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Digital Twin Fidelity Requirements Model For Manufacturing

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Abstract

The Digital Twin (DT), including its sub-categories Digital Model (DM) and Digital Shadow (DS), is a promising concept in the context of Smart Manufacturing and Industry 4.0. With ongoing maturation of its fundamental technologies like Simulation, Internet of Things (IoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI) and Big Data, DT has experienced a substantial increase in scholarly publications and industrial applications. According to academia, DT is considered as an ultra-realistic, high-fidelity virtual model of a physical entity, mirroring all of its properties most accurately. Furthermore, the DT is capable of altering this physical entity based on virtual modifications. Fidelity thereby refers to the number of parameters, their accuracy and level of abstraction. In practice, it is questionable whether the highest fidelity is required to achieve desired benefits. A literary analysis of 77 recent DT application articles reveals that there is currently no structured method supporting scholars and practitioners by elaborating appropriate fidelity levels. Hence, this article proposes the Digital Twin Fidelity Requirements Model (DT-FRM) as a possible solution. It has been developed by using concepts from Design Science Research methodology. Based on an initial problem definition, DT-FRM guides through problem breakdown, identifying problem centric dependent target variables (1), deriving (2) and prioritizing underlying independent variables (3), and defining the required fidelity level for each variable (4). This way, DT-FRM enables its users to efficiently solve their initial problem while minimizing DT implementation and recurring costs. It is shown that assessing the appropriate level of DT fidelity is crucial to realize benefits and reduce implementation complexity in manufacturing.

Keywords

Digital Twin; Virtual Twin; Fidelity; Requirements; Benefits; Value; Digital Shadow; Industry 4.0

1. Introduction

Industrial manufacturing is becoming increasingly individual and complex [1]. Organizations must become more agile to satisfy changing customer needs faster and better. In today's globalized economy, they are under constant pressure to improve their performance [2]. One way to meet the increasing competitiveness is digitalization [3]. In the context of Smart Factory and Industry 4.0, there is a wide range of technologies that can be used for this purpose [4], [5]. One of the promising concepts is the Digital Twin (DT). In recent years, the number of scientific publications on the subject has increased exponentially [6]–[8]. At the same time, many companies, especially large corporations, are launching initiatives to explore the potential of DTs [9]–[12]. Despite this attention, the definition of DT remains controversial. The large number of publications has resulted in a multitude of definitions, each with its own specifics [13]–[16]. Their understanding differs significantly, depending on the industry, use case, and context. The most accepted definitions are from [17][1], who first established the Digital Twin concept, and [18][2]. The term DT is frequently used to profit from the hype [19] surrounding the concept. Claimed implementations are often just Digital Models (DM) or Digital Shadows (DS), which, based on [15], merely represent subcategories of DTs. Additionally, the value added by DTs is commonly unclear and intangible [5], [7], [13], [20]. This prevents the unbiased assessment of investments into DT technology and leads to a lack of acceptance within organizations. If organizations are still willing to invest, they often introduce such technology as an end in itself, with no strategy beyond demonstration [21].

One of the reasons why DT economic benefits are difficult to grasp is that the necessary fidelity seems not to be sufficiently considered. According to [7], fidelity indicates "the number of parameters, their accuracy, and level of abstraction". In line with most academic definitions, it is assumed that DTs have to replicate the physical world as realistically as possible, i.e., in high-fidelity [18], [22]–[29]. Thereby, the DT benefits from the rapid technological progress of closely related technologies, such as Simulation, Internet of Things (IoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI) and Big Data [4], [6], [30]. In practice, however, organizations focus on achieving improvements with minimum effort. Therefore, it is questionable whether it is mandatory to create all-encompassing DTs [7], [31]. In Simulation, which is a core technique of DT [8], [32], focusing on relevant system elements instead of mapping all of its properties, behaviors and states is preferred [33], [34]. In fact, lower fidelity equals less cost compared to high-fidelity [31], [35]. Currently, there is no approach to bridge this gap between academic definitions and practical requirements with regard to DT fidelity. For this reason, the Digital Twin Fidelity Requirements Model (DT-FRM) is presented in this paper. The following sections are structured as follows: Section 2 includes a literary analysis of articles describing DT applications, Section 3 first puts the research question into a broader context and then explains the DT-FRM in detail, and Section 4 summarizes the research findings and discusses implications for scholars and practitioners.

