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Implementing Digital Twins in SMEs: A Step-by-Step Methodology for Digital Production Twins

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Abstract

The Digital Twin has become a hot topic in many industries, which means that more and more companies are starting to familiarise themselves with the technology. This paper presents a step-by-step approach for introducing a Digital Twin in a small or medium-sized enterprise (SME). The approach is specifically related to the creation of a Digital Production Twin and combines a comprehensive scientific methodology with an easily applicable approach for SMEs. This work provides a general overview of the methodology and explains its general structure.

Keywords: Digital Twin, SME, Production Systems

1. Introduction

Digital transformation is becoming increasingly relevant, whether due to current developments in the field of artificial intelligence, changing business models or simply the increasing complexity of processes [1, 2]. In view of increasing competitive pressure, shortening product life cycles or the fear of sudden changes in global supply chains due to global crises, the topic of flexibility and adaptability is becoming increasingly important [3]. In the eyes of many companies, however, this flexibility should not only ensure the aforementioned profitability and competitiveness of the company, but also make the company more resilient through increased adaptability [4]. For many companies, the question therefore arises as to how such an increased adaptability of the company can be achieved. One way of increasing adaptability and also opening up the company to new developments is to digitalise processes, products or even services [1]. In manufacturing industry in particular, there is usually still enormous potential to digitalise. According to PwC (2022), 64% of companies are still at an early stage of digital transformation [5]. However, in the context of digitalising manufacturing companies, the goal of creating a ‘digital factory’ is increasingly important to meet the aforementioned challenges. This then also includes the use of digital twins regardless of company size. While the introduction of such Digital Twins is easy for large companies due to the help of extensive development departments. For smaller companies, the entry barriers to such cyber-physical systems are usually too great an obstacle [6]. In view of these facts, the question arises as to what creates these barriers. A key reason is the lack of expertise and skilled labour, (minimal resources available) which is why small companies do not use Digital Twin technology [7, 6]. For this reason, this paper is concerned with counteracting this. The aim is to make it easier for SMEs to utilise the technology by using a scientifically correct yet understandable methodology for SMEs. To achieve this, the given method is providing the knowledge to use partial services during development which can be used independently and thus bring the company a direct measurable economic benefit. The potential uses of such partial solutions of Digital Twins is often unknown, which is why the economic viability of such systems often cannot be correctly assessed.

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2. State of the Art

In order to clarify the characteristics of the methodology, this chapter describes the theoretical basis for it. This includes an explanation of the understanding of the terms Digital Twin, Digital Shadow and Digital Model used, as many different definitions of those terms exist. It also outlines how these technologies relate to cyber-physical systems, and what their contribution to the digitisation of a company respectively to achieve the previously mentioned objectives, is. Finally, it is shown how these models can be categorised more precisely with the help of maturity models in order to be able to precisely determine the benefits of the methodology

2.1. Contribution of Cyber-physical Systems in a company

Digital Twins (DT), Digital Shadows (DS) and Digital Models (DM) are terms that are often used in the context of cyber-physical systems [8]. The term cyber-physical systems refers to systems that involve a connection between real physical systems or objects with virtual information-processing systems or objects [9, 10]. Accordingly, such systems are used in a wide range of applications and can differ greatly in terms of the type of connection provided. In principle, typical objectives that are to be achieved with the use of cyber-physical systems are increasing the efficiency of systems, reducing costs, increasing transparency or simply speeding up information flows, which support the achievement of the aforementioned general objectives (e.g. profitability, adaptability) [11].

Correspondingly applications for cyber-physical systems include real-time monitoring of systems, predictive maintenance or even virtual commissioning [11, 12]. In all of these use cases, physical systems are connected to virtual objects or systems either uni-directionally or bi-directionally. According to our understanding of the definition of DT, DS and DM, it therefore becomes clear, why these technologies play an important role in the application of cyber-physical systems. In a production-related review [13], the authors explained their understanding of those technologies, resulting in the following definition:

"A Digital Twin is a virtual information construct of a physical product [14], a service system [15], a system behaviour [15], a process [16] or other existing or planned elements, which contain a complete description of the respective object. The Digital Twin is characterized by the possibility of a bi-directional data exchange between the virtual and the physical world [14]. To realize an automated data transfer from the physical world to the virtual world, the Digital Twin uses a so-called Digital Shadow, which is a main component of the Digital Twin alongside the Digital Model [17, 16]. The Digital Model in turn contains the master data, geometric models or other core data and represents the basis of a Digital Twin [18]. Only through the combination of Digital Model, Digital Shadow and an extension of the Digital Shadow with an information transfer to the physical world, a complete Digital Twin can be created" [19].

