–20 April 2018; pp. 1402–1407, ISBN 978-1-5386-2957-4.

113. Pang, T.Y.; Pelaez Restrepo, J.D.; 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]

114. Eickhoff, T.; Forte, S.; Göbel, J.C. Approach for Developing Digital Twins of Smart Products Based on Linked Lifecycle Information. *Proc. Des. Soc.* **2022**, *2*, 1559–1568. [CrossRef]

115. Babiceanu, R.F.; Seker, R. Manufacturing Cyber-Physical Systems Enabled by Complex Event Processing and Big Data Environments: A Framework for Development. In *Service Orientation in Holonic and Multi-Agent Manufacturing*; Borangiu, T., Thomas, A., Trentesaux, D., Eds.; Springer International Publishing: Cham, Switzerland, 2015; pp. 165–173, ISBN 978-3-319-15158-8.

116. Eyre, J.M.; Dodd, T.J.; Freeman, C.; Lanyon-Hogg, R.; Lockwood, A.J.; Scott, R.W. Demonstration of an Industrial Framework for an Implementation of a Process Digital Twin. In Proceedings of the ASME 2018 International Mechanical Engineering Congress and Exposition, Pittsburgh, PA, USA, 9–15 November 2018; ISBN 978-0-7918-5201-9.

117. Liu, C.L.; Hong, X.; Zhu, Z.; Xu, X. Machine tool digital twin: Modelling methodology and applications. In Proceedings of the 48th International Conference on Computers and Industrial Engineering, Auckland, New Zealand, 2–5 December 2018.

118. Carnì, D.L.; Grimaldi, D.; Lamonaca, F.; Nigro, L.; Sciammarella, P.F. From distributed measurement systems to cyber-physical systems: A design approach. *Int. J. Comput.* **2017**, *16*, 66–73. [CrossRef]

119. Shin, D.-H.; He, S.; Zhang, J. Robust and Cost-Effective Design of Cyber-Physical Systems: An Optimal Middleware Deployment Approach. *IEEE/ACM Trans. Netw.* **2016**, *24*, 1081–1094. [CrossRef]

120. Li, H.; Dimitrovski, A.; Song, J.B.; Han, Z.; Qian, L. Communication Infrastructure Design in Cyber Physical Systems with Applications in Smart Grids: A Hybrid System Framework. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1689–1708. [CrossRef]

121. Bernardy, A.; Jordan, F.; Schuh, G.; Stich, V.; Zeller, V. Basic Methodology for Cyber Physical System Modelling. In Proceedings of the 2018 Portland International Conference on Management of Engineering and Technology (PICMET), Honolulu, HI, USA, 19–23 August 2018; pp. 1–6, ISBN 978-1-890843-37-3.

122. Morabito, L.; Ippolito, M.; Pastore, E.; Alfieri, A.; Montagna, F. A Discrete Event Simulation Based Approach for Digital Twin Implementation. *IFAC-PapersOnLine* **2021**, *54*, 414–419. [CrossRef]

123. Lektauers, A.; Pecerska, J.; Bolsakovs, V.; Romanovs, A.; Grabis, J.; Teilans, A. A Multi-Model Approach for Simulation-Based Digital Twin in Resilient Services. *WSEAS Trans. Syst. Control.* **2021**, *16*, 133–145. [CrossRef]

124. Bonci, A.; Pirani, M.; Longhi, S. A database-centric approach for the modeling, simulation and control of cyber-physical systems in the factory of the future. *IFAC-PapersOnLine* **2016**, *49*, 249–254. [CrossRef]

125. Bonci, A.; Pirani, M.; Longhi, S. A Database-Centric Framework for the Modeling, Simulation, and Control of Cyber-Physical Systems in the Factory of the Future. *J. Intell. Syst.* **2018**, *27*, 659–679. [CrossRef]

126. Lopez, V.; Akundi, A. A Conceptual Model-based Systems Engineering (MBSE) approach to develop Digital Twins. In Proceedings of the 2022 IEEE International Systems Conference (SysCon), Montreal, QC, Canada, 25–28 April 2022; pp. 1–5, ISBN 978-1-6654-3992-3.

127. Michael, J.; Wortmann, A. Towards Development Platforms for Digital Twins: A Model-Driven Low-Code Approach. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems*; Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, D., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 333–341, ISBN 978-3-030-85873-5.