2. Literary Analysis

A literary analysis was conducted to examine current DT literature regarding its implementation procedure, investigating whether the identified articles describe structured implementation procedures. The analysis focused on how fidelity is considered in scholarly described DT applications.

2.1 Methodology

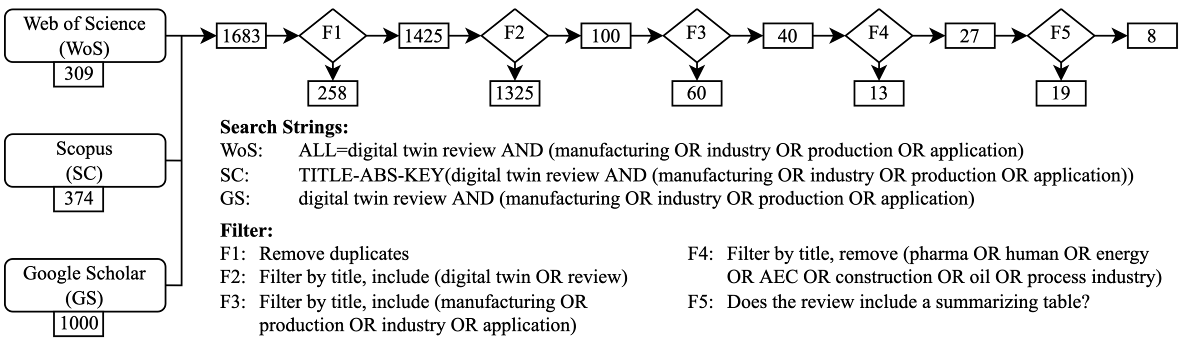

Figure 1: Literature selection process

[1] "The Digital Twin concept model […] contains three main parts: a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together."

[2] "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. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc."

Since there are an extensive number of publications in the field of DT, a two-step approach for finding relevant articles of actual DT applications was used. First, recent DT review articles were identified as such reviews usually include useful categorizations of DT applications. Second, relevant DT application articles were selected from these reviews. The search strings shown in Figure 1 were used to collect all matching articles from Web of Science, Scopus and Google Scholar. Figure 1 also visualizes the general literature selection process and all applied filters. From Google Scholar, only the first 1000 entries were included. The results of all three search engines were merged into one repository and duplicates were removed (F1). In the following steps, results were further refined by filtering for relevant titles (F2-F4). 27 review articles remained for further analysis. This was done by scanning the articles in question for tables providing structured information of considered DT applications. Finally, eight review articles including such tables were identified. Table 1 illustrates which application articles were chosen from each review for detailed investigation. The column "Selection criteria" refers to the review article's categorization by which application articles were selected. From these reviews, 77 application articles were extracted. They were analyzed in detail to what extent they have considered DT fidelity requirements.

Table 1: Review articles, corresponding application articles and selection criteria

Review articles	Number of articles reviewed	Selected application articles	Selection criteria
[16]	26	[36]–[40]	Manufacturing context
[41]	10	[42]–[46]	Manufacturing context
[15]	43	[32], [35], [42], [47]–[56]	Level of integration DT or DS & type case-study
[57]	32	[47], [58]–[69]	Manufacturing phase
[6]	39	[58]–[60], [70]–[83]	Manufacturing phase
[84]	52	[61], [74], [85]–[98]	Control of real system from DT
[99]	40	[12], [14], [46], [60], [100]–[107]	Application examples (A)
[108]	12	[109]–[112]	Level of integration DT or DS/DT
Sum (duplicates removed)		Σ 85 (77)	

2.2 Results

In summary, it can be confirmed that the understanding of DT among the authors is heterogeneous. Regardless of this, it was first analyzed whether the DT application articles describe a procedure for creating or implementing their DT. Figure 2 shows that 60 articles (78%) do not present any procedure at all. They only describe their individual final solution or architecture, e.g. [58], [60], [68], [74], [80], [85], [90], [98], [110], but not how it has been achieved.