However it needs to be emphasized that this definition is one of many existing definitions and doesn't claim to be suitable for every use-case [19]. Nevertheless, in the context of the methodology, presented in the following chapters, it is necessary to provide a clear understanding what is meant by those terms respectively what functionalities can later be provided by those models. Supplementary to this given understanding it therefore becomes clear, that the given definition of those modells can only be a rough description, of what is understood by those terms. For this reason, maturity Models are being introduced below.

2.2. Maturity Levels of Digital Twins

The categorisation of digital tools into Digital Models, Digital Shadows and Digital Twins represents a first step in a classification. However, so-called maturity models exist so that the exact capabilities of a digital twin, for example, can be determined at content level.

In addition to the simple differentiation according to the type of communication, various factors are used depending on the maturity model selected. Examples of such maturity models are the ETRI Maturity Model [20], the Digital Twin 8-dimension model [21] or the Detecon Maturity Model [22]. Each of these models is based on different aspects and therefore results in a different number of different levels. For this reason, it can also be stated that there is not one set way of classifying the models. As a result, the authors have oriented themselves to the existing models and combined them, which means that in addition to the factors of the 8-dimensions model [21], the degree of standardization from the Detecon Maturity Model [22] is also used by the authors to determine the level of a model to be created by the methodology [13]. This results in nine factors that are used to precisely categorise the methodology. However, the factor which takes the kind of connectivity in account is already covered by the division between DM DS and DT. Correspondingly the resulting aspects taken in account to classify each DM, DS and DT are the following:

- **Integration breadth –** categorizes the scope of the model (product, factory etc.)
- **Update frequency –** categorizes how often a model needs to be updated (max. real time communication)
- **CPS (Cyber Physical System) Intelligence –** categorizes the degree of automatization (Human Triggered, Automated, Autonomous etc.)
- **Simulation capabilities –** categorizes the level of flexibility of the model (static, dynamic, ad-Hoc etc.)
- **Digital model richness –** categorizes what a model covers (geometry, control behaviour etc.)
- **Human interaction -** categorizes the interfaces of the Model (Smart Devices, AR, VR etc.)
- **Product life cycle -** categorizes which parts of the product life cycle are being covered
- **Degree of standardisation -** categorizes the amount of standardisation in a model (hands-on solution, basic model, twin of twins etc.)

Since the detailed description of each level would exceed the scope of this paper, the original descriptions of both used maturity models are recommended for further information [21, 22]. However, in the following it will be explained, which level of maturity is targeted by the methodology.

3. Methodology

The methodology described in this chapter (Fig. 1) is used to create a Digital Production Twin. This section describes in particular what the capabilities of the Digital Twin created in this procedure are. Moreover, the structure of the methodology and, due to the limited scope, the first layer of the methodology is explained. The chapter furthermore shows, how the creation of such models can be integrated in existing processed. Finally, the first results of a partial validation of the method are displayed.

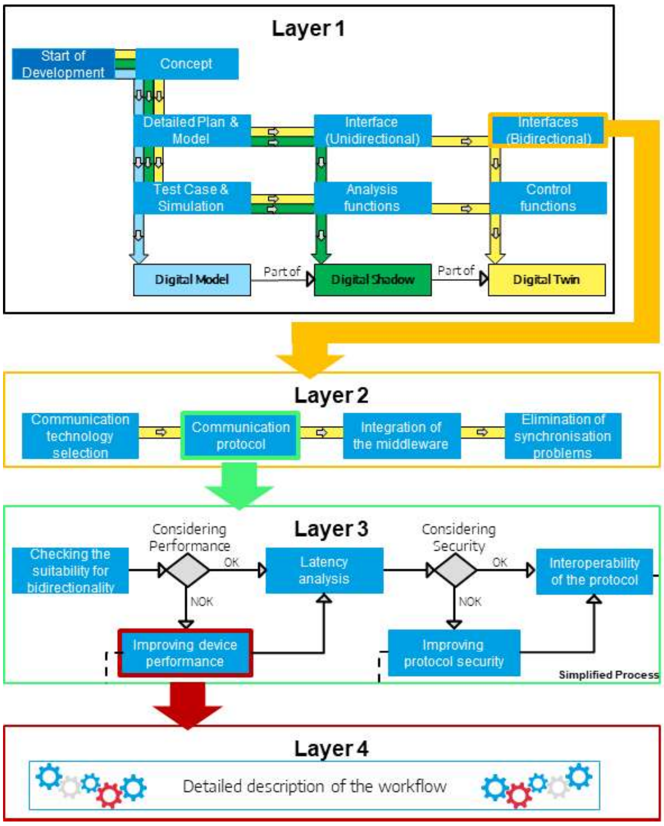

Fig. 1. Structure of the methodology

3.1. Targeted capabilities of a Digital Twin created using the methodology

The methodology has the primary goal of supporting SMEs in the use of digital tools and explaining in understandable language how a DM, DS or DT can be created.