128. Heindl, W.; Stary, C. Structured Development of Digital Twins—A Cross-Domain Analysis towards a Unified Approach. *Processes* **2022**, *10*, 1490. [CrossRef]

129. Babris, K.; Nikiforova, O.; Sukovskis, U. Brief Overview of Modelling Methods, Life-Cycle and Application Domains of Cyber-Physical Systems. *Appl. Comput. Syst.* **2019**, *24*, 1–8. [CrossRef]

130. Qamsane, Y.; Moyne, J.; Toothman, M.; Kovalenko, I.; Balta, E.C.; Faris, J.; Tilbury, D.M.; Barton, K. A Methodology to Develop and Implement Digital Twin Solutions for Manufacturing Systems. *IEEE Access* **2021**, *9*, 44247–44265. [CrossRef]

131. Follath, A.; Bross, F.; Galka, S. Vorgehensmodell zur Erstellung Digitaler Zwillinge für Produktion und Logistik. *Z. Wirtsch. Fabr.* **2022**, *117*, 691–696. [CrossRef]

132. Koch, Y.; Husung, S.; Röhnert, F.; Mahboob, A.; Frank, M.G.; Kirchner, E. A Method for the Support of the Design for Digital Twin Solution and Its Application on a Gearbox System. *Proc. Des. Soc.* **2022**, *2*, 1609–1618. [CrossRef]

133. La, H.J.; Kim, S.D. A Service-Based Approach to Designing Cyber Physical Systems. In Proceedings of the 2010 IEEE/ACIS 9th International Conference on Computer and Information Science (ICIS), Yamagata, Japan, 18–20 August 2010; pp. 895–900, ISBN 978-1-4244-8198-9.

134. Zheng, M.; Tian, L. A Hierarchical Integrated Modeling Method for the Digital Twin of Mechanical Products. *Machines* **2022**, *10*, 2. [CrossRef]

135. Sales, D.C.; Becker, L.B.; Koliver, C. The systems architecture ontology (SAO): An ontology-based design method for cyber–physical systems. *Appl. Comput. Inform.* **2022**. [CrossRef]

136. Steinmetz, C.; Schroeder, G.N.; Sulak, A.; Tuna, K.; Binotto, A.; Rettberg, A.; Pereira, C.E. A methodology for creating semantic digital twin models supported by knowledge graphs. In Proceedings of the 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), Stuttgart, Germany, 6–9 September 2022; pp. 1–7, ISBN 978-1-6654-9996-5.

137. Kolberg, D.; Berger, C.; Pirvu, B.-C.; Franke, M.; Michniewicz, J. CyProF—Insights from a Framework for Designing Cyber-Physical Systems in Production Environments. *Procedia CIRP* **2016**, *57*, 32–37. [CrossRef]

138. Schroeder, G.N.; Steinmetz, C.; Rodrigues, R.N.; Henriques, R.V.B.; Rettberg, A.; Pereira, C.E. A Methodology for Digital Twin Modeling and Deployment for Industry 4.0. *Proc. IEEE* **2021**, *109*, 556–567. [CrossRef]

139. He, X.; Dong, Z.; Fu, Y. A Systematic Approach for Developing Cyber Physical Systems. In Proceedings of the 30th International Conference on Software Engineering and Knowledge Engineering, San Francisco, CA, USA, 1–3 July 2018; pp. 456–505.

140. Timoshenko, A.V.; Perlov, A.Y.; Kazantsev, A.M.; Khodataev, N.A.; Lvov, K.V. Methodology for the Development of a Digital Twin of Radar Stations of a Functional Block Structure. In Proceedings of the 2022 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SYNCHROINFO), Arkhangelsk, Russia, 29 June–1 July 2022; pp. 1–4, ISBN 978-1-6654-7064-3.

141. Gao, Z.; Xia, H.; Dai, G. A model-based software development method for automotive cyber-physical systems. *Comput. Sci. Inf. Syst.* **2011**, *8*, 1277–1301. [CrossRef]

142. Zheng, Z.; Ni, D. A Hybrid Modelling Approach for the Digital Twin of Device Fabrication. In Proceedings of the 2022 China Semiconductor Technology International Conference (CSTIC), Shanghai, China, 20–21 June 2022; pp. 1–3, ISBN 978-1-6654-9758-9.