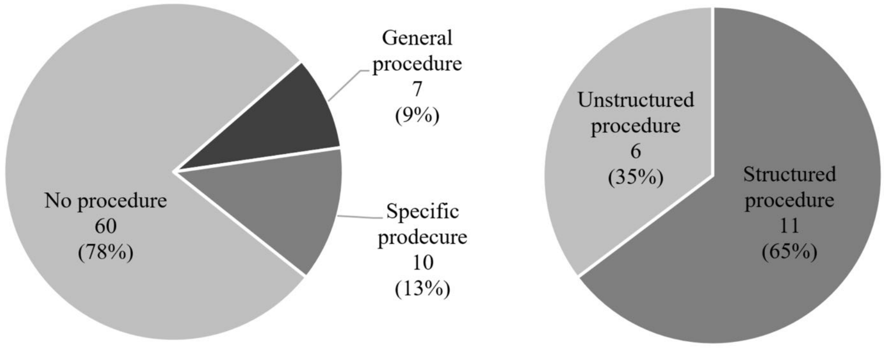

Figure 2: Share of articles describing their DT implementation procedure

The articles with a description of the procedure can be divided into specific [45], [62], [64], [72], [87], [100]–[102], [106], [111] and general procedures [37], [46], [66], [67], [69], [78], [88]. A specific procedure is explicitly tailored to a particular use case, while a general procedure is also transferable to other similar applications. In about two thirds (65%) of the applications described, a structured procedure is recognizable that includes certain steps and sequences. Only one single article from the sample considers fidelity within its procedure. Although the term fidelity is not used directly, an iterative model evolution procedure exists in [67], which adjusts the fidelity step by step to the necessary degree. However, the ultimate goal in [67] is also a high-fidelity model. Due to the low consideration of fidelity within the described procedures, it was investigated whether fidelity is considered in general within the application articles. Figure 3 illustrates the results.

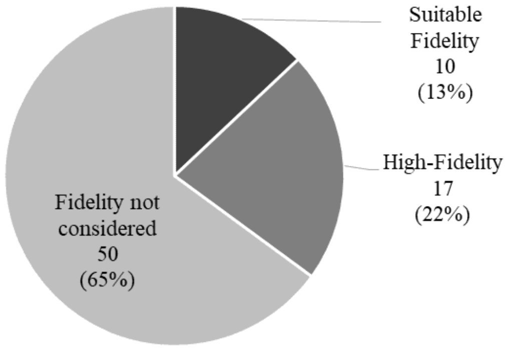

Figure 3: Share of articles considering fidelity

Almost two thirds of the articles do not address fidelity at all. 17 articles (22%) [12], [40], [42], [44], [46], [54], [60], [65], [67], [69], [74], [83], [90], [102]–[105] share the view that DT should represent the physical world in high-fidelity, with most articles referring to the NASA DT definition [18]. The authors usually do not question this definition with regard to fidelity. Only a minority of 10 articles (13%) [14], [32], [35], [37], [55], [56], [62], [97], [101], [110] mention that a suitable fidelity should be chosen. A dominant opinion comes from [32], who clearly mention that an application-specific fidelity should be selected for the DT to achieve a desired goal. [55] cite [32] and adopt their view. Moreover, [14], [37], [56] mention that a specific level of detail should be considered.

Nevertheless, the benefits of applying DTs remain unclear in most articles. In [72] the increase in resource efficiency is evaluated and quantified. However, the authors neglect the cost of implementing the DT and only focus on the positive impact. To achieve economic benefits with the application of DTs, a structured approach must be developed that also takes the necessary DT fidelity level into account since fidelity significantly drives costs.

3. Digital Twin Fidelity

This section first puts the DT-FRM into a broader perspective by highlighting its relevance inside a cost-benefit analysis. Then the methodology for the development of the DT-FRM is explained. Finally, the DT-FRM is presented in detail.