As already described in section 2, this also means that the companies exactly need to know what is being created with the present methodology. As the terms of the digital tools already mentioned do not provide a clear basis for this, a precise categorisation must be made in advance based on maturity factors. This part therefore describes the maturity levels (described in detail in publications od Stark and Weber [21, 22]) of a Digital Twin as a possible result of this method based on the already mentioned maturity factors:

- **Integration breadth – Level 0-2:** The user is able to create a DT of a Machine, a production system or a factory
- **Update frequency – Level 0-3:** The user is able to create a DT which can be updated up to real time
- **CPS (Cyber Physical System) Intelligence – Level 0-1:** The user is able to create a DT which can be automated by following rules or algorithms
- **Simulation capabilities – Level 0-3:** The user is able to create a DT which can interact Ad-Hoc and include current data in its calculations
- **Digital model richness – Level 0-2:** The user is able to create a DT which can control the behaviour of a physical counterpart
- **Human interaction – Level 0:** The user is able to create a DT which can communicate through current devices with a Human
- **Product life cycle – Level 0-2:** The user is able to create a DT which could cover all parts of the product life cycle
- **Degree of standardisation – Level 0-3:** The user is able to create a DT which is using standardized protocols to easily communicate with other twins or models

The maturity levels of the partial services (DS and DM) are derived from this, but will not be explained further in this paper.

3.2. Structure and Scope of the Methodology

The overall structure of the methodology for creating a Digital Production Twin is based on the fact that the Digital Twin is intended to provide support in the product life cycle [23]. However, the focus of this methodology is particularly on the part of the production life cycle that deals with the development of a production unit, as this is usually when the Digital Twin or other Digital Models are created for the first time. (Exception is the retrofit of an existing unit) In the development process, there are various tasks in which digital applications are used. Such processes are for example layout planning, mechatronic design, electrical and fluid design, program creation, virtual commissioning, assembly or commissioning [23-25].

The methodology therefore deals with how a digital twin can be set up to accompany the existing classic processes in production development, while at the same time ensuring that the existing processes can already benefit from the Digital Twin during the development phase. This point is to be guaranteed in particular by an iterative approach in which deployable subservices are created.

The structure of the methodology shown in Fig. 1 is designed to provide clarity for SMEs applying it. This is achieved by dividing the methodology into different layers. At the top level, there are only overarching terms to clarify the general approach, as well as the division into Digital Model, Digital Shadow, and Digital Twin. Each of these overarching terms is broken down into the main tasks it contains on a subordinate layer. This provides companies a more detailed overview of the specific tasks without going into detail. Each main task described in this layer is further broken down into a more granular procedure on the next layer, similar to the structure of a Business Process Model and Notation (BPMN) diagram [26] (simplified in Fig. 1). Finally, at the lowest level, each of these granular procedural steps is articulated in language appropriate for SMEs.

This division of the methodology is based on the fact that the different layers are relevant to different people within the company, as long as these positions are not handled by the same individual. The top layer is suitable for understanding the relationship between the Digital Twin, Digital Shadow, and Digital Model, allowing leaders to make decisions on further development at the management level. In the second layer, for example, the development management can assess which tasks are already covered within the company and which areas are necessary for building or further developing their own Digital Models, Shadows, and Twins. Finally, the two lowest layers offer the most precise instructions for the person responsible for implementation. While layer 3 presents the relevant tasks, providing the employee with a clear procedure, layer 4 can only be referred to if one of the steps mentioned is unfamiliar to the employee.

This division ensures that a scientifically comprehensive methodology can be built without losing clarity, especially for SMEs. Furthermore, it allows an adaptability of the methodology depending on the need of the user. This means that regardless of whether a user wants to build a DT, a DS or a DM, the path to be followed is clearly described for the user. Furthermore, the model is designed to describe a maturity of a Digital Twin which is able to covers a majority of the needed applications necessary in SMEs. In this context it is of course also possible for the user to skip certain steps, if a lower maturity level is targeted in their specific use case. To ensure this fact, the methodology will be extended by a clear mapping of the tasks in the lowest layer to the Maturity Model shown in chapter 2 (described in CIRP Design conference 2024 [13]) in the future.