143. Wan, J.; Canedo, A.; Al Faruque, M.A. Functional Model-Based Design Methodology for Automotive Cyber-Physical Systems. *IEEE Syst. J.* **2017**, *11*, 2028–2039. [CrossRef]

144. Ma, J.; Wang, Q.; Jiang, Z.; Zhao, Z. A hybrid modeling methodology for cyber physical production systems: Framework and key techniques. *Prod. Eng. Res. Devel.* **2021**, *15*, 773–790. [CrossRef]

145. Yang, H.; Lai, Z.; Liu, Y.; Hu, N.; Diao, B.; Pan, Y. Research on Modeling Method of System Reliability Digital Twin. In Proceedings of the 2021 2nd International Conference on Electronics, Communications and Information Technology (CECIT), Sanya, China, 27–29 December 2021; pp. 1005–1013, ISBN 978-1-6654-3757-8.

146. Constantinescu, C.; Giosan, S.; Matei, R.; Wohlfeld, D. A holistic methodology for development of Real-Time Digital Twins. *Procedia CIRP* **2020**, *88*, 163–166. [CrossRef]

147. Wan, G.; Wang, P.; Xue, L.; Zeng, P. An Integrated Design Method for Cyber-Physical Production Systems. In Proceedings of the 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chongqing, China, 12–14 October 2018; pp. 791–796, ISBN 978-1-5386-4509-3.

148. Luo, W.; Hu, T.; Zhang, C.; Wei, Y. Digital twin for CNC machine tool: Modeling and using strategy. *J. Ambient. Intell. Humaniz. Comput.* **2019**, *10*, 1129–1140. [CrossRef]

149. Luo, W.; Hu, T.; Zhu, W.; Tao, F. Digital twin modeling method for CNC machine tool. In Proceedings of the 2018 IEEE 15th International Conference on Networking, Sensing and Control (ICNSC), Zhuhai, China, 27–29 March 2018; pp. 1–4, ISBN 978-1-5386-5053-0.

150. Pinto, A. Modeling Methodology for Autonomous Cyber-Physical Systems. In Proceedings of the 2022 2nd International Workshop on Computation-Aware Algorithmic Design for Cyber-Physical Systems (CAADCPS), Milan, Italy, 3–6 May 2022; pp. 1–2, ISBN 978-1-6654-8201-1.

151. Afendi, M. Afendi, M. A Correct by Construction Approach for the Modeling and the Verification of Cyber-Physical Systems in Event-B. In *Rigorous State-Based Methods*; Raschke, A., Méry, D., Houdek, F., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 401–404, ISBN 978-3-030-48076-9.

152. Bruno, G. A modeling approach for Cyber-Physical Systems based on collaborative processes. *IFAC-PapersOnLine* **2019**, *52*, 2764–2769. [CrossRef]

153. Levshun, D.; Chechulin, A.; Kotenko, I.; Chevalier, Y. Design and Verification Methodology for Secure and Distributed Cyber-Physical Systems. In Proceedings of the 2019 10th IFIP International Conference on New Technologies, Mobility and Security (NTMS), Canary Islands, Spain, 24–26 June 2019; pp. 1–5, ISBN 978-1-7281-1542-9.

154. Sanfelice, R. Analysis and Design of Cyber-Physical Systems: A Hybrid Control Systems Approach. In *Cyber-Physical Systems*; Rawat, D., Rodrigues, J., Stojmenovic, I., Eds.; CRC Press: Boca Raton, FL, USA, 2015; pp. 3–31, ISBN 978-1-4822-6332-9.

155. Zhao, P.; Liu, J.; Jing, X.; Tang, M.; Sheng, S.; Zhou, H.; Liu, X. The Modeling and Using Strategy for the Digital Twin in Process Planning. *IEEE Access* **2020**, *8*, 41229–41245. [CrossRef]

156. Ungureanu, G.; Sander, I. A layered formal framework for modeling of cyber-physical systems. In Proceedings of the 2017 Design, Automation & Test in Europe Conference & Exhibition (DATE), Lausanne, Switzerland, 27–31 March 2017; pp. 1715–1720, ISBN 978-3-9815370-8-6.

