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Digital Twins: A Maturity Model for Their Classification and Evaluation

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ABSTRACT Digital Twins represent a powerful tool for transforming production and logistics towards Industry 4.0. They mirror physical assets in the digital world, enriching them with additional capabilities and features such as decision-making or lifecycle management. Due to the diverse possibilities associated with the Digital Twin, their design and implementation are also wide-ranging. This paper aims to contribute to the formalization and standardization of the description of Digital Twins. It presents a method for evaluating them through their lifecycle, from design to operation. The paper is based on an overview of their potential functionalities and properties with ranked stages of development. This method allows for an application-specific evaluation of Digital Twins and describes how they can be improved to suit the application better. The maturity model development follows the procedure for developing maturity models for IT management. Relevant capabilities and features were identified with a systematic literature review following the PRISMA guidelines. The results of this review were ranked and categorized and constitute the core of the maturity model, which was validated on five use-cases from different domains in production and logistics. The maturity model assesses Digita Twins in seven categories (context, data, computing capabilities, model, integration, control, human-machine interface) with 31 ranked characteristics. It evaluates existing solutions for potential improvements for a given application or the transfer to a new use-case. The resulting method and a supplementary web service present a generalized model for the evaluation of Digital Twins. Based on a description of a potential application, this is the first step towards a systematic evaluation, improving the structured development of such applications.

INDEX TERMS Digital twin, maturity model, characteristics, dimensions, literature review, use cases, product development, systematization, digital twin application.

ACRONYMS

DT	Digital Twin
MM	Maturity Model
UC	Use Case

I. INTRODUCTION

Digital transformation is one of the major challenges of our time [1]. Companies and other organizations are searching for new ways to improve their processes using information technology [2]. In production and logistics, relevant concepts include the Internet of Things, Industrial Internet, Industry 4.0, and finally, the concept of Digital Twin (DT). Apart from the definition of DTs itself, the question of DT development and use is of rising importance [3]. This article deals with the assessment of DTs by use of a maturity model (MM) approach in order to show technological options for DT developments in relation to individual premises. Thereby, we focus on the area of production and logistics. It remains unclear to many planners and operators of production and logistics systems, how a DT can be used in their business and how a DT should/could be like. This article is not a guideline

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for the creation of DTs but helps to set the technological DT option in relation to individual premises of planners and operators. It should help to distinguish between good and bad DTs, respectively, efficient and not efficient DTs. MMs have been around for almost 25 years and help to assess processes as well as organisations and other systems. The idea of this article is to use/develop such a MM in order to support short-, middle- and long-term strategies of DT development.

A MM is an instrument that assesses specific domains against a norm [4]. It helps to identify technological or organizational potentials to improve desired outcomes. A MM also enables comparisons with other companies or business units [5]. In general, we determine that the DT development and use is a process of continuous improvement. The requirements and objectives, as well as the dynamic of the physical world, are so complex and dynamic that the DT development is an ongoing process. This means that the DT has to be evolved in different stages in order to realise its full capability for different tasks/requirements again and again. From the view of effectiveness, the DT should be not more complex than required. This is also different from processing MMs with their clearly defined stages because they have lower investment costs than DT implementations. The organisation of a high maturity process costs not much more but is more effective than a low maturity process. In the technical DT world, the calculation of return on investment is much more complex, but nevertheless, it is necessary to assess the DT capability against a norm.

As follows, we have a look at existing MMs, which have relations to industry 4.0 and DTs. [6] presented a contribution for Data-Driven Manufacturing aiming at a Self-Optimizing Factory. It presents a six-level approach, defining DT as the fifth of six levels. With respect to DTs, they highlight that this concept is still under development but represents the way to decentralised self-control of assets on the shop floor. Another perspective is given by [7], describing DTs as part of product lifecycle aspects related to complex products. They define DTs as a specific maturity level of Industry 4.0 with well-defined capabilities. Widening the scope to Industry 4.0 research, many *maturity* models were developed, and there is still ongoing research for different industries with different perspectives and levels of detail. [8] found in their literature review more than 20 different MMs and frameworks were developed by academics and practitioners. The first ideas of DT assessments can be found in [9], presenting an implementation procedure of digital with four steps (*external inspiration*, *inhouse impact analysis*, *shortlisting & assessment*, and *prototyping & implementation*). The steps *impact analysis* and *shortlisting & assessment* point toward a maturity assessment but are not described in detail. Other literature reviews of Industry 4.0 MMs can be found in [10], [11].

We identified four frameworks for the evaluation of DTs, two academic and two evaluation frameworks from practitioners. [12] present their academic MM of DTs by defining four performance levels/stages and four dimensions. The stages are *Pre-Digital Twin*, *DT*, *Adaptive DT* and *Intelligent DT* with the dimensions (*physical twin existence*, *data acquisition*, *machine learning of operator preferences* and *machine learning of system/environment*). The *Intelligent DT* is the final stage and presents a virtual system model of the physical twin with an adaptive user interface and reinforcement learning capabilities. [13] introduces a DT Feature Framework, which presents an analysis method for DTs (Feature-based Digital Twin Analysis - FEDA) based on ten different categories of technical functionalities (DT features), namely *data link*, *coupling*, *identifier*, *security*, *data storage*, *user interface*, *simulation model*, *analysis*, *artificial intelligence*, and *computation*. The analysis method allows a weighting of the individual features and the calculation of a holistic score for evaluated DTs. However, the characteristics of the DT features, as well as their gradation, are not specified and are left up to the user.

From a practical perspective, the MM of [14] has the dimensions of *autonomy*, *intelligence*, *learning*, and *fidelity*, which are very oriented towards cognitive capabilities. Based on these four dimensions, five performance levels are defined and some specifications for the application in smart-city environments are given. The evaluation framework by [15] is built around an online questionnaire. It presents different classifications in the seven categories of *organizational goal setting*, *purpose*, *measurement*, *communication*, *data quality*, *agility and speed*, and *automation*. The system does not provide a score but gives a first idea of such a service in the field of business analytics. In summary, there is no detailed MM with rateable and evaluable dimensions for the assessment of DTs in the area of production and logistics.

The paper is structured as follows. This Section I analysed the application of MMs in the field of Industry 4.0 in common and in the field of DTs in special. We describe the research methodology of this article in Section II, while an extensive literature review of DT dimensions is shown in Section III. In Section IV, the proposed Digital Twin Maturity Model (DT MM) is created, whereby the previously analysed DT dimensions of the literature review are extended by own findings. The evaluation of the MM is done in Section V by assessing five different use cases (UCs). Section VI is about the discussion of the results and Section VII gives a conclusion and some outlook to further research.

II. RESEARCH METHODOLOGY

This section describes the research concept for the development of the Digital Twin Maturity Model.

A. MATURITY MODEL DEVELOPMENT

We followed the process of MM development, which is presented by [16] and shown in Table 1. This two-phase procedure includes four development and three deployment steps:

In the introduction section, we presented steps *"(1) - Problem definition"* and *"(2) - Comparison of existing maturity models"*, in which we state the necessity of evaluating

TABLE 1. Development steps of a MM as presented by [16].

Development
1) Problem definition
2) Comparison of existing maturity models
3) Determination of development strategy
4) Iterative maturity model development
a) selecting the design level
b) selecting the approach
c) designing the model section
d) testing the result
Deployment
5) Conception of transfer and evaluation
6) Implementation of transfer media
7) Evaluation

the DT and the lack of existing MMs for this topic. In step *"(3) - Determine the development strategy"* we defined developing a completely new MM, but we would use a literature review on the DT functionalities to have a systematic procedure for deriving the dimensions and their properties of the model (see section II-B). So we did this before the core development phase *"(4) - Iterative maturity model development"* began.

In *"(4a) - Selecting the Design Level"* we assumed that we would have hierarchical levels of maturity, such as the Business Process Maturity Model (BPMM). Additionally, we assumed to have some DT functions, which require no previous maturity levels and we assumed to have some context categories that would not have any impact on the maturity level. To evaluate the maturity level, we would implement a scoring system, which helps the user derive actions from it. In *"(4b) - Selecting the approach"* we started by using the Collective Notebook method as a creativity technique [17]. The collective notebook is a creativity technique in which individual participants independently generate ideas about a given problem and record them on their whiteboards. The ideas of all participants are then brought together on a new whiteboard and further developed in a group session. We used this in *"(4c) - Designing the model section"* to get a first draft of the MM cluster, its parameters, and its scoring. With this draft, we began the process of balancing the MM. This means comparing the score of each parameter with other parameters, as well as the maximum score of the clusters. This was an iterative discussion process of the authors, which took a lot of time. The next step *"(4d) - Testing the result"* was performed by the authors, where we evaluated five different DT UCs to get a better understanding of the balancing and scoring as well as the evaluation and analysis possibilities/techniques. Based on the results of this test, we revised the MM and started the implementation phase.

In *"(5) - Concept of Transfer and Evaluation"* we decided to start with an academic transfer through publication in parallel to further practice DT assessments. The size of the MM brought us to *"(6) - Implementation of Transfer Media"*, where we decided to develop an online tool for using our MM, which leads directly to *"(7) - Evaluation"*. We invite every reader to use the tool[1] and thus contribute to the improvement of the underlying MM.

B. SYSTEMATIC LITERATURE REVIEW (SLR)

Research on DTs is very dynamic and efforts in finding a shared understanding of their concept have raised significantly over the last years. While the majority of DT-related publications focus on concepts and applications in a specific application domain, several publications already address a more comprehensive definition of the DT and its conceptual background based on or influenced by literature reviews.

With this systematic review, we aim to provide an overview of the different approaches and their findings of domain-independent analyses of DT-concepts. Therefore, we systematically analysed literature reviews focusing on holistic systematizations of the DT-concept.

We follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement, which was initially developed for Meta-Analyses and Systematic Reviews in the healthcare sector, to minimise bias and provide reliable and repeatable findings in this review [18]. Fig. 1 summarises our paper selection procedure based on the PRISMA methodology.

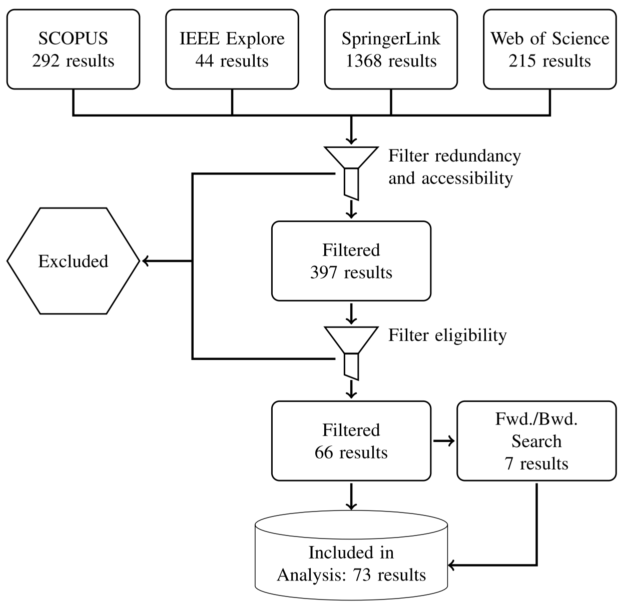

FIGURE 1. Literature selection, based on PRISMA methodology.

Depending on the database, we had to conduct minor search string adoptions to ensure compatibility with the search engine. Searched databases and respective search strings are specified in Table 2.

This review includes book chapters, journal and conference articles published from 2003 to 10/2021. As a preliminary

[1] The tool is available at https://dt-maturity.eu.

TABLE 2. Searched databases and search strings.

Database	Search-String
SCOPUS	*(TITLE-ABS-KEY ("Digital Twin") AND TITLE-ABS-KEY ("Literature Analysis" OR "Systemization" OR "Systematization" OR "Literature Review "OR "State of the Art"))*
IEEE Explore	*("All Metadata":"Digital Twin") AND ("All Metadata":"Literature Analysis" OR "All Metadata":"Systemization" OR "All Metadata":"Literature Review" OR "All Metadata":"Systematization" OR "All Metadata":"State of the Art")*
SpringerLink	*"Digital Twin" AND ("Literature Review" OR "Systemization" OR "Systematization" OR "Literature Analysis" OR "State of the Art")*
Web of Science	*((TS=("Digital Twin")) AND ((TS=("Literature Review")) OR TS=(Systemization) OR TS=(Systematization) OR TS= ("Literature Analysis") OR TS=("State of the Art")))*

result we found 1919 papers. In the first step, non-accessible results and duplicates were excluded from further investigation. We evaluated the eligibility of the remaining articles in relevance to the research topic by studying the title, abstract and additionally the introduction of every paper. Based on our research objective, we determined the following exclusion criteria:

1) The term "Digital Twin" has to be an integral part of the title.
2) A review of DT-related literature has to be mentioned as a fundamental part of the work in either the title or the abstract. We introduced this criterion to increase the validity of the results and, in particular, to identify systematization approaches gathered from a broader literature base. Therefore, we only use literature reviews that have developed systematizations based on observations of DTs. We therefore only consider a literature review if the authors have derived these aspects from DT applications. Thus, we want to ensure that the criteria have already proven to be useful and applicable.

To complete the set of literature, we conducted a backward search by screening the references of the relevant articles and added seven additional publications to our database. Ultimately, 73 papers were incorporated into the following systematic review analysis. However, the literature landscape around DTs has gained a lot of momentum in recent years, so we had to divide our analysis into two parts. The quantitative analysis below takes into account all published papers up to 12/2021. For the subsequent qualitative analysis and synthesis of the relevant dimensions, however, we were only able to consider publications up to 12/2020 in order to generate a coherent result.

III. SYSTEMATIC LITERATURE REVIEW - BACKGROUND

This section describes the findings of the systematic literature review. It summarises different definitions for DTs in section III-B and the most relevant findings in the form of classification dimensions in section III-C. Additionally, it also demonstrates the validity of those findings by providing a general overview of available literature reviews for DTs in the following section III-A.

A. QUANTITATIVE FINDINGS

It was not until 2015 that we found the first paper that reviewed DTs. Efforts in reviewing DT publications have significantly increased since then. Publications focused on systematizing the DT concept and providing a consistent view of its limitations and challenges have reached fifteen papers per year in 2019 and count twenty-eight until October 2021 (Fig. 2).

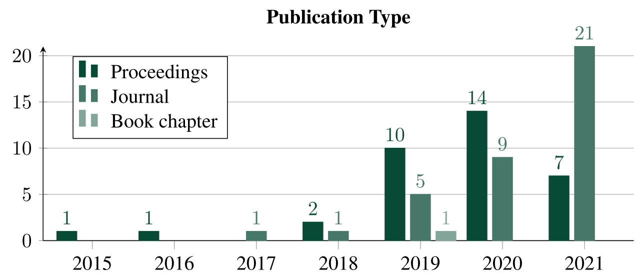

FIGURE 2. Publication types of DT reviews between 2002 and October 2021, no reviews until 2015.

Fig. 3 shows an increase in the average number of reviewed publications per review throughout the last five years. While the number of analysed papers in journal-published reviews has continuously increased (with an outlier of a mean of 181 references in 2020) from a mean of 51 referenced papers in 2017 to an average of 105 referenced publications in 2021 until October, citations in conference papers show no recognizable trend throughout the last years, with an average of 41 (2018), 37 (2019), 46 (2020) and 37 (2021) citations per publication in the last four years. These values may indicate that the scope and quality of the literature reviews in journal articles have risen in step with the availability of DT-related literature throughout the last years.

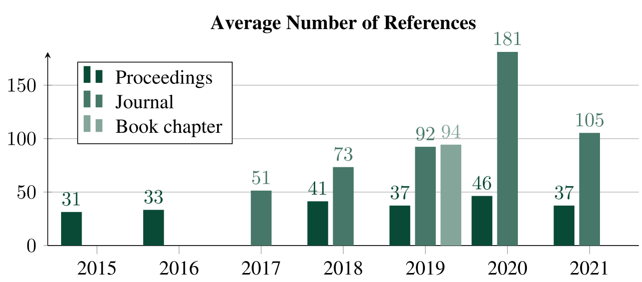

FIGURE 3. Mean number of references reviewed per publication.

B. DIGITAL TWIN DEFINITIONS

Besides conceptual reflections, recent contributions have become more application-oriented, but theoretical considerations remain prominent. This is mainly caused by the fact that the scientific description of the DT is still incomplete [19]. This, together with the very high interest in the DT in industry and research, has led to the concept becoming the subject of repeated hype and confusion. The confusion stems from the fact that due to a lack of standardisation and sometimes vague definitions, many misconceptions about DTs and similar concepts and applications have sometimes been wrongly titled "digital twin" [20]. The list below illustrates that many authors use different definitions for the DT, depending on their research domain and their associated goals and approaches. The earliest citeable description from Glaessgen is frequently referenced in the literature [21]. Another well-recognised definition originates from CIRP, which integrates the service perspective of products into the concept and emphasises its lifecycle-wide applicability [22]. Despite different reference systems, many definitions differ in the concretization of conceptual elements. Some authors emphasise a near real-time synchronization between physical and virtual twin [23]. In contrast, others state that the design of the DT elements has to be suitable for their intended purpose [24].

The following dimensions have been chosen to illustrate the wide range of possible interpretations of the DT concept. They also correspond to the distribution of the identified publications on DTs across the different application areas (refer to section III-C2), even though we could not fully represent all domains here.

1) AEROSPACE

"A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." [21]

2) CROSS-DOMAIN

"The DT is not one complete model of the physical product, but a set of linked operation data artefacts and simulation models, which are of suitable granularity for their intended purpose and evolve throughout the product life-cycle." [24]

3) MANUFACTURING

"A digital twin is a computerised model of a physical device or system that represents all functional features and links with the working elements. A digital twin is more than a virtual computer system for simulation study. It provides the operation status, insights, outcomes, and knowledge that are associated with the proper functions of the physical system." [25]

4) MANUFACTURING

"A digital twin is a high-fidelity representation of the operational dynamics of its physical counterpart, enabled by near real-time synchronization between the cyberspace and physical space." [26]

5) MANUFACTURING

"Digital Twin is a digital representation of an active unique product (real device, object, machine, service or intangible asset) or unique product service system that comprises its selected characteristics, properties, conditions and behaviours by means of models, information and data within a single or even across multiple lifecycle phases." [22]

6) MARITIME

"A digital twin is a digital replica of a real-world "thing". Operational dynamics are critical elements of a digital twin because a twin's behaviour is based on near real-time data coming from the actual physical counterpart." [23]

The multitude of definitions has also led to a collection of related concepts, such as Virtual Twin, Digital Shadow, Digital Model, Digital Simulation, which are sometimes used synonymously [20]. However, due to space limitations, we do not intend to discuss the differences further since the focus in our MM is on identifying overarching classification dimensions. We are aware that a deeper discussion can be made in future works.