3.3. Overview of the first layer of the methodology

The first layer of the method exists out of seven main steps. It furthermore displays which steps are necessary to complete a DM, a DS or a DT, as shown in Fig. 1. Each of these steps is aligned with current literature. Furthermore, the sequence of steps is also based on the literature and endeavors to combine common procedures from the planning of technical systems [27,28], factory planning [29] and computer integrated design [30]. To understand the origin of this setup, the main steps of this layer are being described below.

Concept: Concept planning is the first main step and is performed in various approaches in literature. Both in the development of mechatronic systems and in the planning of entire factories (which in the broadest sense must also be considered in the design of a digital production twin). Concept planning as part of the plant development process [27], factory planning [29] or computer-integrated design [30] is considered a concept-giving component at the beginning of development. To create such concepts, the use of first simple simulation models can be helpful and can already be the first step towards a Digital Twin. However, it must be emphasised that before a real concept planning can be started, general factors have to be defined. This previous definition of goals of a production unit for example or other important factors, is a known part in factory planning [29] or computer-integrated design [30]. Described as goal definition or as clarification of the task, this would, however, be considered as part of concept planning within the framework of this methodology in order to maintain the clarity of the overall methodology.

Detail Plan & Simulation: Just like concept planning, detailed planning is also described in a variety of methodologies as a process, following the concept plan [27,29]. Detailed planning is also referred to as detailed design [30] or system design [27], but these terms are to be understood synonymously. Since detailed planning is increasingly supported by simulations and these models are particularly necessary when setting up Digital Twins, detailed planning is directly linked to the creation of simulation models. The fact that modelling begins at an early stage of plant planning is made clear, for example, in the VDMA guidelines [25] or in Gausemeier's explanations [27]. Processes such as virtual commissioning, part of which takes place at the beginning of the development process, are therefore particularly dependent on the simultaneous creation of simulation models and detailed planning. At this point, it must be emphasised that the first models are of course already created in the concept phase. However, the models created during the detailed modeling step represent a much larger level of detail (they should of course be based on previously created models if possible).

Test Cases & Simulation: The simulation of test cases is described in many sources as an important part of virtual commissioning [27,25], which on the one hand cannot be carried out by a Digital Twin at this stage (the model is not yet able to communicate), but on the other hand this also is not always necessary. However, it should be noted that the test cases set up here can be expanded or adapted at a later stage once the corresponding analysis and control functions of the Digital Twin or Digital Shadow have been created.

Interfaces (unidirectional): As already stipulated in VDI 4499 Sheet 2 [31], consistent data management is relevant when planning production plants. The 'automatic, permanent, detailed and fast feedback of the actual data of the real factory into the virtual models' is described as an essential characteristic for the use of simulation methods [31]. The uni-directional communication described here corresponds to the understanding of a Digital Shadow, which is why this step is not absolutely necessary for every simulation model, but is required if at least the functions of a Digital Shadow are aimed for.

Analysis functions: The main segment of the analysis function results from the specifications of a Digital Shadow described in Chapter 2.1. The possibility of uni-directional data exchange provided by the Digital Shadow enables the direct evaluation and analysis of data. Especially during virtual commissioning analysing certain parts eather in real time (at the end of the commissioning process) or in advance plays an important role [27]. Furthermore the use of digital tools to analyse specific use cases, is in particular mentioned as one "use-case" for a Digital Factory [31]. As this determines how the Digital Shadow can generate a benefit for the company, the creation of the necessary functions, which are essentially based on the previously conducted test cases and simulations, forms an essential part of the overall methodology.

Interfaces (bidirectional): In order for a Digital Twin to be realised in accordance with the aforementioned understanding, it is necessary to ensure bi-directional communication, for which the creation of a bi-directional interface is essential. However, this form of interface is not necessary for upstream applications, which is why this step is only listed at a later stage in the methodology. Nevertheless, preparatory work for a problem-free establishment of this interface is listed in upstream phases.

Control functions: The control functions represent the functions that, in contrast to the functions of a Digital Shadow, require bi-directional communication. Such control functions can either be used to serve as direct control of a physical counterpart or, more likely, to optimise the control of a unit, without interrupting the physical unit [25]. This makes it particularly clear how a Digital Twin can be used and how the advantages of the Digital Twin can be utilised. Those Functions are in particular necessary to reach the required skills mentioned in chapter 3.1.

3.4. Partial validation of the methodology

As the methodology presented is not yet fully finalised in detail, complete validation is not yet possible. Nevertheless, the basic structure of the methodology and some task areas already exist in detail, which enables partial validation of the methodology and the general structure. The following therefore describes how the methodology was fundamentally validated using the existing descriptions for creating a unidirectional interface.