157. Wang, Y.; Yang, W.; Zheng, Y.; Zhang, L.; Zhang, Z. Digital Twin Modeling Method for Container Terminal in Port. In Proceedings of the 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, St. Louis, MO, USA, 14–17 August 2022; ISBN 978-0-7918-8621-2.

158. Yusupbekov, N.; Abdurasulov, F.; Adilov, F.; Ivanyan, A. Concepts and Methods of "Digital Twins" Models Creation in Industrial Asset Performance Management Systems. In *Intelligent and Fuzzy Techniques: Smart and Innovative Solutions*; Kahraman, C., Cevik Onar, S., Oztaysi, B., Sari, I.U., Cebi, S., Tolga, A.C., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 1589–1595, ISBN 978-3-030-51155-5.

159. Bagozi, A.; Bianchini, D.; de Antonellis, V. A data-driven context-based approach for modelling Resilient Cyber Physical Production Systems. In Proceedings of the 29th Italian Symposium on Advanced Database Systems, Pizzo Calabro, Italy, 5–9 September 2021.

160. Yang, K.-X.; Xia, Z.-W.; Wang, Y.-F.; Jin, L.-J. Research on Digital Twin Modeling Method of Electrical Equipment Spraying Production Line Based on Kalman Filter. *J. Mech. Eng. Robot. Res.* **2022**, *11*, 227–233. [CrossRef]

161. Zhang, L. Multi-dimensional Analysis and Design Method for Aerospace Cyber-physical Systems. In Proceedings of the 2013 12th International Symposium on Distributed Computing and Applications to Business, Engineering & Science (DCABES), Los Alamitos, CA, USA, 2–4 September 2013; pp. 197–201, ISBN 978-0-7695-5060-2.

162. Zhang, L. Multi-view Approach for Modeling Aerospace Cyber-physical Systems. In Proceedings of the 2013 IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing, Beijing, China, 20–23 August 2013; pp. 1319–1324, ISBN 978-0-7695-5046-6.

163. Zhang, L. View Oriented Approach to Specify and Model Aerospace Cyber-physical Systems. In Proceedings of the 2013 IEEE International Conference on Dependable, Autonomic and Secure Computing (DASC), Chengdu, China, 21–22 December 2013; pp. 296–303, ISBN 978-1-4799-3381-5.

164. Zhang, L. An Approach to Model Complex Big Data Driven Cyber Physical Systems. In *Algorithms and Architectures for Parallel Processing*; Sun, X., Qu, W., Stojmenovic, I., Zhou, W., Li, Z., Guo, H., Min, G., Yang, T., Wu, Y., Liu, L., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 740–754, ISBN 978-3-319-11196-4.

165. Zhang, L. Specification and Design Method for Big Data Driven Cyber Physical Systems. In *Progress in Systems Engineering*; Selvaraj, H., Zydek, D., Chmaj, G., Eds.; Springer International Publishing: Cham, Switzerland, 2015; pp. 849–857, ISBN 978-3-319-08421-3.

166. Zhang, L. Convergence Approach to Model Physical World and Cyber World of Aviation Cyber Physical System. In Proceedings of the 2014 IEEE 12th International Conference on Dependable, Autonomic and Secure Computing (DASC), Dalian, China, 24–27 August 2014; pp. 418–423, ISBN 978-1-4799-5079-9.

167. Zhang, L. Specification and Design of Cyber Physical Systems Based on System of Systems Engineering Approach. In Proceedings of the 2018 17th International Symposium on Distributed Computing and Applications for Business Engineering and Science (DCABES), Wuxi, China, 19–23 October 2018; pp. 300–303, ISBN 978-1-5386-7445-1.

168. Buffoni, L.; Ochel, L.; Pop, A.; Fritzson, P.; Fors, N.; Hedin, G.; Taha, W.; Sjölund, M. Open Source Languages and Methods for Cyber-Physical System Development: Overview and Case Studies. *Electronics* **2021**, *10*, 902. [CrossRef]

169. Attarzadeh-Niaki, S.-H.; Sander, I. An extensible modeling methodology for embedded and cyber-physical system design. *Simulation* **2016**, *92*, 771–794. [CrossRef]

170. Staroletov, S.; Shilov, N.; Zyubin, V.; Liakh, T.; Rozov, A.; Konyukhov, I.; Shilov, I.; Baar, T.; Schulte, H. Model-Driven Methods to Design of Reliable Multiagent Cyber-Physical Systems. In Proceedings of the MacsPro 2019—Modeling and Analysis of Complex Systems and Processes, Vienna, Austria, 21–23 March 2019.