3.1 Cost-Benefit Analysis for Digital Twin Implementation

The decision whether to implement a DT is a complex task. A cost-benefit analysis [21], [113], [114] must be conducted prior to the DT introduction to support an investment decision for or against the use of DT. Figure 4 describes such a procedure for a problem centric cost-benefit analysis based on the DT-FRM. All individual steps and their connections are briefly described below. This section shall help to increase the understanding of how the DT-FRM improves DT implementation decisions.

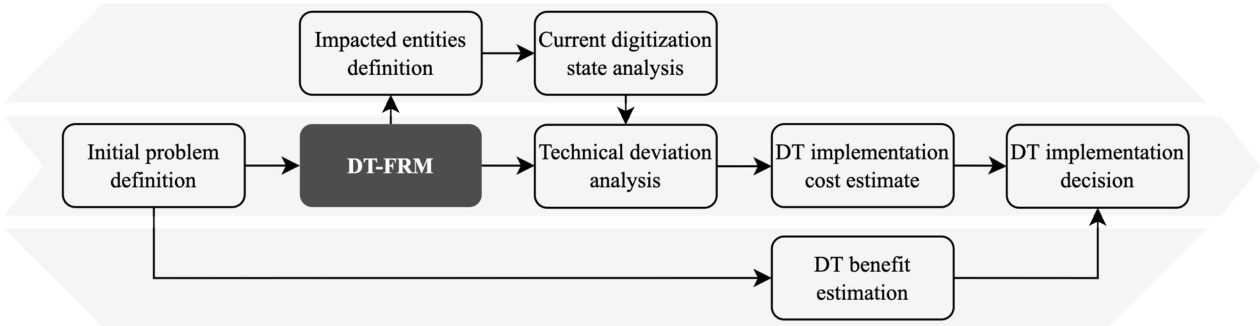

Figure 4: Procedure for Digital Twin cost-benefit analysis

3.1.1 Initial problem definition

First, an existing problem in production must be identified. Once a Digital Twin is perceived to be a viable solution to this problem acknowledged by all stakeholders, an initial problem statement has to be formulated. The problem statement is the foundation of the entire project and facilitates common understanding within the project team. It should therefore precisely describe what constitutes a problem in the current state of a production.

3.1.2 Digital Twin Fidelity Requirements Model (DT-FRM)

This article's main contribution is a structured approach for the elaboration of the required fidelity level for a specific DT implementation serving as a solution to the initially described problem. The DT-FRM is presented in detail in section 3.2.

3.1.3 Impacted entities definition

Following the joint agreement on the problem to be solved by DT implementation, an investigation is needed to identify impacted entities. In manufacturing environments, these might be products, processes and resources. Every relevant variable identified in the DT-FRM has to correspond to at least one entity. While reviewing those entities, the focus always needs to be on the initial problem.

3.1.4 Current digitization state analysis

After identifying all entities which are impacted by the initially defined problem, a technological analysis must be carried out. The result of such an analysis is a detailed overview of the current state of digitization, e.g., data, model or control loop availability. It includes an assessment of all relevant entities for a subsequent estimate of the technical changes required to introduce a DT.

3.1.5 Technical deviation analysis

For each identified entity, the individual deviation between the required fidelity level, which has been elaborated within the DT-FRM, and the current state of digitization has to be determined. Some variables might already be digitally mapped or even controlled autonomously in current production. For this reason, it is necessary to identify gaps while working towards the elaborated level of fidelity.

3.1.6 Digital Twin implementation cost estimate

After the necessary changes in production have been identified in the technical deviation analysis, they must now be evaluated in terms of additional cost. This is where the individual comparison between actual digitization state and required DT fidelity becomes important. The identified deltas give guidance for estimating recurring and non-recurring costs to reach the desired target state and achieve initial problem solution.

3.1.7 Digital Twin benefit estimation

Based on the initial problem defined, benefits have to be estimated. The calculation is carried out independently of a specific technical implementation and its costs, purely on the basis of potential savings achieved by a still undefined solution. The aim of this analysis is to make an initial statement about the savings that can be expected as a result of fully solving the central problem.