C. CLASSIFICATION DIMENSIONS OF DIGITAL TWINS

Reviews that focus on the concept of DTs mostly aim at providing a reference model for it. These reference models oftentimes systematise DTs using several dimensions. We analysed the selected articles with respect to such classification dimensions. Fig. 4 presents the listing of all identified dimensions. In total, we identified 103 different concepts in the literature reviews to distinguish DTs. Since authors often use different expressions for similar ideas, we have further explored these concepts with the aim of finding equivalent perceptions. After deleting the same concepts and grouping similar ones together, we finally arrived at 31 dimensions. Of these, three did not make it into our selection in Section IV because they did not allow for a meaningful subdivision of expressions (*Data Security, Service Effectiveness, Product Identification*).

In the following, we describe the above dimensions based on the common denominator of the different perceptions of the various authors. However, since a very long list has been compiled, these extensive descriptions are limited to those dimensions that appear in at least five review papers. In addition, an explanation of the usage of the dimensions in the MM, including possible characteristics of each dimension, is given. This leads to 15 dimensions derived from scientific literature and described in detail hereinafter. The other dimensions are briefly depicted in the respective Section III-C16.

1) BENEFITS

DTs can provide benefits from different perspectives. Twelve authors distinguish DTs by evaluating the value the DT provides to its user or owner. Finding common ground for this dimension is difficult, as there are various approaches to cluster benefits and some of the identified distinctions are ambiguous. We distinguish systematization by asking *How* and *Where* the DT generates the benefits. For this dimension, we focus on *How* a DT creates value and cover the *Where*-perspective in the Classification Dimensions

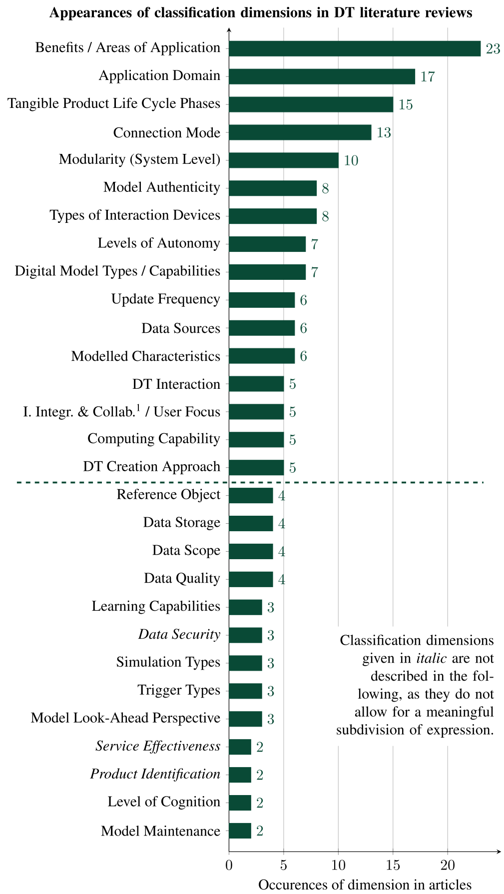

FIGURE 4. Reviews on DT-related literature often use or define systemizations of DTs in the form of classification dimensions.
[1] Interorganizational integration & collaboration.

"*Application Domain*" (above) and "*Tangible Product Lifecycle Phases*" below.

The analysed documents use different names to address the generated benefits, e.g., *Objectives*, *Purpose* or sometimes *Service Scope*. In general, different services or product-related processes can benefit from new (combinations of) data DTs supply. [19] synthesised a detailed list of service results that lead to perceived benefits of DTs, e.g., reduced cost, risk, or design time, but also improved after-sales service, maintenance decision-making or safety and security. Several authors created a more generic classification by subdividing the purposes of DT services, e.g., monitoring and visualization, simulations and predictions, decision support, or control purposes [23], [27]–[29]. Barth *et al.* further distinguished that established services can be either enhanced by improving their availability, performance or quality [30].

Comprising these different approaches, some authors state that DTs create benefits by either enhancing established services, e.g., improving their efficiency or enabling fully new services and value-adding opportunities [28], [30], [31].

2) APPLICATION DOMAIN

The majority of literature reviews on DTs provide an overview of DT applications in a specific domain or focus on a spectrum of tasks. As the covered research domains of the analysed literature reviews vary, we often found different expressions and taxonomies for similar tasks. In this publication, we cluster the reviewed DT-applications by their application domain.

We distinguish ten different application domains for DTs across the analysed literature reviews (see Table 3). Foremost expressed domains are industrial settings, e.g., DTs in the context of manufacturing (shown in 22 literature reviews) or the aerospace sector (11). Automotive and Maritime Industries (including Wind, Shipping, and Oil & Gas) are still prominent, with six and five reviews, respectively. However, the adoption diversifies and Smart Product or Healthcare-related tasks are identified as notable application domains in five literature reviews already. More recent literature reviews also mention Agriculture, Smart Cities, Energy, Mining, Logistics and Education as promising application domains but are yet underrepresented.

TABLE 3. Identified application domains in DT literature reviews.

Application Domain	Number of Reviews	Review Publications
Manufacturing	22	[32, 3, 33, 20, 31, 34, 35, 28, 27, 19, 36, 37, 23, 38, 39, 40, 41, 42, 43, 44, 29]
Aerospace	11	[32, 31, 35, 45, 27, 46, 19, 38, 34, 44, 29]
Healthcare	10	[20, 35, 27, 19, 34, 41, 42, 43, 44, 29]
Automotive	8	[31, 27, 46, 19, 20, 34, 44, 29]
Maritime	6	[31, 27, 36, 29, 34, 44]
Construction	5	[47, 48, 44, 43, 34]
Smart Cities	5	[27, 20, 34, 41, 42]
Logistics	5	[34, 44, 43, 42, 41]
Smart Products	4	[49, 33, 19, 34]
Energy	4	[27, 34, 42, 44]
Education	3	[34, 41, 42]
Agriculture	2	[27, 19]
Mining	1	[27]

3) TANGIBLE PRODUCT LIFECYCLE PHASES

Albeit with different terminology, the vast majority of literature reviews analysed DTs from a lifecycle perspective. Therefore, we also consider the lifecycle as a core theme for DTs. This is in line with the initial concept of the DT being a new basis for product lifecycle management [50]. [51] considers the DT as an entity that accompanies the product throughout its entire cycle and continuously accumulates data and makes it available for future use. A small number of papers indicate that DTs exist for specific UCs along with multiple lifecycle phases of the product [52]. However, most DTs only affect specific lifecycle stages [19]. The most frequent lifecycle perspective was the *Product Lifecycle* [22], [33], [45], [49], but overlapping lifecycle approaches, e.g. the

Production Lifecycle, the *Internet of Things (IoT) Lifecycle*, or the *Complex Technical System Lifecycle*, have also been discussed [32].

Since DT applications stretch across various domains (e.g., products, services), we chose an abstract description of the lifecycle stages to equally cover different domains, only distinguishing between the fundamental stages, i.e. beginning of life, mid of life, and end of life [53].

4) CONNECTION MODE

Nine literature reviews distinguish DT related applications with regards to the integration of the physical and the virtual world. Throughout most analysed literature reviews, it was a consistent view that the design of DTs requires a bi-directional connection, consisting of a means for communication in both ways, "physical to virtual" and "virtual to physical". Even though a virtual-to-physical link is not necessary to technically create a DT in the form of a "twinned" virtual model, this design paradigm is not considered to be useful, as the benefits of this approach are unclear and a conceptual differentiation from traditional multi-physics simulation and modelling approaches would be difficult [19]. The most referenced systematization is the distinction by Kritzinger [3]. Four publications followed their proposal to distinguish between fully manual, semi-automatic, and fully automatic data and information exchange [20], [22], [40], [52]. However, it is still controversial if a DT has to have a fully automatic information exchange in both directions. While some authors identified a seamless connection and continuous bi-directional data exchange as a central characteristic of DTs [20], [35], others interpret Kritzingers distinction as a means to differentiate certain design patterns of DTs [40], [52], [54]. We believe that a bidirectional connection should not be a prerequisite for labelling a concept a DT. However, we would like to use this criterion to further distinguish DTs and therefore adopt Kritzinger's characteristics for our MM.

5) MODULARITY (SYSTEM LEVEL)

A frequently seen type of subdivision is the systematization according to hierarchically arranged system levels. A common order uses three system levels, in particular a "Unit", a "System" and a "System of Systems" level [30], [52], [55]. Industrial companies adopted this approach using more manufacturing-related terms, e.g., "Equipment", "Plant" [29] or even "Process" [37]. Authors assign different constituting parts and functionalities to DTs of different system levels. Some unit level DTs aim to provide status information and supply high-fidelity visual simulations, whereas system level DTs can additionally make and execute decisions [55]. A clear distinction between different system levels however is difficult, as it is not always clear when something should be considered a "Unit", i.e. an integral part of a larger system or a closed system itself [56]. Current trends, such as the increasing integration of information and communication technologies or mechatronic systems, lead to steadily increasing complexities in technical systems [57], [58]. Industrial initiatives, such as Industry 4.0 or the Internet of Things, reinforce the trend as they create additional heterogeneity (of the different connected systems among each other) and a higher degree of interactions (due to interconnections between different actors) in technical systems.

As the capabilities of a DT may be useful for different layers, e.g., higher system level DTs using aggregated data of lower system levels, the different system levels cannot always be seen as independent ecosystems [30]. Therefore, an interesting feature of a DT solution is its capability to traverse different system levels. Whether a DT is capable of integrating several system levels depends on its design, particularly the overall software architecture. Accordingly, we distinguish between three different DT software architectures

- Unit: DTs with monolithic software architecture, suitable for low complexity systems.
- System: DTs that mirror systems with several interacting, constituting parts of lower complexity might be suitable for modular software architectures.
- System of Systems: DTs for a system of systems with a high number of dependencies could benefit from microservice-oriented software architectures with a set of smaller, interconnected modules and services. We consider this especially for DTs that operate and link to multi-technology domains and agile environments. Just as its physical counterpart, a DT can be built based on several software modules that provide special functionalities on a certain level but can also interact and be integrated into an aggregated parent twin. The backbone of microservice-oriented DTs are libraries of DT-related data and models that can be used by different DT applications (services).

6) MODEL AUTHENTICITY

Often used terms to describe the ability of the DT to conform to its physical twin are *Fidelity* [19], [54], *Digital Model Richness* [22], or *Completeness* [27]. We use *Authenticity*, as it, similarly to the DT-concept, focuses on the characteristics of the original and model [59]. *Authenticity* describes how conform the DT (the model) is compared to the real product (original). Several factors can play a role in describing this dimension. Many of the dimensions described in Chapter 3.3 add to the description of the *Authenticity* of a DT, e.g. the capability to represent status changes of the original with higher frequency (*Update Frequency*). However, we would like to bring other aspects to the fore with this dimension. Our interpretation is not focused on a spatial grid resolution, as spatial information is not essential for all DTs.

To describe different levels of *Authenticity*, we adapted the systematics of resolution proposed by [60] and focus on different subsets of parameters that the DT is able to mirror. Fig. 5 shows three relevant aspects of DT *Authenticity* that we consider to describe this dimension.

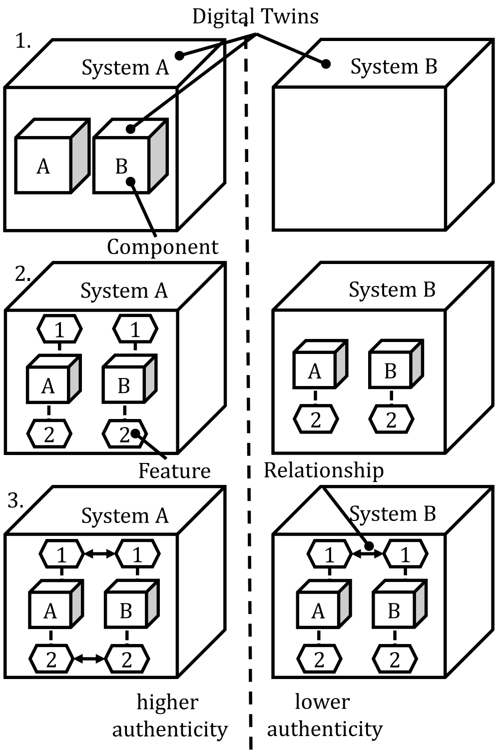

FIGURE 5. Three aspects of the authenticity of DTs.

1. A DT may be more authentic as it covers more fine-grained entity models (the DT provides models for components instead of just for the whole system). For the maturity rating, it is therefore beneficial if the DT can be detailed or aggregated by including or summarizing sub-assets of arbitrary detail level (Fig. 5 (1)).
2. Furthermore, DTs that encompass the same number of entities may have different levels of *Authenticity*, as they describe these entities with a richer set of features (Fig. 5 (2)). We therefore also grade a DT's *Authenticity*, based on the number of features it is capable of mirroring from its physical counterpart, i.e. the capability to only simulate the kinematics vs. the capability to simulate both kinematics and aerodynamics of the counterpart. These features can be of different kinds, as e.g. product master data, product features (i.e. regarding product design or product state), descriptions of products capabilities and behaviours, process parameters, etc. More features lead to a higher maturity rating of the DT.
3. Finally, DTs with the same entity granularity and feature granularity may differ because one DT may be better in capturing the dependencies that may exist between those (Fig. 5 (3)). In practice, we often see that distinct model packages focus to represent one features of a system, i.e. a computer-aided design model mimics the geometric features. In this MM we therefore consider DTs to be more authentic if they have the capability to integrate and link features of different entities that may originate from different (source) information systems.

7) LEVELS OF AUTONOMY

Autonomy generally describes a state of "*Freedom from external control or influence; independence*." [61]. Autonomous DTs need to react to changes in their environment and need the ability to act proactively to pursue their objectives. Hence, autonomous DTs have to fulfil several preconditions, e.g.,

1) the capability to receive and process information about their environment,
2) a bi-directionally link their physical and (decision-making) virtual worlds and
3) that they "*contain [...] a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's predictions [...].*" [62].

Hence this dimension is highly dependent on other DT dimensions, in particular on the degree of an automated bi-directional data flow (*Connection Mode*), a DTs Look-Ahead capability (*Model Look-Ahead Perspective*), and its *Learning Capabilities*.

Interlinks to these dimensions can also be found in six literature reviews that used different grades of autonomy to cluster their studied domain. *Purpose*, *Level of Smartness*, and *Cyber-Physical Sytem (CPS) Intelligence* are terms authors used to describe this dimension. Generally, DTs can be divided into those with and without autonomous features [13].

DTs without any autonomy features need external triggers to take action. These triggers have to be activated by humans or external technical systems in a direct [22] or indirect manner (e.g., via predefined thresholds, [30]). [52] and [23] used different grades of automation to further distinguish non-autonomous DTs by assigning increments of tasks that are needed to prepare a certain action implementation to DT capabilities.

DTs with autonomous features can show different grades of autonomy. Following an elaborated taxonomy for autonomy for on-road vehicles [63], we distinguish five different levels of autonomy:

1) DTs can assist the user without interfering in the controls of the physical counterpart (Level 1 – User Assistance).
2) The DT can execute autonomous decisions for just a fraction of the DT functionalities (Level 2 - Partial Autonomy) or
3) limited to certain conditions (Level 3 – Conditional Autonomy).
4) Beyond that, DTs can be fully autonomous, in a way that the virtual representation, independently from external control inputs, decides and controls its own executive elements with full or limited (Level 4 – High Autonomy) or

5) limited (Level 5 – Full Autonomy) possibilities for the user to intervene.

8) DIGITAL MODEL TYPES (PRODUCT MODELS, MANUFACTURING INFORMATION MODELS, SIMULATION TYPES)

The dimension *Digital Model Types* describes how the characteristics of the DT are modelled. DTs may encompass multiple models of different types [45]. Options are conceptual models, physics-based models and machine-learning based models. We are also introducing an option for hybrid models based on the hybrid analysis and modelling approach by [42], which combines the interpretability, robust foundation and understanding of physics-based modelling approaches with the accuracy and efficiency of advanced data-driven machine learning and artificial intelligence algorithms. We have found these criteria, together with the ‘‘Modelled Characteristics’’, in both authors [45] and [23]. For the MM, we have separated the two aspects as they represent two different distinguishing characteristics. Models can also be analysed through simulation, making them simulation models [64]. For each model, the MM allows describing if they are used in simulations or not. Models used in simulations comprise some additional properties. [65] developed a taxonomy to distinguish simulations in DTs based on several dimensions. We adapt this subdivision, which can also be found in further literature on simulations [66] and similar ideas as well in DT literature [22]. According to this, simulations are characterised by whether a time component is represented or not (simulations can be static or dynamic), whether the simulation calculates with probabilities or not (a simulation is deterministic or stochastic) and whether the processed values in the simulation are discrete (values within a finite range) or continuous (values within an infinite range).

9) MODELLED CHARACTERISTICS (PRODUCT MODELS, MANUFACTURING INFORMATION MODELS)

Two authors distinguished DTs according to which characteristics of the reference object are modelled within a DT. [45] names among others 3D geometric models, multi-physics models or manufacturing models (mock-ups). [23] names several alternative ‘‘manufacturing information models’’, as e.g. Factory Design or Behaviour. However, they have not identified these characteristics as a single distinguishing criterion but rather mention these characteristics together with various model types (see below). In the MM, we distinguish between geometry-kinematics or control-, sensor-, (multi-)physical- or production system-behaviour.

10) DT INTERACTION (INTERACTION AND COLLABORATION)

[33] stated that DTs need to interact with each other to solve complex problems. He named three different kinds of interaction and collaboration between the physical and the virtual representation. In this dimension, we only focus on what Tao called the ‘‘virtual - virtual’’ connection, the connection between different DTs. The simplest case is a single, standalone DT that is not connected and integrated with other DTs. More complex is a System of DTs which are connected. The next level is the collaboration between different DTs, each with an individual goal. The highest-ranked version is a system of DTs with a common goal for all.

