INTERNATIONAL DESIGN CONFERENCE – DESIGN 2020
https://doi.org/10.1017/dsd.2020.23

CONCEPTION OF A DIGITAL TWIN IN MECHANICAL ENGINEERING - A CASE STUDY IN TECHNICAL PRODUCT DEVELOPMENT

S. Schweigert-Recksiek [1,✉], J. Trauer [1], C. Engel [2], K. Spreitzer [2] and M. Zimmermann [1]

[1] Technical University of Munich, Germany, [2] Viessmann Werke GmbH & Co. KG, Germany
✉ schweigert.recksiek@tum.de

Abstract

A Digital Twin as a virtual representation of a physical system is becoming a key technology. While potential benefits are evident, there is no approach in literature or practice comprehensively supporting its introduction. In an industrial case study, a generic procedure model for the conception and implementation of a Digital Twin was developed. The relations between use cases, usage data, and virtual models resulted in a target concept as well as requirements for the implementation. Thereby, companies can access the potentials of a Digital Twin taking into account their specific situation.

Keywords: digital twin, design process, simulation-based design, case study, industry 4.0

1. Introduction

The increasing application and complexity of simulation models has led to the possibility to unlock many potentials of virtual product development (Reicheneder, 2015; Schlenkrich, 2015). While simulation software has become ever more powerful, the available input data is getting more into the focus of efforts to increase the potential benefits of product simulations. If it is possible to feed use phase data from real life applications into the simulation models or utilise use phase data to validate simulation results against, more accurate simulation models can be built that lead to better products in the end. The term *use phase data* in this work is built on the definition of Wilberg et al. (2017), where it refers to the data that is generated during the use phase by the product itself (e.g., by sensors or microprocessors) or by related services (e.g., Apps, maintenance reports, or repair reports). Such a coupling of simulation models and use phase data is often referred to as a Digital Twin. This contribution uses the definition of Trauer et al. (2020), where a Digital Twin is defined as *"a virtual dynamic representation of a physical system, which is connected to it over the entire life cycle for bidirectional data exchange.*"

As many other companies these days, the industry partner of this case study from the heating and cooling systems industry is facing challenges in the transition from a "traditional" mechanical engineering company to a future-oriented enterprise that makes full use of the potentials of digitization. While the products in the field work well on a technical basis and in many cases even already provide some basic data from the use phase, an exploitation of the potentials of data-driven engineering and the integration of the products in the internet of things is only beginning. Some first steps like the possibility for the costumer to control their heating system via app have been taken. But as the products of the industry partner are used by private as well as industrial customers and many after-sales and service activities are carried out by partner companies, most of the potential data from the use phase cannot be used in the current engineering processes. Additionally, simulation models and IT tools are not ready to incorporate this use phase data. In most cases, this is also true for the data generated in test environments as well as test systems at the costumer. This leads to the motivation of building a Digital Twin to combine models of product development to use phase data to enable more customer-centric development. The technology of Digital Twins is becoming a key factor for the digitization. Although potential benefits for companies are manifold and range from predictive maintenance to the development of new business models, there is no approach in literature and practice that comprehensively supports companies to introduce their own Digital Twin, taking into consideration their respective needs and conditions.

2. State of the art and research

The term of a Digital Twin is part of a broader context and is located at the intersection of the three research areas virtual product development, cyber-physical systems and product lifecycle management. (Grieves and Vickers, 2017). In a broader sense, it can also be regarded as part of the whole industry 4.0 discussion (Michels, 2018). Regarding case studies on the conception and implementation of Digital Twins in literature and at vendor conferences and brochures so far, technical product development plays a minor role. Most case studies are from manufacturing as the ones shown in Kritzinger et al. (2018). In their categorical literature review, Kritzinger et al. (2018) list many publications that have the twin in the title, although according to their definition many of them rather have a digital shadow or model as a content. Here, They defined a digital model as a representation of an existing or planned physical product in the virtual space but without any automatic connectivity to the real space. One of the case studies presented by Bottani et al. (2017), for example, describes the transition from a cyber-physical system to a Digital Twin for cyber-guided vehicles. Other case studies like Sommer et al. (2019) describe the automatic generation of a Digital Twin based on scanning and object recognition. Both of the solution processes for the build-up of the Digital Twin suggested in these two exemplary works are very specific to a production use case, while the procedure model developed in the case study of this paper is applicable to a broader context of engineering. There are some case studies in technical product development, however, too. Jones et al. (2019), for instance, explain how to use Digital Twins in early stages of engineering design. Its function in these early stages can be regarded as “provotypes” rather than twins that take product lifecycle considerations into account. The term “provotype” stresses the use of a prototype to provoke reactions from a possible costumer (Boer and Donovan, 2012). Riesener et al. (2019) conducted a case study on wind energy converters. Their use of a digital shadow, as they call it, does not include bidirectional data-transfer, as they focus on information handling.