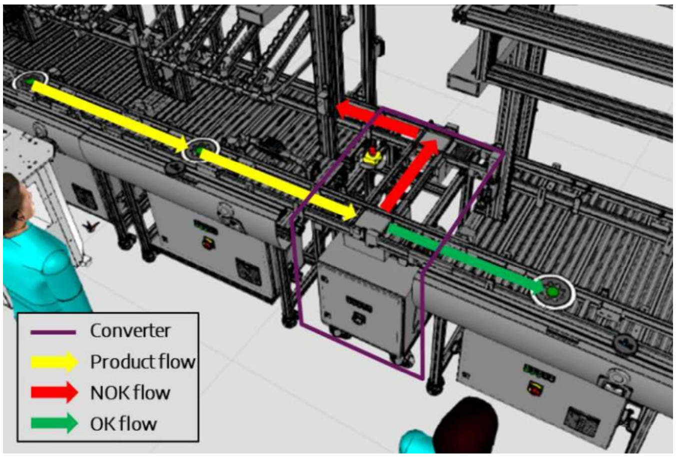

Fig. 2. Validation use-case: Digital Shadow of a converter unit

The validation process relates to the converter shown in Fig. 2, which is an integral part of a versatile assembly system. The converter executes different routines depending on the status of the previously assembled part. Parts classified as ‘OK’ pass through the transfer unit and reach the final processing station. In contrast, parts that are categorised as ‘not OK’ are sent back for reworking. In the validation case, the steps of the methodology were followed, which showed that by following the methodology, a Digital Shadow could be created without the person carrying out the process being familiar with the topic beforehand. As this validation case relates to an existing system and preparatory work has already been carried out, the steps of concept planning, detailed planning and the creation of simple test cases (in this case the mapping of the process flow) are already in place and represent the initial situation for the validation. Accordingly, the phase of uni-directional interface creation could be validated in relative isolation, although it should be emphasised that the methodology provides the possibility of intervening in upstream steps at any point in time if new findings arise within a step.

Following the methodology, the main steps shown in Fig. 3 were carried out to create the unidirectional interface. These steps (orientated on [32–34]) were followed in practice, which made it possible to create a unidirectional interface between the physical system and the simulation environment in the software “Visual Components”. Showing each detailed step in the subordinate layers would exceed the scope of this paper.

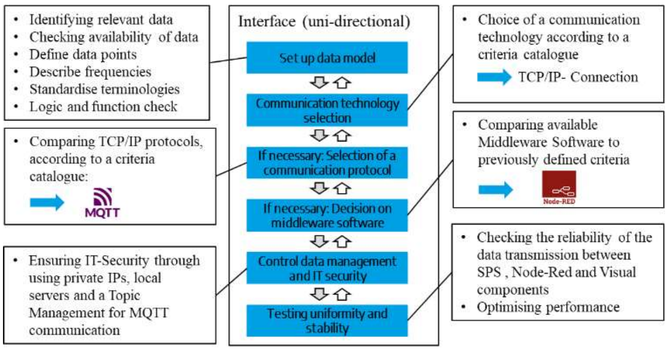

Fig. 3. Main steps for creating a uni-directional interface as partial validation

However, the validation has shown that the instructions within the methodology are sufficient to qualify an employee. The steps were also described generically enough that there was no fixation on specific software packages or protocols. For example, it was possible to freely decide which protocols to use (such as MQTT or OPC-UA), and also the middleware was selected based on a catalogue of criteria.

However, it was noted that despite the division into different layers, some steps are too abstract in the levels of detail, or need to be more application-orientated in the future. Accordingly, as a result of the validation, especially in the more detailed layers of the methodology, the use of SME-compliant language is ensured on the one hand, and on the other hand, the existing steps are re-examined to determine whether they represent a real practical need for action or whether they would merely be applied in an ideal scientific environment.

4. Conclusion and Outlook

It can be summarised that the digital transformation of companies is still an enormous task for many companies, especially for SMEs. The use of Digital Tools such as Digital Twins, Digital Shadows or Digital Models are one approach to increase the digitalisation of a company and correspondingly its economic efficiency. The methodology presented in this paper provides support for companies to enter into these technologies and develop corresponding models. Especially for

SMEs such a simple guideline is important to reduce the amount of human resources necessary to get started with the digital twin. Through a layer-based design the methodology can provide the right amount of information at a time. Addressing different target groups with each layer, the method displays a complete but yet understandable guideline. The first components of the methodology have already been validated in initial tests. However, since the method is not completely developed yet, more research as well as validation has to be carried out especially in the lowest and most detailed layers.

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