11) DT CREATION APPROACH (CREATION TIME)

In their review, [27] introduced the distinguishing criterion of the *Creation Time* of a DT, in which they assigned DTs either to a ‘‘before’’ or ‘‘after’’ physical twin creation. We follow this idea and add the dimension *DT Creation Approach* to our MM. Users can indicate whether their DT was designed after its counterpart (‘‘*Retrofitted-DT*’’) or whether it was designed together with the product and always planned as an integral part of it from the beginning (*‘‘Design-for-DT’’*).

12) UPDATE FREQUENCY AND COMPUTING CAPABILITY

DTs can have different levels of capabilities to process the incoming information and provide an output that can be used by either their physical counterpart or a user. The processing time between physical and virtual entities is a part of the so-called ‘‘Twinning’’ process, which [19] defines as the ‘‘act of synchronization between the two entities’’. The Twinning process begins when a state change of either the physical or virtual entity is detected and transmitted to its counterpart. The counterpart processes this information to update its own state. The frequency in which the DT is capable of performing this process defines how often the DT is updated. Authors describe this feature as ‘‘*Twinning Rate*’’ [19] or ‘‘*Update Frequency*’’ [67]. Higher *Update Frequencies* lead to more *authentic* DTs, as the virtual counterpart can encompass more timely information and therefore constitutes a more accurate mirror of the physical entity.

The Twinning Process is strongly affected by the DTs *Computing Capability*, which influences the speed at which processes of the virtual counterpart can be performed. Besides the speed of the updating of the virtual counterpart, the *Computation Capability* also affects the computation of downstream applications, e.g., forecasting or visualization for user interfaces [13]. The *Computation Capability*, therefore, determines the overall response time of the DT and how time-sensitive data processing can be performed [23].

13) DATA SOURCES

Data is a key component of DTs. Considering the DT as a central access point for entity-related data, a high variety of data sources may contribute to the DT-specific data pool. The different data sources can provide data with different levels of structure. Structured data is characterised by a high degree of organization, clarity, and consistency. Besides highly structured data, e.g., from sensors, unstructured data like documents or pictures (binary large objects - BLOBs) can provide potential value. However, the exploitation of unstructured data requires higher efforts. Therefore, in

"*Data Interpretation*" we attribute a higher maturity to DTs that can interpret and exploit unstructured data.

[33] and [52] discussed that data sources of DTs are not restricted to physical objects and physical measurements, e.g. IoT sensor readings, but may also have the ability to include data from the simulation, forecasting, analysis, or optimization tools. The latter is created by fusing different data sources. Data fusion is a key technology for DTs to provide value to its users. The ability to reuse fused data on a higher level for more advanced analysis and simulation allows more complex and higher-value applications to be performed. E.g., the fusion of load sensor measurements with a physic-based model enables the calculation of instantaneous stress on a component, while the reuse of this result in combination with a data-driven model may lead to predicting its remaining useful life. To do this, however, the DT design must already provide the ability to feed back and integrate merged data into its information model as a potential data source. We cover this ability in the maturity dimension "*Data Sources*".

This feature is not only valid for data sources within the DT (both physical and virtual parts) but applies to external data sources like third-party weather data as well (historical weather measurements vs. simulated forecasts).

14) TYPES OF INTERACTION DEVICES

User interfaces are the intermediate element between user and DT. They provide insights into the status and functionality of the DT and are means to interact with it. [67] distinguishes between three different kinds of DT interaction devices (tailored off-the-shelf hardware, virtual reality (VR) & augmented reality (AR) interfaces and "smart hybrid devices"). In addition, [42] identified two further enabling technologies for effective human-machine interfaces: gesture control and natural processing. In general, interaction devices should be designed so that the transmission of information and handling of the DT is as intuitive as possible [68]. Further requirements can result from the necessities of the *application domain*, e.g., high robustness and security features. Inspired by [68], we distinguish between three different *Interaction Device Types*:

- Traditional, unimodal interaction devices, e.g. mechanical system inputs (via keyboard, mouse, or touch screens) and visual displays for system replies.
- Multi-modal interaction devices, that might include visual displays, haptic interfaces, voice and gesture recognition. These kinds of interaction devices can use different kinds of technologies, e.g. smart mobile devices (smart phones, tablets) or VR/AR devices combined with dialogue-driven voice recognition, gesture control systems and touch screens.
- Adaptive assistance system, which combines multi-modal interaction devices with *Learning Capabilities* and supplementary technologies (e.g. indoor positioning systems, integrated cameras, object recognition to detect the user's activities), and is able to dynamically detect and adapt to the context of the support situation and the user's tasks.

15) USER FOCUS & INTERORGANIZATIONAL INTEGRATION & COLLABORATION

Depending on the underlying business model, DTs can contribute to the value proposition of different stakeholders (SH) linked to the product. Depending on the number of SHs considered as DT users, different design paradigms for the DT become relevant. A significant distinction has to be made whether a DT is developed for intra-organizational usage, i.e. i) for a single user, ii) several users in one division or iii) across one enterprise, or if the DT is integrated into a cross-company network and serves multiple users across several organizations. The latter can be defined as an inter-organizational DT [59].

Inter-Organizational DTs have users in several independent companies related to each other through the product. Barriers to inter-organizational DTs arise from the fundamental challenges of sharing information across organizations, such as opportunistic actions and mutual dependencies between companies [69]. To mitigate this conflict of interest, various approaches can be pursued, which can be categorised under the topic of inter-organizational information sharing systems (IOIS) [70]. We see DT as a special form of IOIS because, similar to the product avatar of [71], they can serve as an important interface in the context of cross-company information systems but can constitute elements with different owners.

Barrett and Konsynski define different participation levels of companies in IOIS, which we adapt to the area of cross-company DTs [70]. Furthermore, based on [72], we take into account the degree of integration of the DT system into the information systems of the participating companies. Based on this, it is possible to define different degrees of participation, influence and access to different DT elements of the involved partner companies. Less participating companies can only access DT modules for their own tasks, while more participating companies can also add or change them.

- *No Collaboration*
  - Independent DTs for different SHs
  - No exchange/access of/to DT elements for other SHs
- *Minimal Collaboration*
  - Integration of SHs via Services / defined interfaces
  - Basic Collaboration between partners
- *Limited Collaboration*
  - Different grades of integration are possible
  - Aligned relationships between SHs
  - Defined areas of work for SHs
- *Full Collaboration*
  - Different grades of integration possible
  - High trust between SHs

- *Collaborative development and usage of DT*
  - Platform owns/hosts DT
  - Software as a Service (SaaS)

16) REMAINING DIMENSIONS

In the following, all the remaining literature-based dimensions are briefly summarised that we integrated into the MM but could not describe in detail due to space constraints. Each dimension is summarised by the following points:

- MM Name of the dimension.
- Found labels and references for the underlying idea from the literature (in Braces).
- The expressions of the dimensions in the MM.

a: REFERENCE OBJECT

A real-world counterpart is a fundamental prerequisite for the creation of a DT. The reference object represents the entity the DT is twinning and thereby bringing into the digital world. Most authors focus on tangible, physical objects of different levels of abstraction (e.g., manufacturing asset, factory, production network). Focusing on physical artefacts in the context of manufacturing, many authors distinguish between objects that are used in a spatially fixed manner (e.g., manufacturing assets) and those that pass through different spheres of influence in the course of their product life (product, material) [23], [27], [55]. For some authors, manufacturing assets include all objects from a single machine to complete production lines and factory [27], while others propose additional categories for large-scale pooling of manufacturing assets (e.g. factories [23]).

More comprehensive categorizations further include intangible elements describing the logical connection of elements or their surrounding processes, such as execution [55], process [35], or system and model [19]. We combine these aspects under the term process. The inclusion of this aspect allows for the description of more complex entities like production networks, described as a combination of manufacturing assets, people and services [23]. This is similar to the infrastructural systems described by [27].

In Table 4 we mapped these findings to the product-process-resource concept often used in manufacturing and its description [73]–[75]. Besides these direct components of value chains, most authors describing reference objects in DTs classify the human as a vital – and individual – part of the DT [23], [27], [35], [55]. Broadening the scope of physical entities, [55] and [19] also include the environment of an individual asset, which is similar to factories described by [23].

b: MODEL MAINTENANCE

As reality changes, the model needs to adapt to these changes and update itself. For this reason, [43] have recognised the need for constant validation of models. Unlike the validation of traditional simulation models directly at the model generation stage, with DTs, we need to regularly compare the physical and model results to ensure a valid and accurate system. In particular, they suggested the application of periodic validation procedures or maintenance routines that should be used regularly at a certain speed or frequency. Following this idea, we use this dimension to describe the DT's abilities to ensure the validity of its models. These range from a manual adaptation of the model to an autonomous model, which is able to detect a lack in quality and improve itself.

TABLE 4. Reference objects of DTs in literature reviews.

Reference Object	Description
Product	Object with a focus on the use and change of the said object.
Process / Service	Logical linking and interaction of properties or entities.
(Manufacturing) Asset / Component / Resource	Spatially fixed object or group of objects of which transformation is not a main feature.
Human / People	Either as a customer or operator.

c: DATA STORAGE (DATA STORAGE OPTIONS, DATA WAREHOUSING)

Data Storage describes different options for storing the data that the DT uses. [54] argued that *Data Warehousing* is a relevant requirement and research topic for DTs. [23] named two high-level *Data Storage Options* that are ''tailored to different kinds of data formats and application requirements'', namely relational and non-relational databases. We do not follow the approach by [23] but differentiate between different locations of the data used by the DT. In particular, we distinguish between data at the location of the counterpart (edge-based), in the local network (local servers or on premises cloud) or an external cloud.

d: ''MODEL LOOK-AHEAD PERSPECTIVE'' AND ''LEVEL OF COGNITION'' (VIRTUAL PROCESSES, SIMULATION CAPABILITIES)

The capabilities of simulations that a DT may use are another dimension that we could already find in its basic features in literature. However, [22] and [19] more generally distinguished whether a DT has the capability to predict or prescribe by using simulation (or virtual processes) or if it is limited to monitoring and diagnostic tasks. We distinguish between two different dimensions: *Model Look-Ahead Perspective* focuses on the length of time a DT is able to look ahead. We distinguish between long, middle and short term look-ahead capabilities. The exact definition of long, middle and short is left to the user. The *Level of Cognition* describes how intelligent and capable the DT is in analysing the system. Therefore five different types have been identified that range from descriptive to diagnostic analysis and further to the ability to conduct predictions or prescriptive or cognitive analytics.

e: LEARNING CAPABILITIES (LEVEL OF SMARTNESS)

DTs can have different grades of learning capabilities. [30] have already described that the mirrored products and their DTs can have different *Levels of Smartness*. Among other things, they can be able to optimise themselves based on past experience. We have taken up this idea and developed different characteristics for this ability from our own project experiences. So far, we have identified four different learning capabilities: no learning capabilities, reactive learning, supervised learning and reinforcement learning.

f: DATA QUALITY (DATA QUALITY)

[54] identfied *Data Quality* as a relevant requirement and research topic for DTs. [76] has developed a multidimensional framework for data quality of digital shadows through a review of 62 papers using statistical methods, which [77] has further processed into a methodology for deriving data quality improvement needs. Their approach is based on the fitness-for-use principle, according to which the quality of the data must be in line with the application-specific requirements. We do not want to prescribe the fitness-for-use approach in our MM but adopt it as a feature attribute that can be used to characterise the DT. In addition, we consider the following data quality attributes in our MM:

- *Accuracy*: According to [77], preciseness is a data quality attribute that measures the inaccuracy or the degree of error of the stored data. We call this attribute in line with [78] *Accuracy*. The assessment of this attribute could be achieved by calculating the mean and standard deviation for all data points shown (for numerical values).
- *Completeness* describes whether all the data needed for a particular task is available. This attribute supports [76]'s sufficiency dimension, according to which the information needed for important decisions must be supported by a sufficient database.
- *Consistency* describes whether the representation of data values is the same in all cases [78]. For the MM, we follow the distinction between semantic and structural consistency of [76]. *Semantic Consistency* describes the consistency of the meaning of data and can be achieved through uniform definitions or standardised vocabularies for the objects and their attributes represented in data. *Structural Consistency* describes whether similar attributes in the datasets are reflected by uniform format or structure.
- *Uniqueness* describes the redundancy of data. The fewer irrelevant or duplicate attributes are stored, the more efficiently and compactly relevant attributes are mirrored.

An additional option is a regular check for the data quality by the DT.

g: TRIGGER TYPES (SIMULATION CAPABILITIES)

This dimension describes different ways in which the processing of a task by a DT can be initiated. Following distinction of [22] between different grades of *CPS Intelligence*, we distinguish here between *Human Triggered* and *Automatically Triggered DTs*. The latter can be triggered *Continuously* or *Ad-hoc*, based on specific events.

17) ADDITIONAL DIMENSIONS BY THE AUTHORS

In the following, the additional dimensions proposed by the authors are described. These dimensions have emerged from the discussions of the authors and represent characteristics that have not yet been taken into account in the literature but which should be part of the consideration and evaluation of DTs. In defining the new dimensions, we have deliberately ensured that there are no redundancies with aspects of other dimensions. The additional dimensions are relevant because they add important aspects to the categories synthesised from the literature that have not been covered so far. In particular, they have arisen because for some of the UCs presented below, certain aspects have been identified as a key differentiator that could not be covered by the current dimensions. We thus achieve that the real range of DTs can be better represented in the MM.

a: DATA SCOPE

This dimension describes the scale of data that is considered. This ranges from the acquisition at only one asset up to internal and external data of a supply chain and many assets. An option is the usage of big data by the DT.

b: HIERARCHY

This dimension describes if DTs in collaboration are on equal rank. Three different variants are defined, ranging from a decentral organization and control to a centralised one. As an intermediate, the organization in clusters is considered.

c: HUMAN INTERACTION CAPABILITIES

This dimension describes the abilities of the DT to interact with a human. On a basic level, the DT is only able to process pre-defined requests of the user in which format and structure are given. A more advanced DT can react to questions of the user and is able to provide an answer to these. While at the simple level, the set of questions is predefined, on the complex level, the questions are free. As an option, the adaptability of the DT to the user is given.

IV. DIGITAL TWIN MATURITY MODEL

This section shows an overview of the Digital Twin Maturity Model and how the maturity of a DT can be gathered if the MM is applied. In the previous section, different dimensions and characteristics derived from the literature have been described. For a more straightforward assessment, these 31 dimensions have been clustered into seven categories: context, model, computing capabilities, data, control, integration and human-machine-interaction (HMI). These categories and their dimensions are shown in Fig. 6. For each category, a detailed table with the dimensions and their attributes is given in Appendix VIII-A. Each dimension has an entry in the

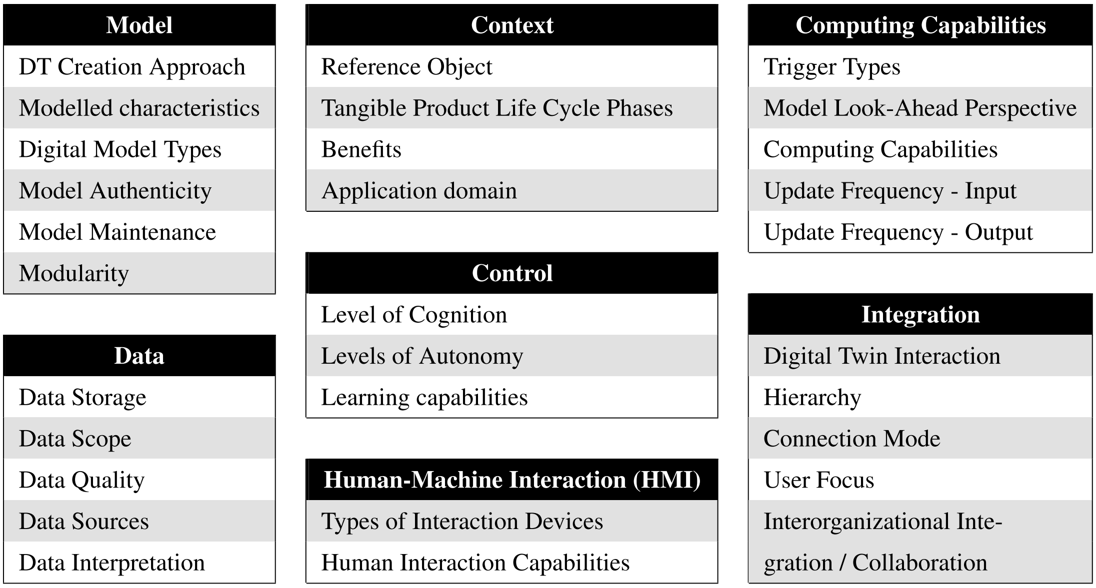

FIGURE 6. Overview of the dimensions of the DT MM gathered from the literature and own considerations and grouped into seven categories.

table consisting of the name of the dimension, a related question that is answered by this dimension, the scores, if applicable, and their possible characteristics named attributes. Some dimensions also have optional attributes, which enhance the dimension.

The score is the basis for the quantification of the maturity of the DT. The details of the calculation will be described in the following. However, at this point, the basic scoring will be introduced: Not all dimensions are rateable, as some have attributes we identified of equal rank and which we are not considering integrating into the maturity calculation. In this case a score of "-" is assigned in the table. If the category has a score, each of the attributes and options, if present, got a score assigned. There are two types of scoring systems used. Some dimensions have a single-choice scoring where only one of the attributes can be selected, and the corresponding score is set for this dimension. It can be increased if the options are applied as their scores are added to the score of the selected dimension. The other variant is a multi-choice-scoring. In this case, all chosen dimensions sum up to the score of the dimension. Again options are added to this score if selected. Given this definition of the score, the range of the scores, as shown in the upper right corner of the dimension, can be calculated as the minimum possible score, selecting the lowest-scored attribute or now attributes and options on multi-selection, and the maximum score, selecting the highest-score attribute and all options or all attributes and all options. The assignment of the scores was done collaboratively by the authors.

In the following the calculation of the maturity, the application of the weighting and a visualization of the maturity are described.