171. Woo, H.; Yi, J.; Browne, J.C.; Mok, A.K.; Atkins, E.; Xie, F. Design and Development Methodology for Resilient Cyber-Physical Systems. In Proceedings of the 2008 28th International Conference on Distributed Computing Systems Workshops (ICDCS Workshops), Beijing, China, 17–20 June 2008; pp. 525–528.

172. Zhang, L. QoS Modeling for Dependable and Distributed Cyber Physical Systems Using Aspect-Oriented Approach. In Proceedings of the 2011 Tenth International Symposium on Distributed Computing and Applications to Business, Engineering and Science (DCABES), Wuxi, China, 14–17 October 2011; pp. 354–358, ISBN 978-1-4577-0327-0.

173. Zhang, L. Modeling Methods for Cloud Based Cyber Physical Systems. In Proceedings of the 2018 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), Guangzhou, China, 8–12 October 2018; pp. 1271–1276, ISBN 978-1-5386-9380-3.

174. Zhai, X.; Chen, Q.; Ji, S.; Li, B. A Unified Modeling and Verifying Framework for Cyber Physical Systems. In Proceedings of the 2012 12th International Conference on Quality Software (QSIC 2012), Xi'an, China, 27–29 August 2012; pp. 128–131, ISBN 978-1-4673-2857-9.

175. Zhou, Y.; Gong, X.; Li, B.; Zhu, M. A Framework for CPS Modeling and Verification Based on dL. In Proceedings of the 2018 IEEE/ACIS 17th International Conference on Computer and Information Science (ICIS), Singapore, 6–8 June 2018; pp. 173–179, ISBN 978-1-5386-5892-5.

176. Tannoury, P.; Chouali, S.; Hammad, A. Model Driven Approach to Design an Automotive CPS with SysReo Language. In Proceedings of the 20th ACM International Symposium on Mobility Management and Wireless Access, Montreal, QC, Canada, 24–28 October 2022; pp. 97–104, ISBN 9781450394802.

177. Sadovykh, A.; Bagnato, A.; Quadri, I.; Mady, A.E.-D.; Couto, L.D.; Basagiannis, S.; Hasanagic, M. SysML as a Common Integration Platform for Co-Simulations. In Proceedings of the 12th Central and Eastern European Software Engineering Conference in Russia, Moscow, Russia, 28–29 October 2016; pp. 1–5, ISBN 9781450348843.

178. Wilking, F.; Sauer, C.; Schleich, B.; Wartzack, S. SysML 4 Digital Twins—Utilization of System Models for the Design and Operation of Digital Twins. *Proc. Des. Soc.* **2022**, *2*, 1815–1824. [CrossRef]

179. Wang, Y.; Zhou, X.; Liang, D. Study on Integrated Modeling Methods toward Co-simulation of Cyber-Physical System. In Proceedings of the 2012 IEEE 14th International Conference on High Performance Computing and Communication & 2012 IEEE 9th International Conference on Embedded Software and Systems, Liverpool, UK, 25–27 June 2012; pp. 1736–1740, ISBN 978-1-4673-2164-8.

180. Wu, L.; Gu, G.; Zhang, W. Cyber-Physical System Fusion Modeling and Simulation Method. In Proceedings of the 2019 3rd International Symposium on Computer Science and Intelligent Control, Amsterdam, The Netherlands, 25–27 September 2019; pp. 1–6, ISBN 9781450376617.

181. He, R.; Wu, L.; Tang, L.; Han, X.; Xu, Z.; Gu, G. Integrated modeling method of Cyber physical system based on extended AADL. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1043*, 22067. [CrossRef]

182. Wawrzik, F.; Chipman, W.; Molina, J.M.; Grimm, C. Modeling and simulation of Cyber-Physical Systems with SICYPHOS. In Proceedings of the 2015 10th International Conference on Design & Technology of Integrated Systems in Nanoscale Era (DTIS), Napoli, Italy, 21–23 April 2015; pp. 1–6, ISBN 978-1-4799-1999-4.