3.1.8 Digital Twin implementation decision

With necessary changes for DT implementation evaluated financially, a final decision on DT implementation must be taken. Therefore, estimated benefits of solving the initial problem are directly compared with estimated costs of achieving required fidelity levels. The present value of all cash flows must be calculated for determining the overall net present value (NPV).

3.2 Development of Digital Twin Fidelity Requirements Model (DT-FRM)

The DT-FRM has been developed by employing concepts taken from the Design Science Research (DSR) methodology [115]. DSR has become the leading approach in the development of information systems [116]. Since the technologies around DTs are based on such systems, applying DSR seems adequate. Design Science comprises two iterative activities: the design cycle and the empirical cycle, which are used for the design and investigation of artifacts in different contexts [116]. Artifacts are single solutions to a problem within a specific context. Using the DSR template from [116], the research question for design is formulated as "How to develop a method that considers appropriate Digital Twin fidelity requirements so that users can increase the likelihood of achieving economic benefits by implementing Digital Twins in manufacturing to solve existing problems?" In this case, the DT-FRM is the final artifact resulting from several iterations of the design cycle. For the development of the DT-FRM, only the design cycle was needed. It includes three steps: problem investigation, treatment design and treatment validation [116]. Here, treatment refers to the desired interaction of artifact and problem context. The DT-FRM is designed as a universal artifact which can be applied to different contexts, i.e. DT application scenarios. Knowledge questions then have to be answered around this specific context. Whenever it is intended to implement DTs in manufacturing, DT-FRM can be used to assist with problem centric fidelity assessment. In the DSR design cycle, validation occurs before implementation and is done by predicting the artifacts' behavior within a given context [116].

3.3 Digital Twin Fidelity Requirements Model (DT-FRM)

This section presents a structured method for the elaboration of fidelity requirements for DTs in production environments, called DT-FRM. Employing the DT-FRM is a crucial part of the cost assessment within the cost-benefit analysis as higher fidelity is associated with higher costs. Therefore, considering appropriate fidelity levels contributes to achieving economic benefits when applying DTs for problem solving. Based on these requirements, an implementation strategy can be derived that provides an efficient solution to the problem statement described initially.

3.3.1 Target variable identification (TV)

The DT-FRM focuses on the decomposition of the initial problem (Section 3.1.1) into its quantifiable components. Therefore, the first step of the DT-FRM is to define target variables (TVs) which are often called Key Performance Indicators (KPIs) in practice. TVs are usually a set of KPIs which are already regularly calculated for monitoring manufacturing performance. Independent of the number of TVs a problem is represented by, the desired direction and magnitude of change for each variable towards the problem solution must be defined. In an example, a defined problem might be characterized primarily by one single KPI. Then for this TV, it needs to be determined whether an increase or a decrease contributes to solving the initial problem and how much the value must change. In a problem graph (Figure 5), the TVs represent the first layer. They are called dependent variables, since their value is dependent on a variety of other, underlying variables.

3.3.2 Intermediate (IV) and elementary variable (EV) derivation

To ensure that the initial problem is comprehensively broken down into its relevant and, in particular, influenceable components, the derivation of the TVs must be followed by a detailed examination of their calculation basis. This has to be done for each KPI defined as a TV in the previous step. If, for example, the initial problem is from the field of machining, a possible TV could be the tool life T. Typically, the tool life results from the theoretical tool life c_v, the cutting speed v_c and the slope of the Taylor line κ. The TV tool life is thus dependent on these three underlying variables, which are referred to as intermediate variables (IVs) in the DT-FRM. IVs neither serve as a reference to the initial problem, nor can they directly be influenced. For complex problems in real manufacturing environments, it is common that the derivation of IVs yields multiple layers of interlaced variables. The goal of the decomposition of TVs into their calculation basis (IV) is the elaboration of all directly influenceable, fundamental variables. These variables are called elementary variables (EV) in the DT-FRM context. They are not based on any underlying variables and are, therefore, independent. In the simple example of tool life as a TV, an EV is the rotational speed of a machine, which in turn has an effect on the cutting speed (IV) of the machining operation. The EV rotational speed in this example can be considered as independent and therefore directly influenced by applying DT technology. Finally, an overall picture of the initial problem and its influenceable variables is obtained: all identified EVs ultimately result in the TVs defined at the beginning by calculating all IVs. Figure 5 illustrates the dependencies of TVs, IVs and EVs for a schematic problem. The use of such problem graphs in complex manufacturing scenarios is especially helpful to identify overlapping influences of individual variables and to provide a uniform understanding among all stakeholders.