A. CALCULATION OF THE MATURITY

The maturity $M \in [0, 1]$ represents the technical readiness of the analyzed DT. The maturity can be calculated for a dimension d, category c or the overall DT. It is defined as the fraction of the reached score for a dimension z to the maximum score possible z_{max}, considering only rateable dimensions, as shown in (1).

$$M = \frac{z}{z_{max}} \tag{1}$$

The calculation of the maximum score z_{max}, e.g. $z_{d,max}$ for a dimension d, depends on the dimension and their type of scoring. If a dimension has no scoring, its maturity can not be calculated as a division by zero is not possible. For dimensions with a score, the score of an attribute a is $s_a \in \mathbb{N}, s_a \geq 0$, so it is a positive, natural number or 0. In the case of a single-choice dimension without an option, the maximum score is the maximum of all attribute scores. If the single-choice dimension has additional options, the sum of the scores of these options is added to the maximum score. For a multi-choice variant, the maximum score is the sum of all attribute scores. If the dimension has options, the sum of the option scores is added to this maximum score. The reached score z, e.g. z_d for a dimension d, is the sum of the selected attributes and options, following the restrictions regarding single- and multi-choice.

The basis for the calculation is the assessment of all dimensions, with a score assigned to each dimension. This approach can be applied to the different levels, starting from a single dimension to the entire DT. The variables for the following formulas are introduced in Table 5.

The calculation of the maturity of a single dimension d is calculated by dividing the actual score of a dimension z_d by

TABLE 5. Variables for the calculation of the maturity.

Variable	Description
$\mathcal{C}$	set of the six categories with rateable dimensions
c	a category $c \in \mathcal{C}$
$\mathcal{D}$	all dimensions with a score
d	a dimension $d \in \mathcal{D}$, uniquely assigned to one category c
$\mathcal{D}_c$	subset of $\mathcal{D}$ with $\mathcal{D}_c \subset \mathcal{D}$, containing all dimensions of category c. $\mathcal{D}_c = \{d \in \mathcal{D} \| c(d_c) = c\}$
z_d	achieved score for dimension d
$z_{d,max}$	the maximum score for dimension d

its maximal score $z_{d,max}$, see (2).

$$M_d = \frac{z_d}{z_{d,max}}, \quad d \in \mathcal{D} \tag{2}$$

The maturity M_c per category c is the average maturity of all dimensions $\mathcal{D}_c$ with a score in that category. It is defined as the sum of all maturities M_d with their dimension d belonging to the category c divided by the number of dimensions in that category, see (3).

$$M_c = \frac{\sum_{d \in \mathcal{D}_c} M_d}{|\mathcal{D}_c|} \tag{3}$$

The maturity M_{dt} of an entire DT is defined as the average of all category maturities, so it is defined as the sum of all maturities M_c divided by the number of categories, see (4). In this approach, all categories are of equal importance. A solution to assign varying importance to each of the categories will be presented in the next section.

$$M_{dt} = \frac{\sum_{c \in \mathcal{C}} M_c}{|\mathcal{C}|} \tag{4}$$

Using the maturities of the different categories, it is now possible to compare DTs. A fictive example is given in Table 6 to show how three DTs could be compared. The highest maturity is reached by DT B.

B. WEIGHTING

As the different dimensions of the MM are of different importance, based on the UC, a weighting should be applied. This allows to adapt the model even more to the specific UC and shows the potential where to continue in the implementation of the DT, as shown in the following subsection.

The individual weighting can be received by applying a pair-by-pair comparison. In the process, always a pair of two elements is shown and the user has to select the element with the higher importance. As all elements are compared, the user receives for each element a number of how important it is. The higher the number, the more important the element is. To keep the effort of this comparison low, the comparison will be made on the category level. Of the previously described seven categories, only six categories have dimensions with scores. Each time the user decides on a category, the weight of the categories is increased by one point.

TABLE 6. Compare different versions of three randomly selected, exemplary DTs. While it is not easy to see in the six dimensions which DT has the highest maturity, the M_{dt} presents an easy assessment and allows to see that DT B outperforms the others directly.

Category	DT A	DT B	DT C
Data	0.33	0.45	0.23
Computing C.	0.24	0.33	0.55
Model	0.42	0.42	0.46
Integration	0.65	0.44	0.52
Control	0.22	0.34	0.24
HMI	0.30	0.53	0.38
M_{dt}	0.36	0.42	0.40

It is assumed that the comparison between two elements is symmetric and commutative, and each comparison is done only once. Therefore, for n elements in total c comparisons are necessary, as shown in (5). Applying this for $n = 6$ categories, leads to $c = 15$ necessary comparisons and decisions.

$$c = \sum_{n=1}^{n-1} n \tag{5}$$

For the following, the results have been scaled to $0 \ldots 1$. Therefore, the points of each element are divided by the total possible amount of points c. The upper limit of positive decisions for a category is $n - 1$ if this category is preferred over all other categories, which is only possible for one category. To scale the category weight, the reached value v of each category is divided by the total number of comparisons c, so $\frac{v}{c}$. This calculation has the side effect that the sum of all categories' weights is 1. As of the previous condition, the scaled weight of an element is between 0 and $\frac{n-1}{c}$. Concrete for the categories, the maximum scaled weight of an element is $\frac{6-1}{15} = 0.\overline{33}$.

However, the assignment of the weighting is also a critical aspect, which could have an influence on the actions following the evaluation of the DT. If the distribution of the weights does not fit the needs of the user, the actions derived from the maturity analysis might not fit the needs. Different actions are possible to ensure the weighting fits to the UC. A simple approach would be to assign the same weight for all categories, leading to the same priority for all categories. But this also reduces the problem to a single dimension and no comparison can be made on how mature the DT is in relation to the importance of the category. The pairwise comparison takes the user by the hand and leads him to the process. The comparison can be made more robust if multiple users of the DT apply it and the results are compared and e.g. the mean of the different weights is taken.

C. VISUALIZATION

Visualization has been developed to support the interpretation of the results. An example with randomly chosen data is shown in Fig. 7. This diagram shows a dot for each of

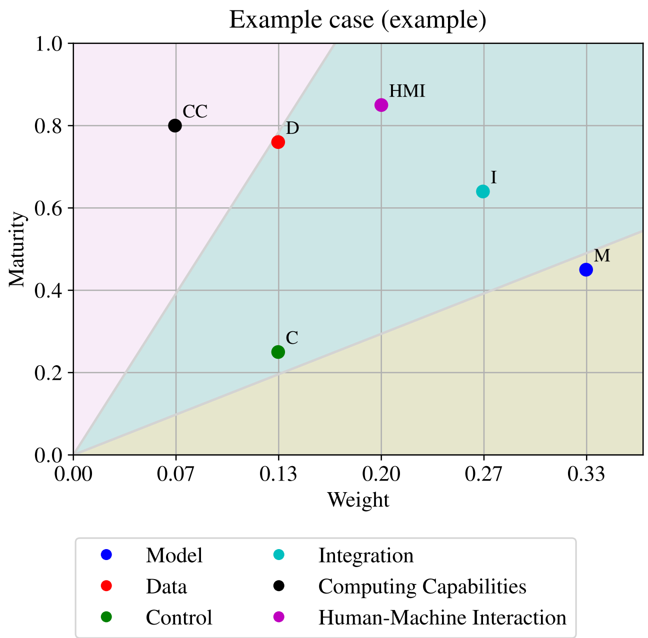

FIGURE 7. Visualization of the maturity over the corresponding weight for each of the six rateable MM categories of an example DT.

the six rateable categories. Each category is located by the weighting on the x-axis and the reached maturity level on the y-axis. So this diagram allows the reader to quickly identify how mature a category is and how important the category is for the applicant. The more right the category is, the more important is the category. Analogous, the higher the category is, the more mature it is. So in the best case, all categories are on a diagonal from the bottom left to the top right. In this case, all categories would be in the correct ratio between the importance of the category (weight) and their technical readiness (maturity). The diagram has a background with three corridors, each at 30°, to support this understanding. If a category is in the red area, this category is overperforming as its maturity is high, while at the same time, the user has weighted the categories' importance as low. So there has been spent too much effort into this category. In the green area is assumed that the right effort has been spent. If a category is in the olive area, this category is underperforming. It has been rated as important, but the maturity is low. If the analyzed solution is further developed, the most effort should be spent on categories in this area.

Concrete for Fig. 7, the Computing Capabilities are high mature but did only receive a low weight. Therefore it can be assumed that this category is over-developed based on the weighting. In contrast, the dimension Control has been weighted as important but only has a maturity of 0.25, which is very low. The other dimensions are in balance between importance and maturity. Only the Model category is a bit low. Therefore most effort in the DT's further development should be spent in the category Control, followed by Model.

V. CASE STUDY: DIGITAL TWIN MATURITY MODEL

We evaluated the MM described above by assessing different DT applications across multiple domains to prove the usability and practicability of the proposed concept in five different scenarios. Apart from the context category, we use the characteristics of the DT developed in Section IV to evaluate the maturity of a DT application. The dimensions of the context category are used to categorise the different scenarios, which are described in the following.

A. SELECTION OF USE CASES

The category *context* gathers characteristics free of valuation, describing the general UC of the DT. Therefore, we categorised DT-based applications in manufacturing regarding the DT's reference object, the product lifecycle affected by the DT, the resulting benefit of its implementation, and the application domain. Based on the presented categorization, we identified distinct applications to cover a wide range of possible implementations and purposes of the DT. To allow for a realistic evaluation, we focused on applications developed in cooperation with the authors of this study. The selected applications comprise all identified categories; however, some are only evaluated on a conceptual basis since the demonstrators are in development.

TABLE 7. Analyzed UCs according to their context.

Context Dimension	Characteristics			
Reference Object	Product[1]	Process[2]	Resource[3,4,5]	Human
Lifecycle Phase	Begin of Life [1,2]	Middle of Life[1,3,4,5]	End of Life[1]	
Benefit	Improved Service [2,4,5]	New Service[1,3]		
Domain	Manuf.[2,4]	Maritime[1]	Logistics[3,5]	Education[5]

TABLE 8. Overview of the different UCs.

#	Title
UC 1	Product-Avatar
UC 2	Configuration of manufacturing process chain using Digital Twins
UC 3	Digital Twin of Warehousing Activities for Educational Purpose
UC 4	Digital Twin for Production planning and control
UC 5	Human-Machine-Interaction in Container-unloading using the Digital Twin

Table 7 depicts the unique capabilities of these UCs and their correspondence to the categories. Overall, five distinct use-cases were identified and evaluated according to the method described above. The UCs UC 1... UC 5, as shown in Table 8, are ordered with respect to the affected lifecycle stage.

UC 1 presents the impact of DT-based services on different stages of the product lifecycle, including both the design of the product and different services for the customer during the middle of life. Similarly, UC 2 allows for an early optimization of manufacturing parameters based on a cause-effect model of the production process, while UC 3 describes a DT-based training and education of heavy equipment operators in a warehouse environment. During operation, UC 4 utilises the DT for optimizations of the process on a shop-floor level, and UC 5 presents a DT-based approach for an improved HMI, using the individual DT-modules to support the operator task-specific throughout the entire process.

B. UC 1 PRODUCT-AVATAR

1) MOTIVATION

This UC describes first experiences with DTs of leisure boats in the shape of product avatars, which digitally represent aspects of the product's state and behavior. It focuses on a low-cost solution to allow the predominantly very small leisure boat producers to use product related-information generated throughout its lifecycle for improving their design, development and manufacturing processes, and provide digital services to strengthen their customer relationships.

Leisure boats are complex, high-value consumer products which lend themselves easily to servitization due to their inherent characteristics. They are often produced in small series, designed, or made to order and often unique. Maintenance plays a key role in safety and ownership costs. The products can be in use for a considerable time. Many stakeholders in the leisure boat lifecycle can profit from DTs. This includes i.a. designers and manufacturers (OEM), boatyards, maintenance and insurance providers, suppliers, the user (assumed to be the owners in this case), and, in the case of digital service applications, the platform.

The DT for leisure boats extends the physical product towards a digital representation and enables value-added digital services with new revenue streams for its stakeholders. It can bridge requirements for all stakeholders and enable collaboration, as e.g. the use of actual and historic product lifecycle information, to optimize manufacturing and design processes.

2) METHOD

Fig. 8 shows the concept of the leisure boat DT. The DT consists of three components representing different aspects of the leisure boat. The system design and configuration component contains computer-aided design (CAD) models of different UC-specific parts of the leisure boat (i.e. the hull and pilot seats) as well as the bill of materials (BOM) and design and configuration parameters. The system state component consists of a time-series database, which stores the middle-of-life data from a maritime data standard network (NMEA 2000) and sensors, collected via a universal sensor gateway (USG). Measurable data streams include engine, steering control and environmental parameters as well as shock, humidity and pressure data. The collected data provides a digital usage profile that the DT can utilize to compare begin-of-life as well as middle-of-life parameters and provides a better

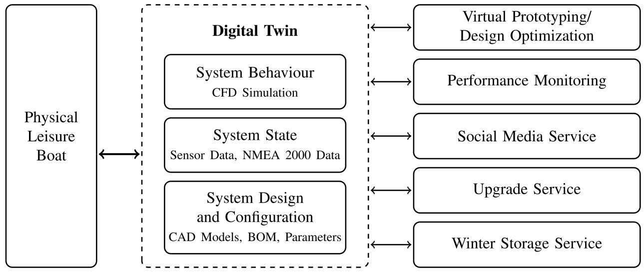

FIGURE 8. Leisure boat DT-concept.

perspective into decision-making. The system behavior component contains simulation models such as complex fluid dynamics, used in combination with system state data to simulate and predict the boat's behavior in lifelike situations.

3) APPLICATION

The elements on the right of Fig. 8 show the applications in the shape of several services for different stakeholders of the DT. They include i.e. a virtual prototyping service, which combines real-time and historical data with CAD models and computational fluid dynamics (CFD) simulation on a high-performance computing cloud. Virtual prototyping is of particularly important in limited series runs since it usually requires the production of a physical prototype for each model, incurring high costs [79]. Boat owners can use the social media service to expose the status of their boat on social media as a Product Avatar, e.g. on Facebook [80]. Other services are performance monitoring, upgrade services and winter storage services [81].

4) EVALUATION

a: MODEL AND COMPUTING CAPABILITIES

The DT contains CFD simulation models to simulate the hydrodynamic behavior of a prototype boat, which were designed according to manufacturers' and designers' specifications. The realization of the data acquisition via the USG considers several stakeholders' requirements, as e.g., which types of data points and sensors are necessary on the physical boat during trial phases. Experts (e.g., designers and manufacturers) control the model quality of the simulation. The Update Frequency varies depending on the requirements for the boat monitoring (e.g. high-frequency data for shocks and impact forces vs. low-frequency data for engine parameters). Capturing higher frequencies in the range of 20 Hz helps the DT acquire information that may not be readily calculated (Linear Acceleration on the hull, Impact forces during high-speed runs, etc.) from CFD simulation models.

b: DATA AND CONTROL

So far, the DT for leisure boats only integrates physical data as data sources. Even though it contains unstructured data, the DT can only interpret structured data, such as sensor readings. Depending on the types of sensors deployed on the physical boat and based on the various stakeholders' requirements, we could tune the data quality accordingly.

Currently, the DT does not provide feedback loops regarding the acquired data. Artificial intelligence/machine learning capabilities are presently underrepresented but may be added in the future if needed. Due to the higher accessibility of information from sea trials and CFD simulation results, human-supervised interventions during manufacturing new prototypes or adapting changes within the present physical models would be possible. In terms of data scope, the data acquisition can be increased many-fold, e.g., by broader sets of different CFD simulation models for different physical boats and USG-assisted sea trials.

c: INTEGRATION

Even though each boat has only one individual DT, multiple DTs and their data can be aggregated. This way, users can interpret comparative analyses and create collaborative services between different stakeholders.

The DT is well-integrated into the limited IT landscape in the small and medium-sized enterprise leisure boat sector. It integrates with design systems, customer-relationship management, enterprise resource planning (ERP), service and maintenance systems as well as boat owners. Data acquisition to higher-level IT infrastructure (data sinks, web services) is possible via the usage of the USG. Interoperability is further possible by using product lifecycle management and maritime data standards (NMEA2000, NMEA0183) via the USG.

5) RESULTS AND OUTLOOK

Using the evaluation mechanism presented in Subsection IV-A, the product avatar for leisure boats achieves an ***Overall Score*** of *44 %* at its current stage of development. The focus of the product avatar lies on the topic of interoperability, as the ***Integration***-category is significantly rated highest (*66 %*). The ability to integrate into a heterogeneous system- and information landscape as well as to seamlessly share data in an efficient and usable way is one of the key objectives of the presented system. As we designed the system to support multiple stakeholders along its lifecycle, it is also sensible that its ***HMI*** rating is the third-highest among all six classification dimensions (*46 %*). Its versatility, however, leads to only moderate ***Model*** (*47 %*) and ***Data*** (*46 %*) as well as weak ***Control*** (*27 %*) and ***Computing Capability*** (*33 %*) characteristics. The visualised comparison of these results with the weighting of the associated categories in Fig. 9 shows that the overall development is in reasonable proportion to the relevance of the respective development priorities in the categories. One exception is the HMI category, which we have classified as relatively unimportant for the avatar, but developed in the same proportion as the rest.

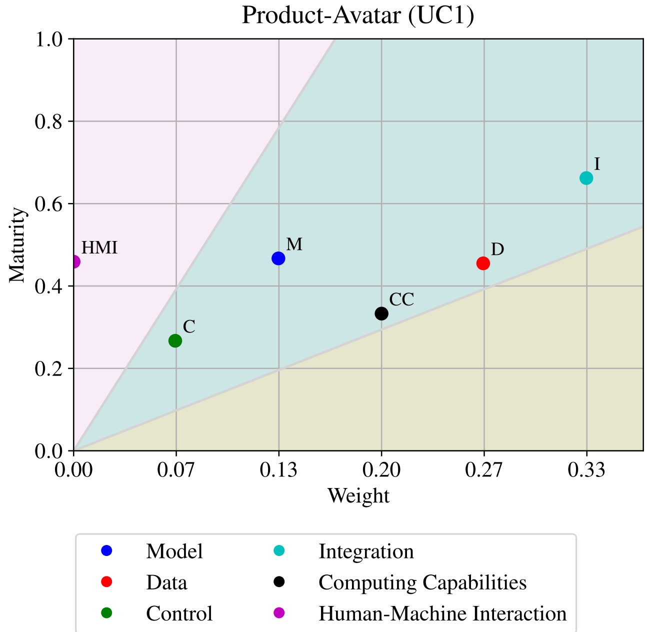

FIGURE 9. Results of the UC "Product avatar"[2].