3. Methodology

3.1. Initial situation and research gap

As there is no approach in literature and practice that comprehensively supports companies to introduce their own Digital Twin, there is a research gap of a systematic procedure model for the conception and implementation of a Digital Twin in the mechatronic engineering industry. This procedure model has to take into consideration factors from the five dimensions of virtual product development: people, process, data, product, and tools (Kreimeyer et al., 2005).

On the level of **people**, current barriers between departments as described in Schweigert-Recksiek and Lindemann (2018) have to be considered as the usage of a twin also changes the significance of certain tasks or even departments of the product development process.

Many of the **processes** in a company will change with the introduction of a twin, as for example some simulations will be conducted automatically instead of a simulation assignment being handed over from one department to the other. While this poses one of the greatest challenges for the implementation of a Digital Twin, this *change* and process improvement was also one of the intentions for the industry partner when deciding on the conception and implementation of a Digital Twin.

Of course the generation and usage of **data**, especially from the use phase of products, has to be altered in many places to enable the implementation of a Digital Twin.
Concerning the **product**, a redefinition of the term might be necessary, as starting with the implementation, a product always has to be considered as the combination of two: the physical product and its Digital Twin.
Finally, on the level of **tools**, many challenges have to be faced. Depending on the maturity of the software landscape of a company (e.g. “Is there a well established product lifecycle management system in place or not?”), this dimension will bring the most chances, as it is the enabler for all other dimensions.

3.2. Research questions and applied methods

These considerations result in the following research questions:

- **RQ1** How can a company in the area of mechatronic engineering systematically exploit the potentials of a Digital Twin, with respect to its specific boundary conditions?
- **RQ2** Which methodical procedure supports a conception and implementation of a Digital Twin?
- **RQ3** Which activities and methods have to be used in order to conceptualize and implement a Digital Twin effectively and efficiently?

In the case study of this contribution, a generic procedure model for the conception and implementation of a Digital Twin was developed. Relevant activities were analysed, and both methods and templates were developed. As part of the work, a collection of Digital Twin use cases was developed, clustered, and selected for implementation. In doing so, an analysis of the relations between the main system elements resulted in a target concept of the Digital Twin. These elements were use cases, models of relevant tools and IT-systems applied in the use cases, use phase data, interfaces, and the developed target processes. Finally, requirements for the target concept were derived and the developed procedure model with its activities, methods, and results were evaluated in the case study.

4. Results: Procedure model for the introduction of a Digital Twin

4.1. Overview

The procedure model that resulted from the case study has five steps. After an initiation of the project and definition of its goals, use cases become the main part of all activities (cf. Figure 1). Initially, they are used for the collection of expectations of all internal stakeholders. Subsequently, they are the main instrument to conceptualize the Digital Twin in the third step. The target concept, the result of the third step, is used for deriving requirements in the fourth step of the vendor analysis. These requirements are further elaborated to test cases that can be used in the implementation of the fifth step to validate the implementation of the use cases. While the basic order of the procedure model is linear from steps one to five, there are iterations between steps one and two and two and three respectively. They are necessary as only the further elaboration of the use cases in the steps two and three can lead to a final goal definition and lead to further insights into the current situation. The case study has shown that initiating the supplier analysis (step four in Figure 1) already at an earlier stage is beneficial for the implementation. A first analysis of the capabilities of different possible vendors already in step two can give important insights on the possible scope of a Digital Twin. In addition, the requirements for the implementation might be in a certain form depending on the vendor. Much rework can be prevented if this is already taken into account when the elaboration of the use cases gains velocity in steps two and three.

4.2. Step 1: Project initiation and goal definition

The most important part for step one of the procedure model, the project initiation and goal definition, is to understand the term *Digital Twin* and to identify the main stakeholders within the company. This is completed by activities from project management like setting up a team and ensuring the necessary capacities (cf. Figure 2).

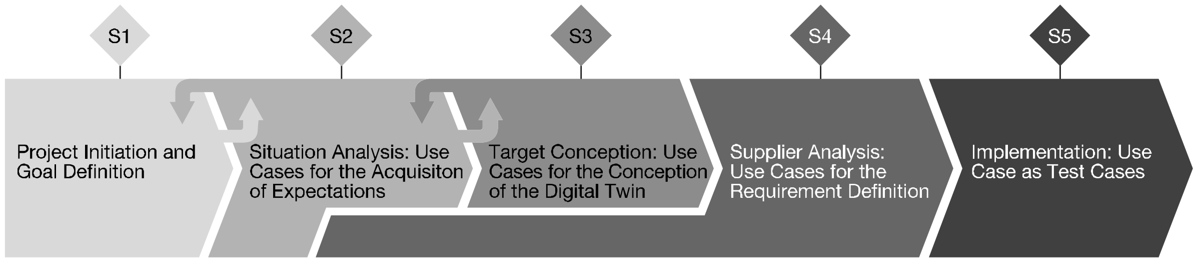

Figure 1. Procedure model for the conception and implementation of a Digital Twin in industry