183. Tang, J.; Zhao, J.; Ding, J.; Chen, L.; Xie, G.; Gu, B.; Yang, M. Cyber-physical systems modeling method based on Modelica. In Proceedings of the 2012 International Conference on Software Security and Reliability Companion, Gaithersburg, MD, USA, 20–22 June 2012; pp. 188–191, ISBN 978-1-4673-2670-4.

184. Centomo, S.; Avogaro, A.; Panato, M.; Tadiello, C.; Fummi, F. A Design Methodology of Multi-level Digital Twins. In Proceedings of the 2021 22nd IEEE International Conference on Industrial Technology (ICIT), Valencia, Spain, 10–12 March 2021; pp. 961–966, ISBN 978-1-7281-5730-6.

185. Lehner, D.; Sint, S.; Vierhauser, M.; Narzt, W.; Wimmer, M. AML4DT: A Model-Driven Framework for Developing and Maintaining Digital Twins with AutomationML. In Proceedings of the 2021 IEEE 26th International Conference on Emerging Technologies and Factory Automation (ETFA), Vasteras, Sweden, 7–10 September 2021; pp. 1–8, ISBN 978-1-7281-2989-1.

186. Fitzgerald, J.; Pierce, K.; Gamble, C. A rigorous approach to the design of resilient cyber-physical systems through co-simulation. In Proceedings of the 2012 IEEE/IFIP 42nd International Conference on Dependable Systems and Networks Workshops (DSN-W), Boston, MA, USA, 25–28 June 2012; pp. 1–6, ISBN 978-1-4673-2266-9.

187. Fitzgerald, J.; Gamble, C.; Larsen, P.G.; Pierce, K.; Woodcock, J. Cyber-Physical Systems Design: Formal Foundations, Methods and Integrated Tool Chains. In Proceedings of the 2015 IEEE/ACM 3rd FME Workshop on Formal Methods in Software Engineering (FormaliSE), Florence, Italy, 18 May 2015; pp. 40–46, ISBN 978-1-4673-7043-1.

188. Lee, K.H.; Hong, J.H.; Kim, T.G. System of Systems Approach to Formal Modeling of CPS for Simulation-Based Analysis. *Etri J.* **2015**, *37*, 175–185. [CrossRef]

189. He, X.; Alam, D.M.M. Hybrid Predicate Transition Nets—A Formal Method for Modeling and Analyzing Cyber-Physical Systems. In Proceedings of the 2019 IEEE 19th International Conference on Software Quality, Reliability and Security (QRS), Sofia, Bulgaria, 22–26 July 2019; pp. 216–227, ISBN 978-1-7281-3927-2.

190. Qian, Z.; Yu, H. A TAOPN Approach to Modeling and Scheduling Cyber-Physical Systems. In Proceedings of the 2013 International Conference on Information Science and Applications (ICISA), Suwon, Republic of Korea, 24–26 June 2013; pp. 1–7, ISBN 978-1-4799-0604-8.

191. Singh, S.; Weeber, M.; Birke, K.P. Implementation of Battery Digital Twin: Approach, Functionalities and Benefits. *Batteries* **2021**, *7*, 78. [CrossRef]

192. Song, X.; Li, K.; Wang, S.; Kan, Z.; Li, H.; Zhu, J.; Hao, G. Framework Design of a Digital Twin of an XY Compliant Parallel Manipulator Based on Non-Negative Matrix Factorization. In Proceedings of the 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, St. Louis, MO, USA, 14–17 August 2022; ISBN 978-0-7918-8621-2.

193. Christofi, N.; Pucel, X. A novel methodology to construct digital twin models for spacecraft operations using fault and behaviour trees. In Proceedings of the 25th International Conference on Model Driven Engineering Languages and Systems, Montreal, QC, Canada, 23–28 October 2022; pp. 473–480, ISBN 9781450394673.

194. Negri, E.; Assiro, G.; Caioli, L.; Fumagalli, L. A machine state-based Digital Twin development methodology. In *Summer School F. Turco-Industrial Systems Engineering*; Università degli Studi di Brescia, Dipartimento di Ingegneria Meccanica e Industriale (DIMI): Brescia, Italy, 2019; pp. 34–40.