C. UC 2 CONFIGURATION OF A MANUFACTURING PROCESS CHAIN USING DIGITAL TWINS

1) MOTIVATION

The demand for micromechanical components increased continuously over the last decades due to the ongoing miniaturization, particularly in the consumer-electronics and medical sectors [82]. Such micromechanical components, e.g., connectors, casings, or contacts, are usually required and produced in large amounts. Consequently, cold forming processes have become increasingly attractive, as these can achieve production rates of several hundred parts per minute with comparably low energy consumption and waste. Nevertheless, the novelty of such processes and the occurrence of so-called size effects render the configuration of such processes difficult. The small dimensions of the components require tight tolerances of some micrometers. In contrast, size effects and still imperfect processes induce high uncertainties in the configuration and result in variances that can be hard to describe analytically [83].

2) DESIGN APPROACH

Cause-effect networks can support process planners in configuring their processes internally and adjusting them across whole process chains. They offer a structured methodology to create and combine data-driven and analytical models into DTs for machining operations, processes and complete process chains. While initially developed for micromanufacturing, these cause-effect networks apply to any area in which the outcome of processes can vary strongly and where the actual physical mechanics are yet unknown or inefficient to model purely analytical.

Cause-effect networks model the interrelationships between involved parameters within a manufacturing process regarding the characteristics of processes' in- and output (workpiece), the applied tools and machining parameters,

[2]Details of this UC can be found at https://dt-maturity.eu/dt/6bf3d8e8, and accordingly for the following UCs.

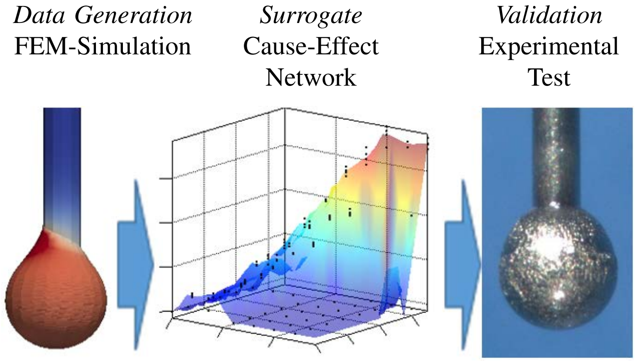

FIGURE 10. Concept (left) and example (right) for the use of cause-effect networks as surrogates to increase the speed of process accompanying DTs.

e.g., forces or speeds. They consider each parameter as a function of its input parameters' values, which can either be represented analytically or by data-driven models, e.g., neural networks, support vector machines or computed regression functions. Thus, by obtaining estimates or measurements of the processes' input parameters, the cause-effect network estimates the output characteristics, constituting a DT for the represented process. Moreover, the general distinction in input workpiece, process, and output workpiece allows chaining several of these DTs to obtain a twin for the overall process chain.

Compared to classical approaches, which usually try to represent the complete process in a single model, these DTs provide additional capabilities for validation and retraining if the conditions for the process change. The focus on single internal relationships between parameters allows a high degree of transparency as the DT monitors the process and compares single relationships to current measurements. If discrepancies between the DT's predictions and the real world occur, errors can be determined more easily and the DT can be retrained partially. The latter reduces costs and efforts in maintaining the DT after its creation. Adapting methods from the statistical process control allows for automation of the monitoring and retraining [84].

3) APPLICATION

In micro-manufacturing, cause-effect networks have been applied, e.g., for the (offline) configuration of rotary swagging, the estimation of tool degradation in micro punching [84], or as surrogate, to reduce the computational times of physical simulations by finite element method (FEM) for a laser rod-end melting process [85], as depicted in Fig. 10. Apart from micro-manufacturing, cause-effect networks have been applied to estimate the power consumption for compound feed manufacturing. Thereby, the cause-effect network aims to provide an additional, quickly computable layer inside the DT. This allows a real-time computation of expected workpiece characteristics based on the results of a high-fidelity finite-element simulation of the process.

4) EVALUATION

a: MODEL AND COMPUTING CAPABILITIES

DTs using cause-effect networks as their underlying modeling paradigm are usually designed in two stages. First, modelers interview process experts to identify relevant parameters and their qualitative relations. Second, they add or compute the required models for each parameter using analytical functions for physical laws or machine learning to derive data-driven models. This process allows achieving a high level of authenticity if all parameters and relationships can be described physically. In cases where modelers apply data-driven models, the authenticity of the DT highly relates to the used training data. Nevertheless, the highly modular nature of these cause-effect networks allows for a targeted retaining and monitoring of single parameters, increasing the precision of the predictions where needed. As data-driven models compute very fast, the resulting DTs can generally be applied in real-time to assess the predicted output of a process, usually even for continuous processes.

b: DATA AND CONTROL

Referring to the applications described before, the DTs used historical data for their training while using separate input data for the evaluation. Most of the applications applied the DT for process planning, i.e., an offline optimization before production started. Nevertheless, by integrating methods for the inversion of mathematical models, process parameters can be optimized with comparably low computational efforts [86]. Regardless, these approaches have not yet been evaluated in practice.

c: INTEGRATION

Currently, cause-effect networks have been mainly used for offline planning of processes. Thus, we used a dedicated software prototype to model and execute the cause-effect networks. However, the final cause-effect networks can easily be implemented within a standalone software to tie directly to existing databases for the data acquisition.

5) RESULTS AND OUTLOOK

This section presents the concept of cause-effect networks, which constitute a modeling paradigm for DTs. By combining expert knowledge with machine learning, cause-effect networks provide a viable alternative to achieve real-time predictions of a process's results if physical models are too complex to formulate or compute in real-time. Currently, the evaluation mechanism (subsection IV-A) shows that the DT achieved an Overall Score of *39 %*. Fig. 11 shows that the categories Data (*61 %*), ***Control*** (*42 %*) and ***Model*** (*42 %*) have reached the highest scores, which correspond to the use for process analysis and prediction and are in line with their allocated weighting. Lower scores have the categories ***Integration*** (*33 %*), ***HMI*** (*29 %*) and ***Computing Capability*** (*27 %*), whereby the low score of HMI leaves some room

[3] https://dt-maturity.eu/dt/e9f5fd06

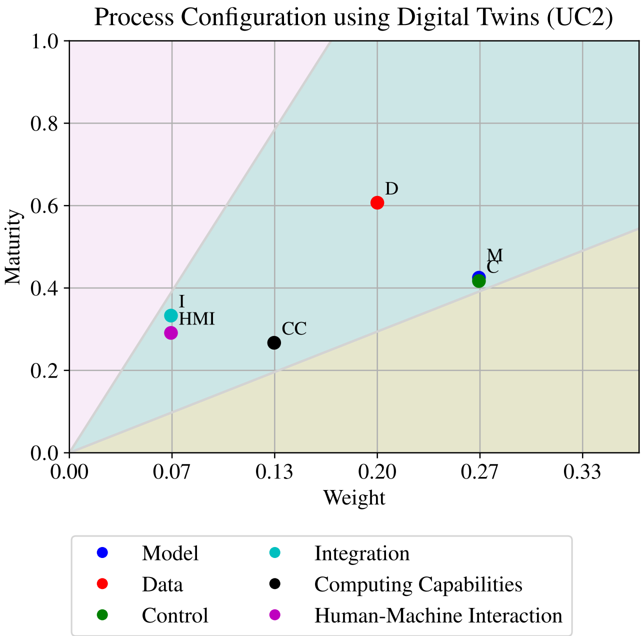

FIGURE 11. Results of the UC "Process configuration using digital twins"[3].

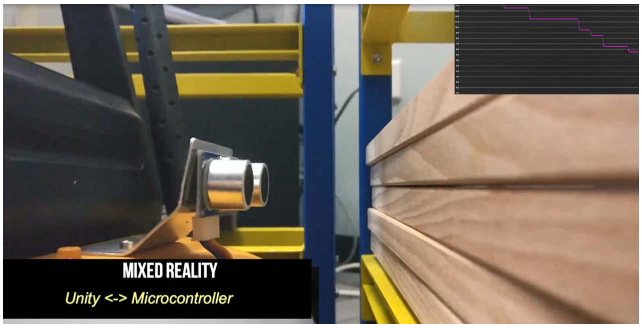

FIGURE 12. The physical test bed from which we import the real-time sensor data.

for optimization because there are some needs for better interpretation possibilities.

D. UC 3 DIGITAL TWIN OF WAREHOUSING ACTIVITIES FOR EDUCATIONAL PURPOSE

Due to changes in the competence requirements on employees in production and logistics operations, there is a need for training and educational offers that prepare current and future employees so that they will fulfill these requirements [87]. This section describes the implementation of a gamified DT for educational purposes, which focuses on how different technologies can support warehousing operations.

1) MOTIVATION

A DT can be more than a testing environment [88]–[90]; it encourages the ideation process and helps analyzing problems from different perspectives. During the exploration phase, different draft configurations of a solution can be tested virtually and the best fitting for the problem can be selected and transferred into the physical environment. The usage of gamification techniques has proven effective for the understanding of complex processes and systems and can enhance a digital twin for a more immersive experience if allowing real-time dynamics, adaptation and personalization to fit the users (learners) need.

2) DESIGN APPROACH

Gamification approaches can be applied to both a virtual and physical training environment. For our purpose, which is the manipulation of data from the physical environment in the virtual to support the planning process, we focus on the virtual part (i.e. the DT). We map only the relevant processes with data imported directly from the physical demo area or reused from a database. The design is based on an analysis and a reduction of real processes. For the design of the gamified simulation model, we applied the Activity-Theory Method for Serious Games (ATMSG) model to connect the different processes with the learning goals. [88], [90]. According to this design and analysis method, the model needs to simulate and mirror those relevant processes for training the users and helping them achieve their learning goals. This means that the DT has a reduced complexity compared to the real world operation. The simulation building focuses on the relationship between intrinsic instructions (in the gameplay/DT) and the learning and gaming activities of a realized scenario. In this case, it is related to the usage of IoT technologies for reducing damages to goods and health risks. Most relevant processes are related to the movements of goods using a forklift, the related risk of bumping into something and the decision process of selecting the most suitable sensors to reduce this risk. The DT will allow the player to investigate the functionality of different components and then decide upon the most suitable one. This implies that the design of the DT is adaptable to cope with different configurations.

3) APPLICATION

We integrated different game mechanics into the decision-making process of a simulation. This includes information on time spent on movement, how the vehicle has moved, the quality of the delivered service, selection of different sensors or actuators, etc. The implemented mechanics depend on the specific aim of our investigation. For a focus on the operating processes, other key performance indicators (like mistakes, bumps, etc.) would have been of more interest as mechanics. To realize the current prototype, we created the DT of a warehouse in which IoT technologies are used.

Fig. 12 shows the physical testbed. It shows one of the typical operations with a high number of damages as well as with high time usage – the process of in- and out-stocking in a rack. The figure shows how several sensors are attached to a fork. The data from the real operation is imported to the DT. The feedback from the DT is both during operation as well as for post-analysis and re-play. To reduce component size, the demonstrator is not at full scale.

The DT scenario teaches whether and how IoT technologies can improve and enhance warehouse operations. The pedagogical method used is problem-based learning (PBL). This approach calls the learner to face a real-world problem, analyze it, and present a possible solution. It has been demonstrated to affect the learning outcomes of engineering students positively. The students need to use the DT, either with data from the database or the demonstrator, to assess the appropriateness and limitations of the different technologies for the different problems. As an example, we use a remote-controlled forklift with environmental sensors, e.g., temperature and humidity, and tilt sensors to detect the tilt of the forklift. The sensors deliver data for the gamified simulation used for the decision-making process. We use Unity to model 3D data from the sensed data, which requires an interface showing the data in real-time.

It is also possible to do it the other way - i.e., instead of collecting data from the real-world sensors, we can manipulate the data and spin them back in the real world to validate the module. However, this underlies some restrictions - like that we need to have the same equipment. In addition, in our case, we have objects with a certain risk for accidents and injuries - in this case the import of manipulated data in the real world needs to undergo a safety assessment before testing.

4) EVALUATION

This DT's usage differs from the previous examples in which the twins are used for planning and operation. The evaluation also reflects this difference.

a: MODEL AND COMPUTING CAPABILITIES

The model maps the real world process in sufficient detail. However, the relevance of the DT's accuracy is not on the same level as the applications used for monitoring and control. Relevant here is only that the processes are sufficiently accurate. Furthermore, the level of complexity needs to be reduced since, for the learning process, it is required that the user of the DT understands cause-effects. Thus, we have to consider different constraints like the human brain's capacity to follow a few variables. The evaluation of one of the first prototypes is described in [90] and [91]. It showed that it was generally well perceived and found engaging, but that there is a need for reducing the execution time, so that the user does not experience it as a stop in the flow.

b: DATA AND CONTROL

The DT is used for teaching and training decision-making. Control is, therefore, less relevant since it needs to be in the hand of the user. This is contrary to the relevance of data and visualisation on which basis the user will decide. These need to be sufficiently exact and their visualisation simple to understand.

c: INTEGRATION

The DT on Technology Assessment is well integrated in its environment. It imports data from its corresponding physical counterpart and can export the manipulated data back. However, there is currently a limitation in the control of the physical environment through the DT.

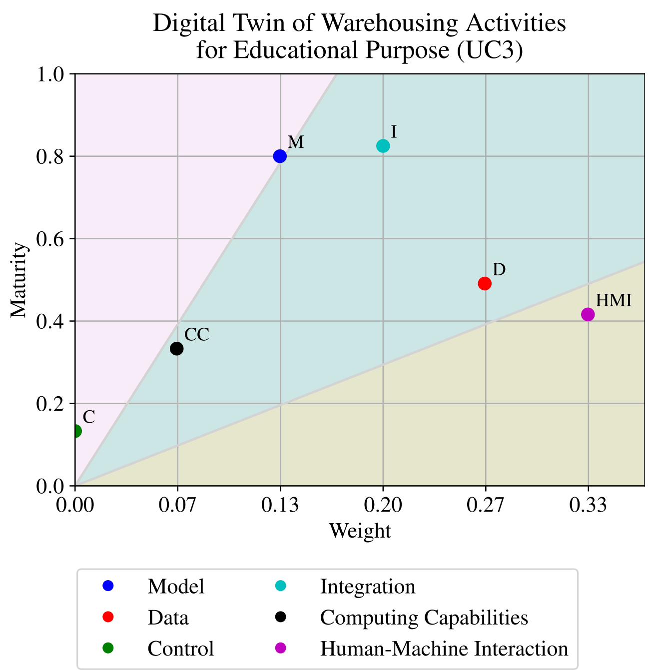

FIGURE 13. Results of the UC "Digital twin of warehousing activities for educational purpose"[4].

5) RESULT AND OUTLOOK

Using the evaluation mechanism, the DT of Technology Assessment achieves an ***Overall Score*** of *50 %* as its currently operated. As shown in Fig. 13, the DT Technology Assessment focuses on the integration and its visualisation, as the ***Integration*** (*82 %*) category is rated highest. This category has increased significantly in relevance over the past year of development as the demonstrator has been better connected to other applications. During the same development period, the relevance of the ***Models*** also has increased significantly compared with the first versions. This is due to a higher granulation level that is required for some of the new training units on warehouse operation. In the early versions of this DT, ***Data*** (*49 %*) was most relevant due to the relevance of data as decision-making support in an educational setting. Currently, it is only rated as third. This does not mean that the data quality is not of high relevance, but more is caused again by expanding the usage of the DT for different levels, and for some of the decisions the students have to make, the data accuracy is less relevant, compared with the ***Integration*** and ***Models***. This is followed by the relevance of ***HMI*** (*41 %*). The results for ***Control*** and ***Computing Capabilities*** are less mature and have a lower weighting factor. This is due to the specific usage of this DT, which is based on experiental learning, and thus requires that the user of the DT can actively interact with the DT and experience the conseqences of this interaction.

[4]https://dt-maturity.eu/dt/08909ea9

E. UC 4 DIGITAL TWIN FOR PRODUCTION PLANNING AND CONTROL

1) MOTIVATION

The manufacturing scheduling and control faces new challenges: Products are becoming more customized, leading to smaller lot sizes and higher product variety resulting in more complex scheduling. Current ERP systems calculate only a basic schedule on the ERP level and the control at the shop floor level is done by static dispatching rules. This approach does not consider the current state of the production system. Additionally, a production system is a highly dynamic system that is affected by external influences, like unpredictable customer demand, high priority orders or disturbances like machine breakdowns, and stochastic influences, like varying processing times. These effects lead to non-optimal schedules and might require a re-scheduling. The addition of sensors to machines and getting to sensor-equipped collaborating machines (''Industry 4.0'') enables the collection of data about the current system state in real-time. This data can be used to build more accurate DTs with an improved and more accurate internal representation of the current system state.

2) DESIGN APPROACH

We developed a DT, which employs a discrete-event simulation model to represent a production system. The simulation utilizes available data of the system, like workstations, routes and jobs. The jobs also include confirmed and assumed jobs in the future. On events that influence the system's state, like a machine breakdown, the DTs model is updated. In this case, the DT applies a distance function that calculates the difference between the current state and the state at which the production schedule was last updated. The DT triggers a re-scheduling if the distance is above a specified threshold. This re-scheduling applies a simulation-based optimization that utilizes the simulation model of the DT to evaluate different possible solutions and gather their quality. The DT actuates the real production system and applies the resulting optimized schedule.

3) APPLICATION

We evaluated the presented concept by applying it in a simulation environment that emulated a real production system and produced the system data that feeds the DT. For the scenario, data from a job shop of a Brazilian automotive supplier has been used [92], [93].