3.3.3 Elementary variable (EV) prioritization

The goal of this step is the prioritization of EVs. All EVs must be evaluated according to their influenceability and their target contribution. For determining the influenceability, an optimization corridor around the current mean value must be defined for each EV. The optimization corridor determines to what extent a change in the corresponding EV is estimated to be realistically achievable, based on financial, technical or organizational constraints. Financial constraints refer to the costs of influencing the EV, technical constraints refer to technological feasibility and organizational constraints are based on the structure of the organization aiming to apply DT solutions. Since estimating the boundaries of the optimization corridor and defining the mathematical relationships between the variables are highly case-specific, a certain experience in the problem context is necessary. If this knowledge is not available within

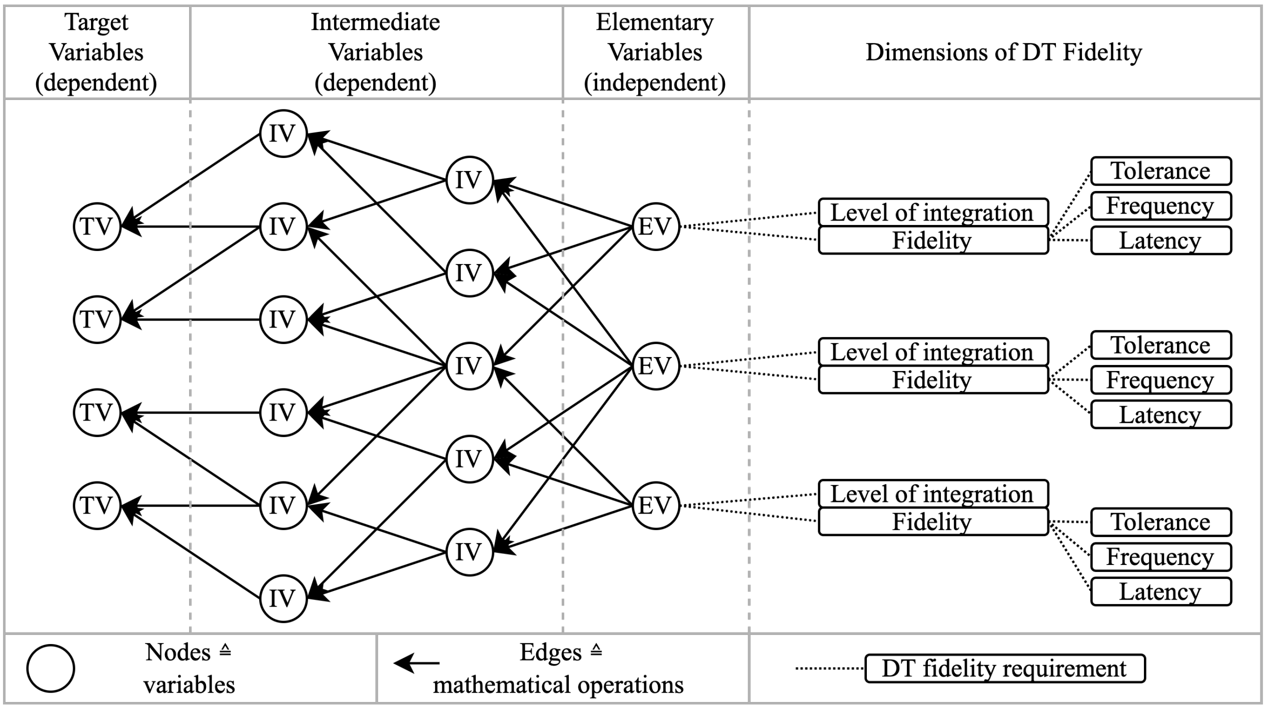

Figure 5: Example problem graph with variable breakdown

the organization, it has to be questioned whether applying DT solutions is effective. Before implementing DTs, it is necessary to clearly understand the initial problem and the implementation objectives (Section 3.1.1). The second step of the prioritization involves conducting a sensitivity analysis to identify target contribution. By conducting a sensitivity analysis, the potential impact of each EV change towards the problem solution is determined. Minimum and maximum values of the optimization corridor serve as input for sensitivity analysis. Ultimately, the EVs which provide the highest influenceability and highest target contribution are prioritized within the next steps to minimize required efforts and maximize benefits. EVs with low influenceability or low target contribution can be neglected in a first step. Figure 6 illustrates a matrix for EV prioritization with different sectors and respective priorities.

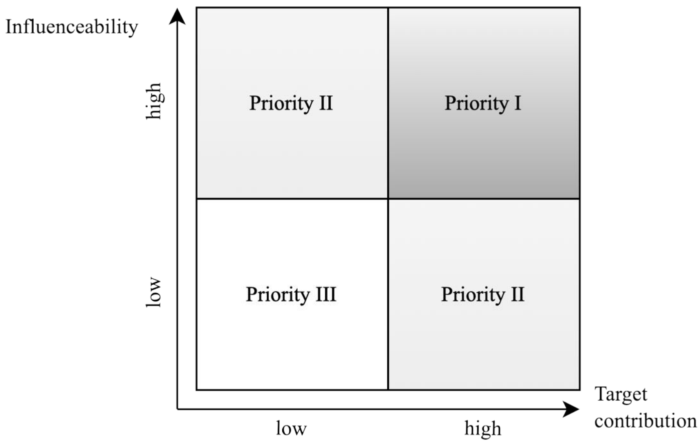

Figure 6: Elementary variables priority matrix

3.3.4 Elementary variable (EV) fidelity elaboration

Once the initial problem is broken down into its underlying EVs, the actual DT concept has to be developed. DT is commonly considered as an ultra-realistic, high-fidelity virtual model of a physical entity, mirroring all of its properties most accurately [13].

Supporting the understanding of what characterizes a comprehensive DT, we concurrently question whether all EVs actually have to receive such treatment in reality. The DT fidelity required for a variable to support target contribution is highly context dependent. Therefore, the DT-FRM proposes a different approach to put DT technology into beneficial use in industrial applications. Starting with priority I EVs, the individual variables