195. Doka, T.; Horak, P. An Approach to Creating a Simple Digital Twin for Optimizing A Small Electric Concept Vehicle Drivetrain. In Proceedings of the 34th International ECMS Conference on Modelling and Simulation, Berlin, Germany, 9–12 June 2020; pp. 328–333, ISBN 9783937436685.

196. Tuo, M.F.; Zhou, X.S.; Guo, Z.X.; Shan, L.J. A Method for Cyber-Physical System Behavior Modeling and Safety Verification Based on Extended Hybrid System Description Language. *MATEC Web Conf.* **2016**, *44*, 2092. [CrossRef]

197. Janda, P.; Hajicek, Z.; Bernardin, P. Implementation of The Digital Twin Methodology. In Proceedings of the 30th International DAAAM Symposium 2019, Zadar, Croatia, 23–26 October 2019; pp. 533–538, ISBN 9783902734228.

198. Erkoyuncu, J.A.; Del Amo, I.F.; Ariansyah, D.; Bulka, D.; Vrabič, R.; Roy, R. A design framework for adaptive digital twins. *CIRP Ann.* **2020**, *69*, 145–148. [CrossRef]

199. Lai, X.; He, X.; Pang, Y.; Zhang, F.; Zhou, D.; Sun, W.; Song, X. A Scalable Digital Twin Framework Based on a Novel Adaptive Ensemble Surrogate Model. *J. Mech. Des.* **2023**, *145*, 021701. [CrossRef]

200. Zhao, X.; Quang Tuyen, L.; My Ha, D. Digital Twining of Horizontal Axis Wind Turbine with Reduced-Order Modelling Approach. In Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering, Hamburg, Germany, 5–10 June 2022; American Society of Mechanical Engineers: New York, NY, USA, 2022; Volume 7, ISBN 978-0-7918-8592-5.

201. Zou, Q.; Hou, Z.; Wang, M.; Jiang, S. The Modeling Method of Digital Twin Models for Machining Parts. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *772*, 12003. [CrossRef]

202. Dashkina, A.; Khalyapina, L.; Kobicheva, A.; Lazovskaya, T.; Malykhina, G.; Tarkhov, D. Neural Network Modeling as a Method for Creating Digital Twins. In Proceedings of the 2nd International Scientific Conference on Innovations in Digital Economy: SPBPU IDE-2020; ACM: New York, NY, USA, 2020; pp. 1–5, ISBN 9781450388313.

203. Tarkhov, D.A.; Malykhina, G.F. Neural network modelling methods for creating digital twins of real objects. *J. Phys. Conf. Ser.* **2019**, *1236*, 12056. [CrossRef]

204. Yang, C.; Ferdousi, R.; El Saddik, A.; Li, Y.; Liu, Z.; Liao, M. Lifetime Learning-enabled Modelling Framework for Digital Twin. In Proceedings of the 2022 IEEE 18th International Conference on Automation Science and Engineering (CASE), Mexico City, Mexico, 20–24 August 2022; pp. 1761–1766, ISBN 978-1-6654-9042-9.

205. Liu, S.; Shen, H.; Li, J.; Lu, Y.; Bao, J. An adaptive evolutionary framework for the decision-making models of digital twin machining system. In Proceedings of the 2021 IEEE 17th International Conference on Automation Science and Engineering (CASE), Lyon, France, 23–27 August 2021; pp. 771–776, ISBN 978-1-6654-1873-7.

206. Fett, M.; Wilking, F.; Goetz, S.; Kirchner, E.; Wartzack, S. Sensor selection and integration for Cyber-Physical Systems in context of Digital Twins—A systematic review of requirements. In Proceedings of the 2023 18th Annual System of Systems Engineering Conference (SoSe), Lille, France, 14–16 June 2023; pp. 1–7, ISBN 979-8-3503-2723-6.

207. Hausmann, M.; Breimann, R.; Fett, M.; Kraus, B.; Schmitt, F.; Welzbacher, P.; Kirchner, E. Systematic approaches for sensor selection and integration—A systematic literature review. *Procedia CIRP* **2023**, *119*, 687–692. [CrossRef]

208. Hausmann, M.; Häfner, L.; Kirchner, E. A Procedure Model for the Systematic Sensor Selection and Integration into Technical Systems. *Proc. Des. Soc.* **2022**, *2*, 445–454. [CrossRef]