4) EVALUATION

a: MODEL AND COMPUTING CAPABILITIES

The model has been constructed based on the available system data. It uses a discrete-event simulation internally to represent the system and its behavior. This simulation uses the simulation library jasima (Java Simulator for Manufacturing and Logistics), which provides a fast evaluation for suggested updates of the production plan. An optimization heuristic, in this case, a genetic algorithm, generates suggested updates. A distance function observes the changes since the last planning and triggers an optimization if the difference is above a specified threshold. For the optimization, currently processed and upcoming jobs are considered. The number of the forthcoming jobs depends on the DT look-ahead setting. The optimization result is applied immediately.

b: DATA AND CONTROL

The DT considers the production's historical, current, and future data, depending on the data type. Distributions are fitted over historic processing times to get realistic input for the simulation. Except for these distributions, the simulation considers no historical job data. Data must be collected at all machines to represent the system state in the DT. The system collects it from different sources (see [92] for details), and compiles and processes it at the ERP or Manufacturing Execution Systems (MES). The DT autonomously changes the scheduling and learns from previous solutions.

c: INTEGRATION AND HMI

A single DT represents the whole system. The connection is bi-directional, as data from the system drive the DT and the DT itself influences the systrems' behavior by changing the schedule. The DT does not provide any HMI as it works in the background. The results are visible in other systems, like ERP.

5) RESULTS AND OUTLOOK

Overall, this approach reaches a DT maturity of *53 %*. The approach is most mature in the categories ***Model*** (*69 %*), ***Computing Capabilities*** (*67 %*) and ***Integration*** (*65 %*). As the system only provides a very basic ***HMI***, it is low mature in this regard (*29 %*). The results are shown in Fig. 14. This graphic shows that this case is overperforming for ***HMI*** and ***Model*** regarding the author's weighting while it underperforms in the ***Data*** category.

F. UC 5 HUMAN-MACHINE-INTERACTION IN CONTAINER-UNLOADING USING THE DIGITAL TWIN

1) MOTIVATION

Systems currently available in logistics, e.g., for container unloading, are either simple handling machines that support action implementation or fully autonomous systems that carry out all process steps independently [94]. Their level of automation is pre-determined and fixed and can therefore not change during operation, leading to difficulties in dealing with unforeseen situations. In this scenario, the DT improves the systems' accessibility by creating a more flexible and user-centered interface between physical object and human operator [95]. The richness of data provided by the DT combined with internal simulations and models, as well as a bi-directional connection to the physical asset, enables the operator to understand and interact with the autonomous processes of the machine.

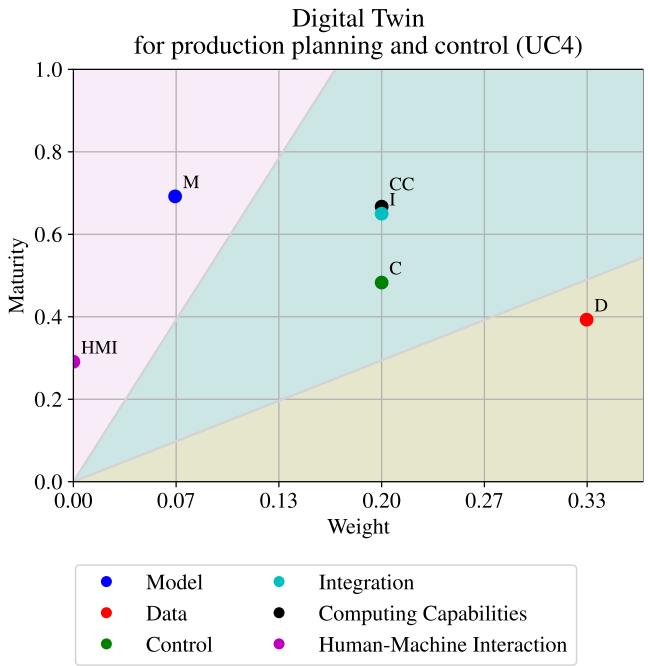

FIGURE 14. Results of the UC "Digital twin for production planning and control"[5].

2) DESIGN APPROACH

According to [96], the process segmentation serves as the basis for a sequentially structured HMI. In trivial situations, the system performs autonomously, though an operator can support in ambiguous or unsolvable situations. A sequential process segmentation allows for structured assistance exclusively in the erroneous process step. Once the operator has given the system the necessary help, it can revert directly to autonomous operation. Furthermore, it is possible to operate the system with the highest level of autonomy at any time [94].

The DT, characterized by bi-directional communication and extensive simulation capabilities, simplifies the HMI. Simulation and prognosis capabilities allow for the evaluation of potential interventions. Human-readable interfaces between the stages of information processing provide multiple paths for a direct HMI. These interfaces empower the operator to understand the system's internal dynamics by analyzing raw sensor data, pre-processed information, and simulation results.

3) APPLICATION

We implemented the presented concept in a CPS for semi-autonomous container unloading. Data from the sensors feed into DT for information analysis, information presentation, and autonomous decision-making. The DT sends the result of the decision-making process to the physical system, which acts accordingly [97].

[5]https://dt-maturity.eu/dt/54c282a6

With the ability to supervise all decisions made by the system, the user can modify or overwrite individual signals within the CPS without interfering with the rest of the processes. Additionally, the operator might bypass the entire process chain of the DT, resulting in teleoperation.

4) EVALUATION

a: MODEL AND COMPUTING CAPABILITIES

We created the models and DT representation of the system in parallel to the design process with specific models re-used in the creation of the DT (e.g., CAD-data, kinematics). First-order models of the individual components and subsystems are linked according to the interaction in the real system. The system and its environment are part of a dynamic simulation combining continuous and discrete models. The models are used to control the system with additional triggers for specific events (e.g., unforeseen situations, sensor thresholds for safety).

b: DATA AND CONTROL

The DT modules are connected to the Programmable Logic Controller (PLC) controlling the physical system (e.g., drivetrain, kinematics, grippers) and serve as the basis for calculating the autonomous behavior of the system. In this cascaded control, the DT represents the outer loop, calculating reference signals for the inner loop. The simulation pre-calculates and optimizes the next grip and the necessary trajectory.

For monitoring and teleoperation, the DT provides the operator with the processed sensor information in the form of a 3D simulation. Based on this data, the operator can develop and analyze control commands. The DT simulation validates these commands and transmits them to the real system afterward.

c: INTEGRATION

A DT exists for each individual unloading system. A control desk combines several DTs, allowing one supervisor to monitor and control multiple systems. The individual systems report key performance indicators to the control desk, which are gathered and sent to downstream processes for control (e.g., the conveyor technique) and higher levels in the company for reporting purposes.

d: HMI

The pre-processed data and its representation within the DT enable the operator to grasp the current situation quickly (Fig. 15). The user can monitor the pre-processed sensor data (e.g., image recognition to highlight edges of cartons) or explore the current situation in a 3D representation. This virtual scenario updates live, combining sensor readings with knowledge about the physical system. The model displays additional information, forecasting the results of the user's decisions. The system is controlled by a physical gamepad and virtual representations on smart devices.

FIGURE 15. DT-based control interface presenting additional control information (red and blue) [94].

5) RESULTS AND OUTLOOK

The evaluation of this system reflects the usage of the DT to support the system's control (*55 %* maturity in ***Control***). Yet, in the context of a DT-based HMI with multiple semi-autonomous systems, the general concept of the DT offers more capabilities in terms of ***Computing Capabilities*** (*87 %*), ***HMI*** (*75 %*) and ***Integration*** into the overall system (*60 %*). Figure 16 allows us to analyse the maturity of system implementation and identify specific areas for further improvement. Overall, however, Fig. 16 indicates that the level of development of the individual categories is reasonably proportional to their relevance. Only the components of the dimensions Integration and Computing Capability are over-performing compared to their low Weigthing Score. Options for enhancement are long-term behavior optimization (simulation), reinforcement learning (control), the combination of multiple DTs and the collaboration of the DT within the IT landscape (integration), and improved output capabilities towards the user (HMI).

G. MATURITIES OF THE DIFFERENT USE CASES

Table 9 shows the maturities of the different, previously presented UCs. The maturity of the UCs varies between *39.0 %* and *66.4 %*, which indicates that these UCs are different mature. This data allows to identify different focuses of the UCs, e.g., UC 4 and UC 5 have a much higher emphasis on Computing Capabilities than the other UCs. Integration is a highly important topic in UC 3, while it got a low score in UC 2. In Figure 17, we visualized the data in a box plot to identify how the maturity spreads for the different categories across the distinct UCs. The orange line in the box gives the median of the categories' maturities. The right column shows the total maturity of the use cases. According to this representation, we can observe that the evaluators rated the maturity in the Data category most uniformly. In contrast, the Computing Capabilities show a relatively high spread.

H. WEIGHTING (PAIR-BY-PAIR)

In the context of this case study, for each of the UCs, the MM has been applied. Accordingly, for each UC, a categories'

[6]https://dt-maturity.eu/dt/06ec5a39

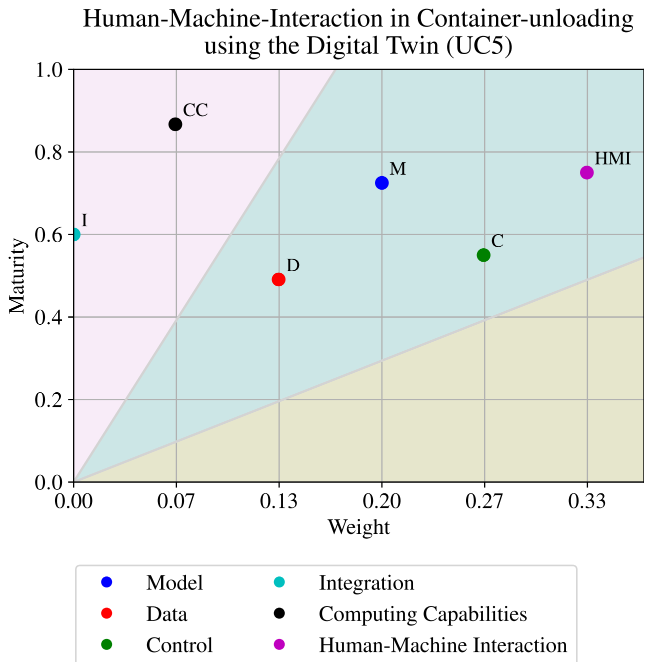

FIGURE 16. Results of the UC "Human-machine-interaction in container-unloading using the digital twin"[6].

TABLE 9. Maturities of the different UCs.

Category	UC 1	UC 2	UC 3	UC 4	UC 5
Model	46.7 %	42.5 %	80.0 %	69.2 %	72.5 %
Data	45.5 %	60.7 %	49.1 %	39.3 %	49.1 %
Control	26.7 %	41.7 %	13.3 %	48.3 %	55.0 %
Integration	66.2 %	33.3 %	82.5 %	65.0 %	60.0 %
HMI	45.9 %	29.1 %	41.6 %	29.1 %	75.0 %
Computing Capabilities	33.3 %	26.7 %	33.3 %	66.7 %	86.7 %
Maturity	44.1 %	39.0 %	50.0 %	52.9 %	66.4 %

pair-wise weighting has been conducted, based on the different use-cases and the individual expertise of the UC authors, resulting in different weightings. Fig. 18 shows a box plot of these five weightings and how they vary. An exception is the category *Model*, which most authors rate equal important. An opposite is the *Integration* category, which is controversial among the authors. One gives the highest and lowest possible importance, while on average, it is medium relevant. This situation is even more for HMI, which is twice weighted at maximum and twice weighted at minimum. The exact weights of the different authors are shown in Table 10.

VI. DISCUSSION

This section discusses the key findings on the validation of the derived classification framework and MM and some inferences from the practical DT development.

The analysis of existing DTs (case studies chapter V) also indicates that the nature of the DTs and their application area

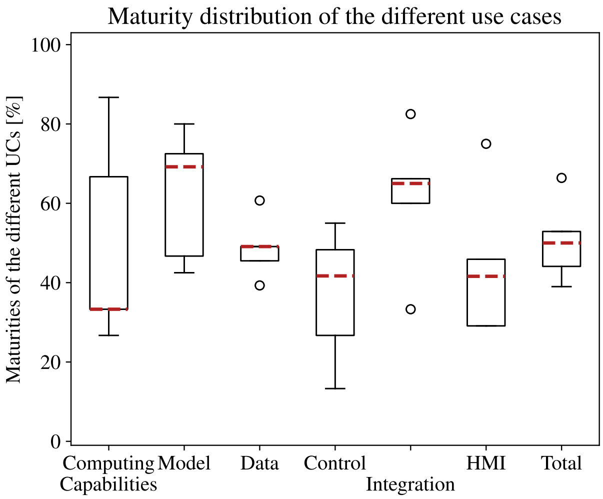

FIGURE 17. Box plot of the UCs maturities.

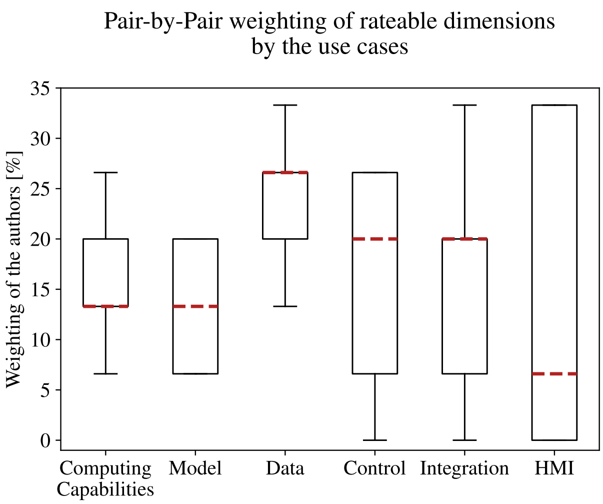

FIGURE 18. Box plot of the authors weightings.

TABLE 10. Weightings of the different UCs.

Category	UC 1	UC 2	UC 3	UC 4	UC 5
Model	13.3 %	26.6 %	13.3 %	6.6 %	20.0 %
Data	26.6 %	20.0 %	26.6 %	33.3 %	13.3 %
Control	6.6 %	26.6 %	0.0 %	20.0 %	26.6 %
Integration	33.3 %	6.6 %	20.0 %	20.0 %	0.0 %
HMI	0.0 %	6.6 %	33.3 %	0.0 %	33.3 %
Computing Capabilities	20.0 %	13.3 %	6.6 %	20.0 %	6.6 %

varies. A comparison of two of these UCs, *UC 4* and *UC 5* (see sec. V-E and sec. V-F), is shown in Fig. 19.

In Fig. 19, we combined the maturity level and the weight of the identified categories and divided the field into corridors. These corridors visualize the ratios of maturity and

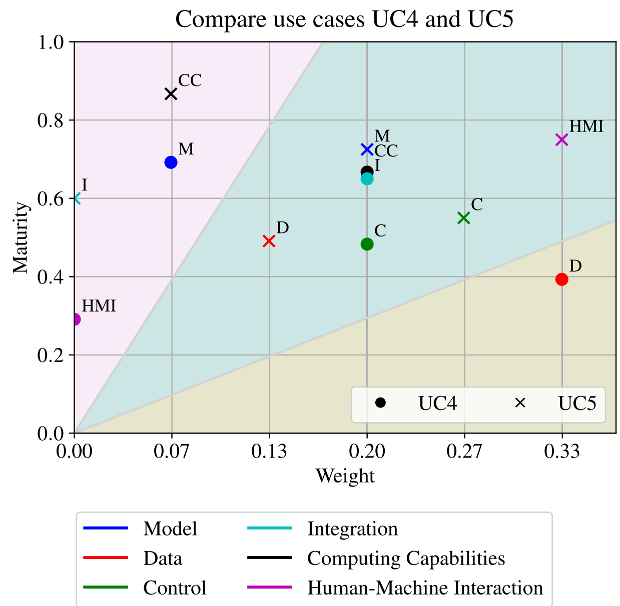

FIGURE 19. Representation of the maturity over the corresponding weight for each of the six rateable MM categories of the UCs 'UC 4' and 'UC 5'. The areas visualize three corridors categorizing the ratio of maturity to weight.

weight and allow a quick assessment of the potential development needs according to the weighting. The figure shows that in terms of *model* (M) and *data* (D), both DTs have a maturity above 0.8. At the same time, the weight (relevance of the dimension based on the subjective assessment of an author for this specific context) differs slightly more. Looking at the dimension *integration* (I), we see that the maturity of this dimension in UC 5 is lower than that of UC 4, while the weight is higher for UC 5. This could indicate that it would be suitable to put more development resources here in the future for the UC 5 DT.

In UC 4, the dimension HMI is of specific interest since it is hardly considered in terms of maturity and weight, indicating that the evaluators don't perceive it as an important dimension for this application. This low rating is thus interesting, because it is an apparent deviation from the systematic literature review's (SLR) results, which present the basis of the framework. The challenge of such a deviation is manifold: If this dimension is not sufficiently considered in the early step of the modeling process, we know that the costs of changes related to non-foreseen functionalities increase. In some cases, it is not possible to consider new required functionalities of that low prioritized dimension at a later stage. This can cause challenges in future development but also make re-use, re-purpose and re-design impossible. Also, adapting to a slightly different context might be costly and complicated. Designing, developing and maintaining DTs is both time-consuming and costly. Thus in this context, it is relevant to investigate how the framework can contribute to reducing these two factors through more lean processes.

Fig. 9, 11, 13, 14 and 16 visualize the maturity and the subjective weight of the five different UCs we have presented in chapter 5 by applying the developed maturity method.

All five DTs are one-of-a-kind products, specifically designed and developed for specific requirements and fitting the needs within a particular context. However, for all five, the main benefit is related to either new or improved services. Furthermore, all but one cover the middle-of-life cycle phase, and most DTs use *Resources* as the reference object. Since developing such DTs is costly, difficult, and time-consuming, we will discuss how the framework can support the creation of flexible and re-usable DTs. A primary challenge of developing the DTs is related to the requirements and the specification. This challenge appears specifically if the system requirements change in the different phases or if the future needs (new services) are not precisely specified.

As previously mentioned, most DTs are expensive, one-of-a-kind products. However, in some cases, it might be possible to re-use a DT for a different purpose, i.e., running another experiment or modding the DT to fit a new reality (could be changing the shop-floor layout). Another option is to transfer a DT from one field to another- i.e., using a DT made for production also for logistics operation or a DT made for maintaining to also work for operation management. In such cases, the DT must be systematically analysed. In our view, the proposed framework can be used both as an analysis and design tool. As a design tool, the framework will support the design of new or adapt existing to a new environment, supporting the re-usage of DT components. It will thereby also support transferring knowledge from one domain to another using the following approach: In a first step, the objectives (or functional specification) of existing DTs could be compared with the requirements of a different environment, but with similar functionalities for DT to be designed. Secondly, a new set of requirements can be generated by combining a pair-by-pair comparison with an analysis of the maturity of the different characteristics for each dimension. The old DT design can be transferred and repurposed if the differences are minor. For large deviations in the requirements, the design would need to be re-developed from scratch.