are assessed for their required fidelity to support TV adjustment towards problem solution. Generally sharing the understanding of [7] in terms of fidelity, the DT-FRM introduces two overall dimensions which are used to determine DT fidelity requirements: level of integration (1) and fidelity (2). Since the meaning of concepts around fidelity like abstraction, accuracy, granularity, precision, etc., is similar but not identical [117], this article additionally defines three sub-dimensions of fidelity.

The first overall dimension is the level of integration. [15] defines the three different DT levels of integration: modeling, shadowing and twinning. Modeling refers to manual data exchange from physical to virtual (P2V) and virtual to physical (V2P). Shadowing describes P2V as fully automatic with V2P still being manual. Twinning is then understood as automatic P2V with the feedback loop V2P being automatic as well. For every EV incorporated into a DT application, the level of integration has to be defined. If the variable needs to be monitored autonomously and digital control is required to alter its value in terms of target contribution, the level of integration to implement is twinning. If monitoring is required but no automatic control is needed, the level of integration is shadowing. If none is the case, modeling is sufficient for the particular variable. The second overall dimension is fidelity, which consists of three sub-dimensions: tolerance (1), frequency (2) and latency (3). For each EV, the technical tolerance for measuring and, in the case of twinning, for control needs to be determined. The tolerance defines how precisely a value needs to be monitored or altered to achieve target contribution. Furthermore, the frequency needed for data exchange between the DTs physical and virtual space needs to be considered. Frequency thereby is regarded as how often data is transferred during a given time interval. The third sub-dimension is latency. Latency describes the amount of time data needs to reach its destination, which is also known as delay. Instead of using scarce financial resources to reach out for maximum fidelity, it must be carefully evaluated which minimum level is required to secure the respective variables' target contribution. Otherwise, over-engineering fidelity leads to excess costs, which must be avoided. Thus, not all EVs require high-fidelity twinning. After the level of integration and the DT fidelity are elaborated for all relevant variables, the EVs can be numbered and plotted into a DT fidelity requirements matrix. Figure 7 gives a basic example of such a matrix. By utilizing such matrices, the overall complexity of proposed DT solutions to different problems can be visualized. The higher the level of integration and fidelity, the higher the estimated costs for implementing the DT.