Applied in this way, the framework supports the inclusion of existing knowledge, reducing the likelihood of design errors or repetition of failures, improving the time to market, and allowing more exact planning. Regarding re-use, the approach would be similar, with an increased focus on comparing whether the requirements are sufficiently similar, using tables 12 and 14 first. Even if a difference is identified – i.e. the existing DT covers begin of life, the new should be middle of life – it does not mean that the DT is not reusable, but it will require a deeper analysis. If the results are satisfactory, the next step would be to compare the individual characteristics of both DTs for each dimension. If the outcome of the analysis for re-usage is unsatisfactory, the transfer analysis can be applied to identify what to adapt or re-design.

VII. SUMMARY

The SLR revealed the large variety of applications that are collectively described using the term ''Digital Twin'', both in terms of functionalities and maturity. We developed a classification framework thought as a tool for analysis of existing DTs and as a support in the development process of existing and future DTs.

The main objective of this research is to improve the development of context-specific DTs by supporting requirement analysis and knowledge transfer from one DT to another. We selected a mixed research approach with a combination of an SLR, giving an overview of already existing maturity and classification models, the Maturity Model Development process of [16], our experience in DTs and the use of case studies for evaluation.

Based on this approach, we identified a set of seven MM categories (context, data, computing capabilities, model, integration, control, human-machine interaction) that are key to the characterization of DTs. We further divided these categories into dimensions to allow a more detailed description. The lists (Table 12 - Table 18, pp. 27ff.) indicate the large set of characteristics to be considered when assessing the maturity and usability of an existing DT in a specific context. However, the specific usability and expected benefits are all related to the application context and the services that it fuels. This is particularly important if the goal is to re-purpose, re-design or re-use the DT for a slightly different topic. For such a mapping, it is important to assess the nature of the DT and

TABLE 11. Structure of the DT MM tables.

Dimension name	Scoring range
Question	
Score	**Attributes/Options**
n/-	first attribute

TABLE 12. Dimensions of the category "context."

Context

Reference Object		-
What is the reference object of our DT(s)?		
-	Product	
-	Resource (Manufacturing) Asset / Component / Resource	
-	Process / Service	
-	Human / People	
Tangible Product Life Cycle Phases		-
In which product lifecycle phase is the DT applied?		
-	Begin of Life	
-	Middle of Life	
-	End of Life	
Benefits		-
How does the DT provide benefit?		
-	New Service Innovation	
-	Service Optimization	
Application domain		-
What is the application domain of the DT?		
-	see Table III, p. 6	

TABLE 13. Dimensions of the category "computing capabilities."

Computing Capabilities

Trigger Types *How is the DT triggered?*		0 ... 3
+1	Ad-hoc (event driven)	
+1	Dynamic (continous)	
+1	Static (once at a time)	
Model Look-Ahead Perspective *How far ahead does the DT think?*		0 ... 3
+1	Long-term	
+1	Middle-term	
+1	Short-term	
Computing Capabilities *How is the runtime/response time?*		0 ... 1
0	Hours	
0	Minutes	
1	Seconds	
1	Milliseconds	
Update Frequency - Input *How often is new data considered and the DT models updated?*		0 ... 2
0	Every day or less frequent	
1	Every hour	
2	real-time / event-driven	
Update Frequency - Output *How often is the result of the DT applied?*		0 ... 1
0	Periodic	
1	Instant / real-time	

TABLE 14. Dimensions of the category "model."

Model

DT Creation Approach *How is the DT designed?*		0 ... 1
0	Retrofitted-DT	
1	Design-for-DT	
Modelled characteristics *Which characteristics of the physical object are modelled?*		-
-	Geometry-kinematics	
-	Control behaviour	
-	Sensor behaviour	
-	(Multi-)Physical behaviour	
-	Production System behaviour	
Digital Model Types *How are the characteristics of the DT modelled?*		-
-	Conceptual Models	
-	Physics-Based Models	
-	Data / Machine Learning-Based Models	
-	Hybrid Models	
-	**Model is used in Simulation**	*(Option)*
-	Time is represented in simulation (dynamic / not static)	*(Option)*
-	Simulation calculates with probabilities (stochastic / not deterministic)	*(Option)*
-	Processed values are within an infinite range (continuous / not discrete simulation)	*(Option)*
Model Authenticity *How is the authenticity of the DT? How good is the representation of reality?*		0 ... 3
0	no	
1	low	
2	middle	
3	high	
Model Maintenance *How is the model quality observed and controlled?*		0 ... 5
0	Model descriptions are not formalized and maintained manually	
1	Models are formalized and periodic maintenance procedures are used	
2	Individual models can detect lacking model quality itself [1]	
3	[1] and reload latest data and code itself	
4	[1] and load additional model plugin or adjust the model parameter itselfs	
5	[1] and full maintain themselves by e.g. organizing new sensors and computing capabilities	
Modularity *How modular and reusable is the DT modelled?*		0 ... 2
0	Unit	
1	System	
2	System of Systems	

the maturity of all its dimensions. If they comply and address the new requirements, a re-design, re-purposing, or re-usage is possible.

DTs have become increasingly important for science and industry in recent years. Due to the complexity and application-dependent interpretability of the DT concept, we also saw intensified research on the characterization and classification of DTs recently, where we observed a range of different classification criteria, including the development of new standards (i.e., ISO23247 [98] for the manufacturing domain) In response to this, we analysed DT related literature reviews with regard to these classification criteria. The SLR showed that DTs are research subjects in various domains with different objectives and hence partly unlike definitions. The main aim of this work was to synthesize a set of criteria valid for a broad set of DT applications. Therefore, it was particularly difficult to integrate similar ideas described from different perspectives by finding their common denominator and identifying applicable characteristics. However, we were able to find several similar ideas more frequently so that we could initially establish 13 theoretically supported criteria. We then used these criteria to propose a MM for DTs, which can be used for a wide range of application scenarios. The proposed model comprises supplementary criteria, which we defined iteratively by comparing the existing literature-backed criteria to additional observations from practitioners resulting from five DT UCs. We placed great importance on serving a broad set of different application scenarios and areas, leading

TABLE 15. Dimensions of the category "data."

Data		
Data Storage *Where is the data storage located?*		-
-	Edge based	
-	Local servers	
-	On premises cloud	
-	External cloud	
Data Scope *How large-scaled is the sourcing of data?*		0 ... 4
0	informal data acquisition of a specific asset	
1	Local-scope data is collected regularly for one asset and its environment	
2	Data of multiple assets	
3	Internal and external Data of a supply chains and very numerous assets	
+1	Big Data	*(Option)*
Data Quality *How is the data quality?*		0 ...7
-	DT follows fitness-for-purpose approach	
+1	Accuracy: Low degree of errors	
+1	Completeness: All needed data available	
+1	Semantic Consistency: Uniform Vocabulary and Definitions	
+1	Structural Consistency: Uniform Format and Structure	
+1	Uniqueness: Few irrelevant/duplicate data	
+1	Check for data quality regularly	*(Option)*
Data Sources *What is the source of the data?*		0 ... 2
+1	Physical Data	
+1	Fused Data	
Data Interpretation *How capable is the DT to interpret incoming data?*		0 ... 1
0	Structured	
1	Unstructured	

TABLE 16. Dimensions of the category "control."

Control		
Level of Cognition *How intelligent is the DT?*		0 ... 5
+1	Descriptive Analytics: *What happened?*	
+1	Diagnostic Analytics *Why did it happen?*	
+1	Predictive Analytics: *What could happen?*	
+1	Prescriptive Analytics: *What should we do?*	
+1	Cognitive Analytics: *Solving Complex problems and cause something to happen*	
Levels of Autonomy *What are the levels of autonomy?*		0 ... 5
0	No Autonomy	
1	User Assistance	
2	Partial Autonomy	
3	Conditional Autonomy	
4	High Autonomy	
5	Full Autonomy	
Learning capabilities *How is the learning capability?*		0 ... 4
0	No learning	
+1	Reactive learning with user based control strategies	
+1	Learning from historical data to make decisions by use of (un)supervised learning	
+1	able to learn new skills with reinforcement learning self-aware with human-like intelligence	
+1	Fast learning	*(Option)*

TABLE 17. Dimensions of the category "Human–machine interaction (HMI)."

Human-Machine Interaction (HMI)		
Types of Interaction Devices *What types of devices are used?*		0 ... 3
1	Traditional, unimodal interaction devices	
2	Multi-modal interaction devices	
+1	Adaptive assistance system	*(Option)*
Human Interaction Capabilities *For which requests can the DT answer?*		0 ... 4
+1	Predefined, structured reports	
+1	Simple Questions and Answers	
+1	Complex Questions and Answers	
+1	DT adjusts to the User	*(Option)*

to a wide range of characteristics. The identified dimensions are universal denominators, which comprise some ambiguous manifestations and avoid features that refer to specific domains so that they are relevant for all application scenarios. The resulting model structures the DT landscape by 30 major distinguishing criteria in the form of dimensions, which we clustered into seven categories. Currently, the scores of the dimensions presented in this paper are based on the application of the framework to five distinguished UCs by experts. Applying the framework to more UCs may verify the approach for a larger spectrum of DTs, but the current version allows a description of different types of DTs and can be used to describe the potentials and limitations of a specific DT understandably. This way, it may help developers allocate resources for further development by supporting the categorization and selection of necessary DT characteristics and indicating if an existing DT can be reused.

We validated and evaluated the MM in different UCs, some of them presented in this paper. The validation has shown that the dimensions are of varying importance for specific applications. This fact could limit the comparability of DT maturities when applied to different application fields. Further fields of investigation will also be related to the suitability of a specific indicator for a particular task. This will help match a DTs maturity with the complexity of tasks since DTs are always designed to reach a specific objective.

Based on this, we conducted a weighting of the dimensions for each UC and discussed an approach to assess the different maturity ratings based on ratios of maturity and weighting.

TABLE 18. Dimensions of the category "Integration."

Integration

Digital Twin Interaction *Is it only one or are there more DTs?*		1 ... 4
1	Standalone	
2	System of System with Interconnection/Network of integrated Systems	
3	System of System with collaboration but independent goals	
4	System of System with one/common goals and optimization	
Hierarchy *Are the DTs in collaboration of equal rank?*		-
-	Decentral organization and control	
-	Cluster-based organization	
-	Central orchestration and control	
Connection Mode *How is the DT connected to the real world?*		1 ... 3
1	Digital Model / Offline	
2	Digital Shadow / Uni-Directional	
3	Ideal DT / Bi-Directional	
User Focus *Who benefits from the DT?*		1 ... 4
1	Single User	
2	Multiple User in one department	
3	Multiple User across enterprise	
4	Multiple User across multiple enterprises	
Interorganizational Integration/Collaboration *How far is the DT integrated in the IT-landscape? Options: max. +1*		0 ... 4
0	No Collaboration: Independent DTs for different stakeholders (SH), No exchange/access of/to DT elements for other SHs	
1	Minimal Collaboration: Integration of SHs via Services / defined interfaces, Basic Collaboration between partners	
2	Limited Collaboration: Different grades of integration possible, Aligned relationships between SHs, Defined areas of work for SHs	
3	Full Collaboration: Different grades of integration possible, High trust between SHs, Collaborative development and usage of DT	
+1	Platform owns/hosts DT	*(Option)*
+1	Software as a Service (SaaS)	*(Option)*

VIII. OUTLOOK

The validation indicates that the relevance of each dimension depends on the application. In this first approach, we have used linear corridors for the ratio maturity/weight. However, we hypothesize that we may expect to see a more sophisticated curvature (e.g. Pareto patterns) with more data. Future research activities, therefore, need to address the variance of the weightings. The current model allows for an evaluation of individual DT applications and the analysis of re-usage of external twins for a different purpose. Since the current weighting is based on only five sources, an extension of the sample is an important step to make the statement generally valid. By adding further UCs for validation, we could check dependencies between the context of a DT and the importance of certain dimensions in the future.

The MM presented in this paper is available online at *https://dt-maturity.eu*. We ask interested readers to submit their DT, contribute to a broader database, and support continuous improvement of the model. Such a crowd-sourced data pool could help in the classification and evaluation of DTs and present new insights on the current stage of DT usage and will besides improve the evaluation of the framework and support the current standardisation initiatives that drive some of the DT developments. In this context, the weighted maturity results may also be compared to the similar concepts of the digital twin (e.g., digital shadow and digital model) mentioned in section III-B.

APPENDIX

A. DIMENSIONS OF THE DIGITAL TWIN MATURITY MODEL

In this appendix the categories, dimensions, attributes and options of the DT MM are shown. The structure of the tables is always as shown in Table 11. The first line shows the dimension name and question. On the top right corner the scoring range of this dimension is given. If no scoring can be applied, this is given by a -. Below the attributes and options of this dimension and their scores follow.

REFERENCES

[1] J. Reis, M. Amorim, N. Mel ao, and P. Matos, "Digital transformation: A literature review and guidelines for future research," in *Trends and Advances in Information Systems and Technologies*, Á. Rocha, H. Adeli, L. P. Reis, and S. Costanzo, Eds. Cham: Springer, 2018, pp. 411–421.

[2] A. Ait-Alla, M. Kreutz, D. Rippel, M. Lütjen, and M. Freitag, "Simulation-based analysis of the interaction of a physical and a digital twin in a cyber-physical production system," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 1331–1336, 2019.

[3] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022, 2018.

[4] R. Santana Tapia, M. Daneva, P. van Eck, N.-H. Castro Cárdenas, and L. van Oene, "Business-IT alignment domains and principles for networked organizations: A qualitative multiple case study," in *Proc. Move Meaningful Internet Syst., OTM Workshops*, R. Meersman, Z. Tari, and P. Herrero, Eds. Berlin, Germany: Springer, 2008, pp. 241–252.

[5] J. Pöppelbuß and M. Röglinger, "What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management," in *19th Eur. Conf. Inf. Syst. (ECIS)*, V. K. Tuunainen, M. Rossi, and J. Nandhakumar, Eds. Helsinki, Finland: AIS eLibrary, 2011, p. 28. [Online]. Available: http://aisel.aisnet.org/ecis2011/28

[6] C. Weber, J. Königsberger, L. Kassner, and B. Mitschang, "M2DDM–A maturity model for data-driven manufacturing," *Proc. CIRP*, vol. 63, pp. 173–178, Jan. 2017.

[7] Q. Qi, D. Zhao, T. W. Liao, and F. Tao, "Modeling of cyber-physical systems and digital twin based on edge computing, fog computing and cloud computing towards smart manufacturing," in *Additive Manufacturing; Bio and Sustainable Manufacturing*. vol. 1. New York, NY, USA: American Society of Mechanical Engineers, 2018.

[8] L. Canetta, A. Barni, and E. Montini, "Development of a digitalization maturity model for the manufacturing sector," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2018, pp. 1–7.

[9] C. Voell, P. Chatterjee, A. Rauch, and J. Golovatchev, "How digital twins enable the next level of PLM–A guide for the concept and the implementation in the internet of everything era," in *Product Lifecycle Management to Support Industry 4.0* (IFIP Advances in Information and Communication Technology), vol. 540, P. Chiabert, A. Bouras, F. Noël, and J. Ríos, Eds. Cham, Switzerland: Springer, 2018, pp. 238–249.

[10] E. Oztemel and S. Gursev, "Literature review of industry 4.0 and related technologies," *J. Intell. Manuf.*, vol. 31, no. 1, pp. 127–182, Jan. 2020.

[11] M. Sony and S. Naik, "Key ingredients for evaluating industry 4.0 readiness for organizations: A literature review," *Benchmarking: Int. J.*, vol. 27, no. 7, pp. 2213–2232, Jan. 2019.

[12] A. Madni, C. Madni, and S. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, p. 7, Jan. 2019.

[13] J. Autiosalo, J. Vepsalainen, R. Viitala, and K. Tammi, "A feature-based framework for structuring industrial digital twins," *IEEE Access*, vol. 8, pp. 1193–1208, 2020.

[14] ARUP. (2019). *Digital twin: Towards a Meaningful Framework*. London, U.K. [Online]. Available: https://www.arup.com/digitaltwinreport

[15] BiZZdesign. (2020). *Are You Ready for a Digital Twin of Your Organization?* [Online]. Available: https://bizzdesign.com/digital-twin-assessment/

[16] J. Becker, R. Knackstedt, and J. Pöppelbuß, "Developing maturity models for IT management," *Bus. Inf. Syst. Eng.*, vol. 1, no. 3, pp. 213–222, Jun. 2009.

[17] A. B. VanGundy, "Brain writing for new product ideas: An alternative to brainstorming," *J. Consum. Marketing*, vol. 1, no. 2, pp. 67–74, Feb. 1984.

[18] D. Moher, P.-P. Group, L. Shamseer, M. Clarke, D. Ghersi, A. Liberati, M. Petticrew, P. Shekelle, and L. A. Stewart, "Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement," *Systematic Rev.*, vol. 4, no. 1, pp. 1–9, Dec. 2015.

[19] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP J. Manuf. Sci. Technol.*, vol. 29, pp. 36–52, May 2020.

[20] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[21] E. Glaessgen and D. Stargel, "The digital twin paradigm for future NASA and U.S. air force vehicles," in *Proc. 53rd AIAA/ASME/ASCE/AHS/ASC Struct., Struct. Dyn. Mater. Conf.; 20th AIAA/ASME/AHS Adapt. Struct. Conf.; 14th AIAA*. Reston, VA, USA: American Institute of Aeronautics and Astronautics, 2012, pp. 1–14.

[22] R. Stark and T. Damerau, "Digital twin," in *CIRP Encyclopedia of Production Engineering*. Berlin, Germany: Springer, 2019.

[23] Y. Lu, C. Liu, K. I.-K. Wang, H. Huang, and X. Xu, "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robot. Computer-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101837.

[24] S. Boschert and R. Rosen, "Digital twin—The simulation aspect," in *Mechatronic Futures*, P. Hehenberger and D. Bradley, Eds. Cham, Switzerland: Springer, 2016, pp. 59–74.

[25] Y. Chen, "Integrated and intelligent manufacturing: Perspectives and enablers," *Engineering*, vol. 3, no. 5, pp. 588–595, 2017.