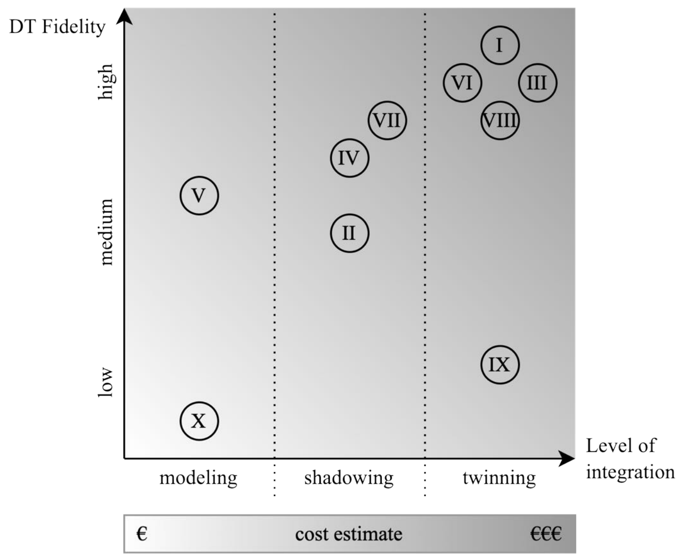

Figure 7: Digital Twin fidelity requirements matrix with example elementary variables

4. Results and Discussion

In today's complex manufacturing environments, organizations face highly competitive pressure and are therefore dependent on promising digitalization concepts like Digital Twins. However, the understanding of what a DT is and how it can effectively be applied to solve existing problems differs among organizations. According to most academic definitions, the fidelity of the virtual models replicating the physical world must be as high as possible, whereas in practice this is not always feasible. Literary analysis of 77 scientific papers describing DT applications in manufacturing has revealed a lack of conceptual basis and guidelines for structured implementation of DTs. This hinders the applicability of DTs in different domains. Even if structured procedures have been described, they tend to be specific and not transferable. Additionally, DT fidelity has not been considered in most application articles. The majority have been found to support academia's common understanding of targeting high-fidelity. Contrary, this article presented the Digital Twin Fidelity Requirements Model (DT-FRM) as part of a cost-benefit analysis for DT implementation decisions. The DT-FRM aims at securing economic benefits when applying DT technology to exploit existing improvement potentials in production environments. Despite questioning the focus of most academics aiming for high-fidelity models, we do not generally reject the available definitions of DT. Instead, we emphasize that elaborating suitable fidelity levels is necessary to maximize benefits by applying DTs to existing problems. Since concrete benefits of using DTs are currently still unclear, applying the DT-FRM to defined problems serves as a good starting point to increase understanding and decrease implementation complexity of DTs and its related technologies. The method helps practitioners to estimate benefits of DT application while assisting with DT concept development. Nevertheless, we suppose that the benefits of applying DTs in the future go beyond merely solving known problems, e.g., by unveiling hidden improvement potentials and enabling new business models. Iteratively increasing fidelity during the lifetime of the DT might be a solution to exploit its full potential while still considering appropriate fidelity levels. Future research should address the application of the DT-FRM to real manufacturing scenarios to confirm its necessity and validity. Additionally, it should be investigated which other factors besides fidelity influence costs for DT implementation.

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