[26] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, "Shaping the digital twin for design and production engineering," *CIRP Ann.*, vol. 66, no. 1, pp. 141–144, 2017.

[27] M. R. Enders and N. Hoßbach, "Dimensions of digital twin applications—A literature review," in *Proc. 25th Americas Conf. Inf. Syst. (AMCIS)*, Cancún, Mexico: Association for Information Systems, Aug. 2019, pp. 1–10. [Online]. Available: https://aisel.aisnet.org/amcis2019/org_transformation_is/org_transformation_is/20

[28] H. Park, A. Easwaran, and S. Andalam, "Challenges in digital twin development for cyber-physical production systems," in *Cyber Physical Systems. Model-Based Design*. Cham, Switzerland: Springer, 2019.

[29] T. R. Wanasinghe, L. Wroblewski, B. K. Petersen, R. G. Gosine, L. A. James, O. De Silva, G. K. I. Mann, and P. J. Warrian, "Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges," *IEEE Access*, vol. 8, pp. 104175–104197, 2020.

[30] L. Barth, M. Ehrat, R. Fuchs, and J. Haarmann, "Systematization of digital twins," in *Proc. The 3rd Int. Conf. Inf. Sci. Syst.*, New York, NY, USA, Mar. 2020, pp. 13–23.

[31] M. Holler, F. Uebernickel, and W. Brenner, "igital twin concepts in manufacturing industries—A literature review and avenues for further research," in *Proc. 18th Int. Conf. Ind. Eng. (IJIE)*, 2016, pp. 1–9.

[32] E. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Proc. Manuf.*, vol. 11, pp. 939–948, Jun. 2017.

[33] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2019.

[34] K. Y. H. Lim, P. Zheng, and C.-H. Chen, "A state-of-the-art survey of digital twin: Techniques, engineering product lifecycle management and business innovation perspectives," *J. Intell. Manuf.*, vol. 31, pp. 1313–1337, Aug. 2020.

[35] B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167653–167671, 2019.

[36] N. Taylor, C. Human, K. Kruger, A. Bekker, and A. Basson, "Comparison of digital twin development in manufacturing and maritime domains," in *Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future*. Cham, Switzerland: Springer, 2019.

[37] Z. M. Cinar, A. A. Nuhu, Q. Zeeshan, and O. Korhan, "Digital twins for industry 4.0: A review," in *Industrial Engineering in the Digital Disruption Era*. Cham, Switzerland: Springer, 2020.

[38] R. B. Roy, D. Mishra, S. K. Pal, T. Chakravarty, S. Panda, M. G. Chandra, A. Pal, P. Misra, D. Chakravarty, and S. Misra, "Digital twin: Current scenario and a case study on a manufacturing process," *Int. J. Adv. Manuf. Technol.*, vol. 107, nos. 9–10, pp. 3691–3714, Apr. 2020.

[39] T. Y. Melesse, V. D. Pasquale, and S. Riemma, "Digital twin models in industrial operations: A systematic literature review," *Proc. Manuf.*, vol. 42, pp. 267–272, Jan. 2020.

[40] A. Orozco-Romero, C. Y. Arias-Portela, and J. A. M. Saucedo, "The use of agent-based models boosted by digital twins in the supply chain: A literature review," in *Intelligent Computing and Optimization* (Advances in Intelligent Systems and Computing), vol. 1072, P. Vasant, I. Zelinka, and G.-W. Weber, Eds. Cham, Switzerland: Springer, 2020, pp. 642–652.

[41] M. M. Rathore, S. A. Shah, D. Shukla, E. Bentafat, and S. Bakiras, "The role of AI, machine learning, and big data in digital twinning: A systematic literature review, challenges, and opportunities," *IEEE Access*, vol. 9, pp. 32030–32052, 2021.

[42] A. Rasheed, O. San, and T. Kvamsdal, "Digital twin: Values, challenges and enablers from a modeling perspective," *IEEE Access*, vol. 8, pp. 21980–22012, 2020.

[43] C. H. dos Santos, J. A. B. Montevechi, J. A. de Queiroz, R. de Carvalho Miranda, and F. Leal, "Decision support in productive processes through DES and ABS in the digital twin era: A systematic literature review," *Int. J. Prod. Res.*, vol. 60, no. 8, pp. 2662–2681, 2021.

[44] I. Errandonea, S. Beltrán, and S. Arrizabalaga, "Digital twin for maintenance: A literature review," *Comput. Ind.*, vol. 123, Dec. 2020, Art. no. 103316.

[45] J. Ríos, J. C. Hernández, M. Oliva, and F. Mas, "Product avatar as digital counterpart of a physical individual product: Literature review and implications in an aircraft," in *Transdisciplinary Lifecycle Analysis of Systems* (Advances in Transdisciplinary Engineering), R. Curran, N. Wognum, M. Borsato, J. Stjepandić, and W. J. Verhagen, Eds. Amsterdam, The Netherlands: IOS Press, 2015, pp. 657–666. [Online]. Available: http://ebooks.iospress.nl/publication/40020

[46] P. Aivaliotis, K. Georgoulias, and K. Alexopoulos, "Using digital twin for maintenance applications in manufacturing: State of the art and gap analysis," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2019, pp. 1–5.

[47] D.-G.-J. Opoku, S. Perera, R. Osei-Kyei, and M. Rashidi, "Digital twin application in the construction industry: A literature review," *J. Building Eng.*, vol. 40, Aug. 2021, Art. no. 102726.

[48] F. Jiang, L. Ma, T. Broyd, and K. Chen, "Digital twin and its implementations in the civil engineering sector," *Autom. Construct.*, vol. 130, Oct. 2021, Art. no. 103838.

[49] H. Zhang, L. Ma, J. Sun, H. Lin, and M. Thürer, "Digital twin in services and industrial product service systems: Review and analysis," *Proc. CIRP*, vol. 83, pp. 57–60, Jan. 2019.

[50] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," in *Transdisciplinary Perspectives on Complex Systems*. Cham, Switzerland: Springer, 2017.

[51] M. W. Grieves, "Virtually indistinguishable," in *Product Lifecycle Management. Towards Knowledge-Rich Enterprises* (IFIP Advances in Information and Communication Technology), vol. 388, L. Rivest, A. Bouras, and B. Louhichi, Eds. Berlin, Germany: Springer, 2012, pp. 226–242.

[52] J.-F. Uhlenkamp, K. Hribernik, S. Wellsandt, and K.-D. Thoben, "Digital twin applications: A first systemization of their dimensions," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2019, pp. 1–8.

[53] S. Terzi, A. Bouras, D. Dutta, M. Garetti, and D. Kiritsis, "Product lifecycle management-from its history to its new role," *Int. J. Product Lifecycle Manage.*, vol. 4, no. 4, p. 360, 2010.

[54] L. F. Durão, S. Haag, R. Anderl, K. Schützer, and E. Zancul, "Digital twin requirements in the context of industry 4.0," in *Product Lifecycle Management to Support Industry 4.0* (IFIP Advances in Information and Communication Technology), vol. 540, P. Chiabert, A. Bouras, F. Noël, and J. Ríos, Eds. Cham, Switzerland: Springer, 2018, pp. 204–214.

[55] F. Tao, Q. Qi, L. Wang, and A. Nee, "Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison," *Eng. Forthcoming*, vol. 5, no. 4, pp. 653–661, 2019.

[56] S. O. Erikstad, "Merging physics, big data analytics and simulation for the next-generation digital twins," in *Proc. HIPER*, 2017, pp. 141–151.

[57] U. Dahmen and J. Rossmann, "Experimentable digital twins for a modeling and simulation-based engineering approach," in *Proc. IEEE Int. Syst. Eng. Symp. (ISSE)*, Oct. 2018, pp. 1–8.

[58] S. Bullock and D. Cliff, "Complexity and emergent behaviour in ICT systems: Project Report," Digit. Media Syst. Lab., HP Lab., Bristol, U.K., Tech. Rep. HPL-2004-187, 2004. [Online]. Available: https://eprints.soton.ac.uk/261478/

[59] J.-F. Uhlenkamp, K. Hribernik, and K.-D. Thoben, "Wie digitale zwillinge unternehmensgrenzen überwinden," *Zeitschrift für Wirtschaftlichen Fabrikbetrieb*, vol. 115, no. s1, pp. 84–89, 2020.

[60] P. K. Davis, "An introduction to variable-resolution Model. cross-resolution model connection," RAND, Santa Monica, CA, USA, Tech. Rep. 4252, 1993.

[61] Lexico. *Autonomy: Definition of Avatar in English*. [Online]. Available: https://www.lexico.com/definition/autonomy

[62] A. H. Louie, "Robert Rosen's anticipatory systems," *Foresight*, vol. 12, no. 3, pp. 18–29, 2010.

[63] SAE On-Road Automated Vehicle Standards Committee, *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, Standard J3016_202104, SAE Standard J. Ed. by SAE On-Road Automated Vehicle Standards Committee, 2014, vol. 3016, pp. 1–16.

[64] J. P. Kleijnen, "Design and analysis of simulation experiments," in *Proc. Int. Workshop Simulation*. Cham, Switzerland: Springer, 2015, pp. 3–22.

[65] H. van der Valk, J. Hunker, M. Rabe, and B. Otto, "Digital twins in simulative applications: A taxonomy," in *Proc. Winter Simul. Conf. (WSC)*, Dec. 2020, pp. 2695–2706.

[66] A. Sulistio, C. S. Yeo, and R. Buyya, "A taxonomy of computer-based simulations and its mapping to parallel and distributed systems simulation tools," *Softw., Pract. Exper.*, vol. 34, no. 7, pp. 653–673, Jun. 2004.

[67] R. Stark, C. Fresemann, and K. Lindow, "Development and operation of digital twins for technical systems and services," *CIRP Ann.*, vol. 68, no. 1, pp. 129–132, 2019.

[68] D. Gorecky, M. Schmitt, M. Loskyll, and D. Zuhlke, "Human-machine-interaction in the industry 4.0 era," in *Proc. 12th IEEE Int. Conf. Ind. Informat. (INDIN)*, Jul. 2014, pp. 289–294.

[69] R. M. Emerson, "Power-dependence relations," *Amer. Sociol. Rev.*, vol. 27, no. 1, pp. 31–41, 1962.

[70] S. Barrett and B. Konsynski, "Inter-organization information sharing systems," *MIS Quart.*, vol. 6, p. 93, Dec. 1982.

[71] K. A. Hribernik, L. Rabe, K. D. Thoben, and J. Schumacher, "The product avatar as a product-instance-centric information management concept," *Int. J. Product Lifecycle Manage.*, vol. 1, no. 4, p. 367, 2006.

[72] R. Shah, S. M. Goldstein, and P. T. Ward, "Aligning supply chain management characteristics and interorganizational information system types: An exploratory study," *IEEE Trans. Eng. Manag.*, vol. 49, no. 3, pp. 282–292, Aug. 2002.

[73] R. G. Brown, "Driving digital manufacturing to reality," in *Proc. Winter Simulation Conf.*, Dec. 2000, pp. 224–228.

[74] A. F. Cutting-Decelle, R. I. M. Young, J. J. Michel, R. Grangel, J. Le Cardinal, and J. P. Bourey, "ISO 15531 MANDATE: A Product-process-resource based approach for managing modularity in production management," *Concurrent Eng.*, vol. 15, no. 2, pp. 217–235, Jun. 2007.

[75] M. Schleipen and R. Drath, "Three-view-concept for modeling process or manufacturing plants with AutomationML," in *Proc. IEEE Conf. Emerg. Technol. Factory Autom.*, Sep. 2009, pp. 1–4.

[76] M. Riesener, C. Dölle, G. Schuh, and C. Tönnes, "Framework for defining information quality based on data attributes within the digital shadow using LDA," *Proc. CIRP*, vol. 83, pp. 304–310, 2019.

[77] G. Schuh, E. Rebentisch, M. Riesener, T. Ipers, C. Tönnes, and M.-H. Jank, "Data quality program management for digital shadows of products," *Proc. CIRP*, vol. 86, pp. 43–48, 2019.

[78] D. P. Ballou and H. L. Pazer, "Modeling data and process quality in multi-input, multi-output information systems," *Manage. Sci.*, vol. 31, no. 2, pp. 150–162, 1985.

[79] S. Wellsandt, M. von Stietencron, K. Hribernik, B. Henriksen, C. C. Røstad, and K.-D. Thoben, "Fact-based design for leisure boats: The HighSea-experiment setup," *Proc. CIRP*, vol. 38, pp. 74–77, 2015.

[80] T. Wuest, K. Hribernik, and K.-D. Thoben, "Can a product have a Facebook? A new perspective on product avatars in product lifecycle management," in *Product Lifecycle Management. Towards Knowledge-Rich Enterprises* (IFIP Advances in Information and Communication Technology), vol. 388, L. Rivest, A. Bouras, and B. Louhichi, Eds. Berlin, Germany: Springer, 2012, pp. 400–410.

[81] K. Hribernik, T. Wuest, and K.-D. Thoben, "Towards product avatars representing middle-of-life information for improving design, development and manufacturing processes," in *Digital Product and Process Development Systems* (IFIP Advances in Information and Communication Technology), vol. 411, G. L. Kovács and D. Kochan, Eds. Berlin, Germany: Springer, 2013, pp. 85–96.

[82] F. Vollertsen, S. Friedrich, B. Kuhfuß, P. Maaß, C. Thomy, and H.-W. Zoch, *Cold Micro Metal Forming*. Cham, Switzerland: Springer, 2020, doi: 10.1007/978-3-030-11280-6.

[83] D. Rippel, M. Lütjen, and M. Freitag, "Local characterisation of variances for the planning and configuration of process chains in micro manufacturing," *J. Manuf. Syst.*, vol. 43, pp. 79–87, Apr. 2017.

[84] D. Rippel, M. Lütjen, and M. Freitag, "Enhancing expert knowledge based cause-effect networks using continuous production data," *Proc. Manuf.*, vol. 24, pp. 128–134, Jan. 2018.

[85] D. Rippel, C. Schattmann, M. Jahn, M. Lütjen, and A. Schmidt, "Application of cause-effect-networks for the process planning in laser rod end melting," in *MATEC Web Conferences*, vol. 190, F. Vollertsen, T. Dean, Y. Qin, and S. Yuan, Eds. Les Ulis, France: EDP Sciences, 2018, p. 9.

[86] P. Gralla, I. Piotrowska, D. Rippel, M. Lütjen, and P. Maaß, "Eine methode zur invertierung von vorhersagemodellen in der mikrofertigung," in *Kolloquium Mikroproduktion: Fachbeiträge. Kolloquium Mikroproduktion Bremen*, Bremen, U.K.: BIAS Verlag, Nov. 2017, ch. 8, pp. 251–258. [Online]. Available: http://nbn-resolving.de/urn:nbn:de:gbv:46-00106272-12

[87] R. Saracco. (2018). *What Would Education be Like in 2050? Digital Twins*. [Online]. Available: https://cmte.ieee.org/futuredirections/2018/02/21/what-would-education-be-like-in-2050-digital-twins/

[88] J. Baalsrud Hauge, M. Zafarzadeh, Y. Jeong, Y. Li, W. A. Khilji, and M. Wiktorsson, "Digital and physical testbed for production logistics operations," in *Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems* (IFIP Advances in Information and Communication Technology), vol. 591, B. Lalic, V. Majstorovic, U. Marjanovic, G. von Cieminski, and D. Romero, Eds. Cham, Switzerland: Springer, 2020, pp. 625–633.

[89] J. B. Hauge, M. Zafarzadeh, Y. Jeong, Y. Li, W. A. Khilji, and M. Wiktorsson, "Employing digital twins within production logistics," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2020, pp. 1–8.

[90] M. Oliveri, "Design and development of an IoT-oriented multiplayer serious game for industry 4.0 innovation," M.S. thesis, Dept. Elect., Electron. Telecommun. Eng. Nav. Archit., Univ. Genoa, Genoa, Italy, 2019.

[91] M. Oliveri, J. B. Hauge, F. Bellotti, R. Berta, and A. D. Gloria, "Designing an IoT-focused, multiplayer serious game for industry 4.0 innovation," in *Proc. IEEE Int. Conf. Eng., Technol. Innov. (ICE/ITMC)*, Jun. 2019, pp. 1–9.

[92] I. R. S. Agostino, E. Broda, E. M. Frazzon, and M. Freitag, "Using a digital twin for production planning and control in industry 4.0," in *Scheduling in Industry 4.0 and Cloud Manufacturing* (International Series in Operations Research & Management Science), vol. 289, B. Sokolov, D. Ivanov, and A. Dolgui, Eds. Cham, Switzerland: Springer, 2020, pp. 39–60.

[93] E. M. Frazzon, M. Kück, and M. Freitag, "Data-driven production control for complex and dynamic manufacturing systems," *CIRP Ann.*, vol. 67, no. 1, pp. 515–518, 2018.

[94] J. Wilhelm, T. Beinke, and M. Freitag, "Improving human-machine interaction with a digital twin," in *Dynamics in Logistics* (Lecture Notes in Logistics), M. Freitag, H.-D. Haasis, H. Kotzab, and J. Pannek, Eds. Cham, Switzerland: Springer, 2020, pp. 527–540.

[95] J. Wilhelm, C. Petzoldt, T. Beinke, and M. Freitag, "Review of digital twin-based interaction in smart manufacturing: Enabling cyber-physical systems for human-machine interaction," *Int. J. Comput. Integr. Manuf.*, vol. 34, no. 10, pp. 1031–1048, 2021.

[96] T. B. Sheridan and R. Parasuraman, "Human-automation interaction," *Rev. Hum. Factors Ergonom.*, vol. 1, no. 1, pp. 89–129, 2005.

[97] M. Freitag, N. Hoppe, C. Petzoldt, J. Wilhelm, L. Rolfs, R. Mortensen Ernits, and T. Beinke, "Digitaler zwilling zur mensch-technik-interaktion," in *Mensch-Technik-Interaktion der digitalisierten Arbeitswelt*. Berlin, Germany: GITO Verlag, Sep. 2020, pp. 165–182.

[98] ISO/Technical Committee 184/SC 4 Industrial Data, *Automation Systems and Integration—Digital Twin Framework for Manufacturing—Part 3: Digital Representation of Manufacturing Elements*, ISO Standard 23247-3:2021, 2021. Accessed: Dec. 20, 2021. [Online]. Available: https://www.iso.org/standard/78744.html

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