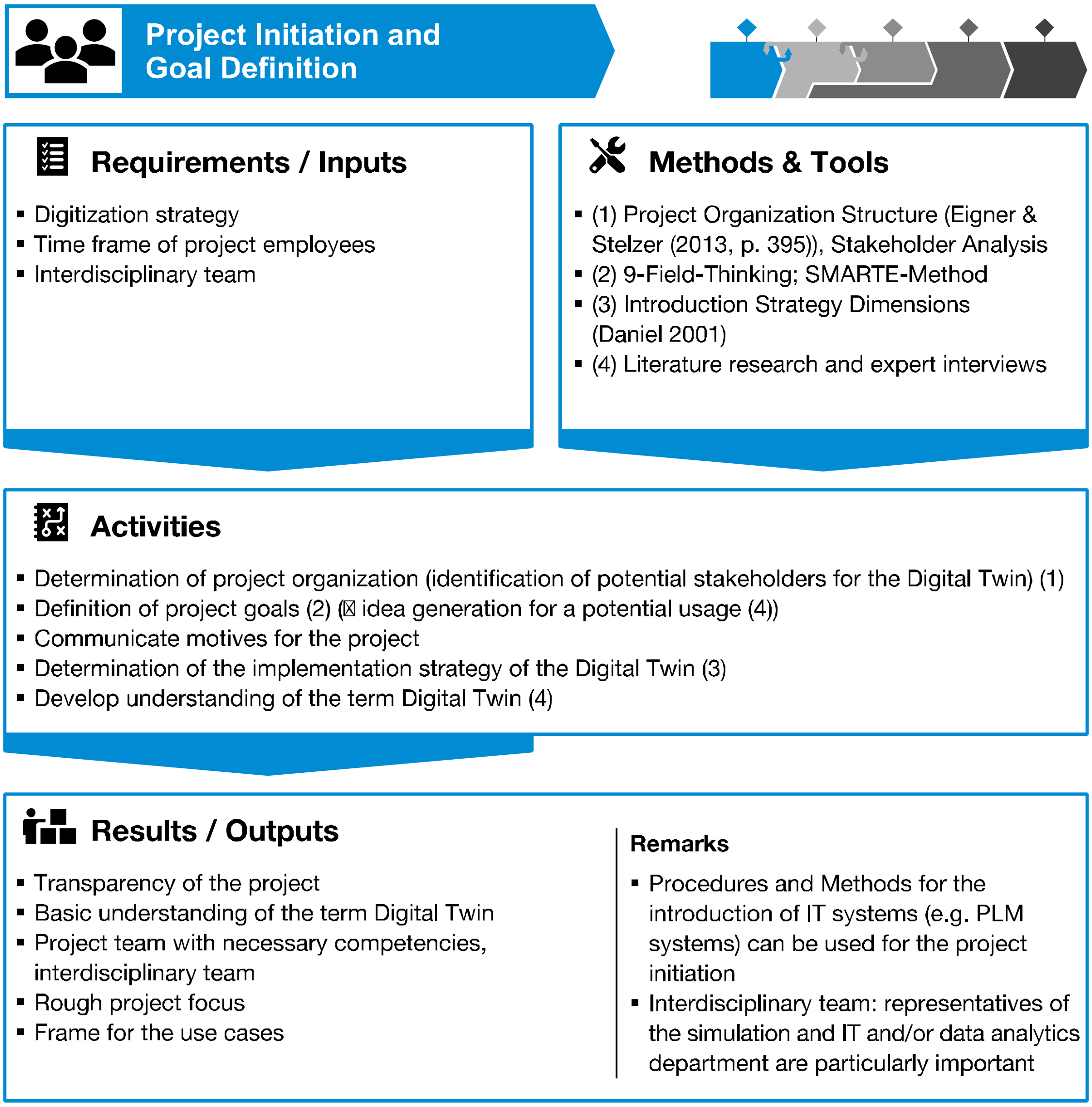

Figure 2. Overview of the first step *Project Initiation and Goal Definition*

4.3. Step 2: Situation analysis

Using the basic understanding of the term *Digital Twin* from step 1, the comparison with the expectations of the internal stakeholders is essential for step 2. While the term *Digital Twin* is somewhat abstract and often leads to extensive expectations, the formulation of concrete use cases can help to get a more realistic picture of what the specific term for the company under consideration might look like. Analysing the current state of the simulation as well the IT landscape helps in identifying problem areas and derive first rough use cases. In many cases, the current processes have to be documented and reflected upon in this stage of the project. This will result in both an overview of the maturity of the company in terms of the requirements for a Digital Twin as well as a more precisely described target state building on the results of step one (cf. Figure 3).

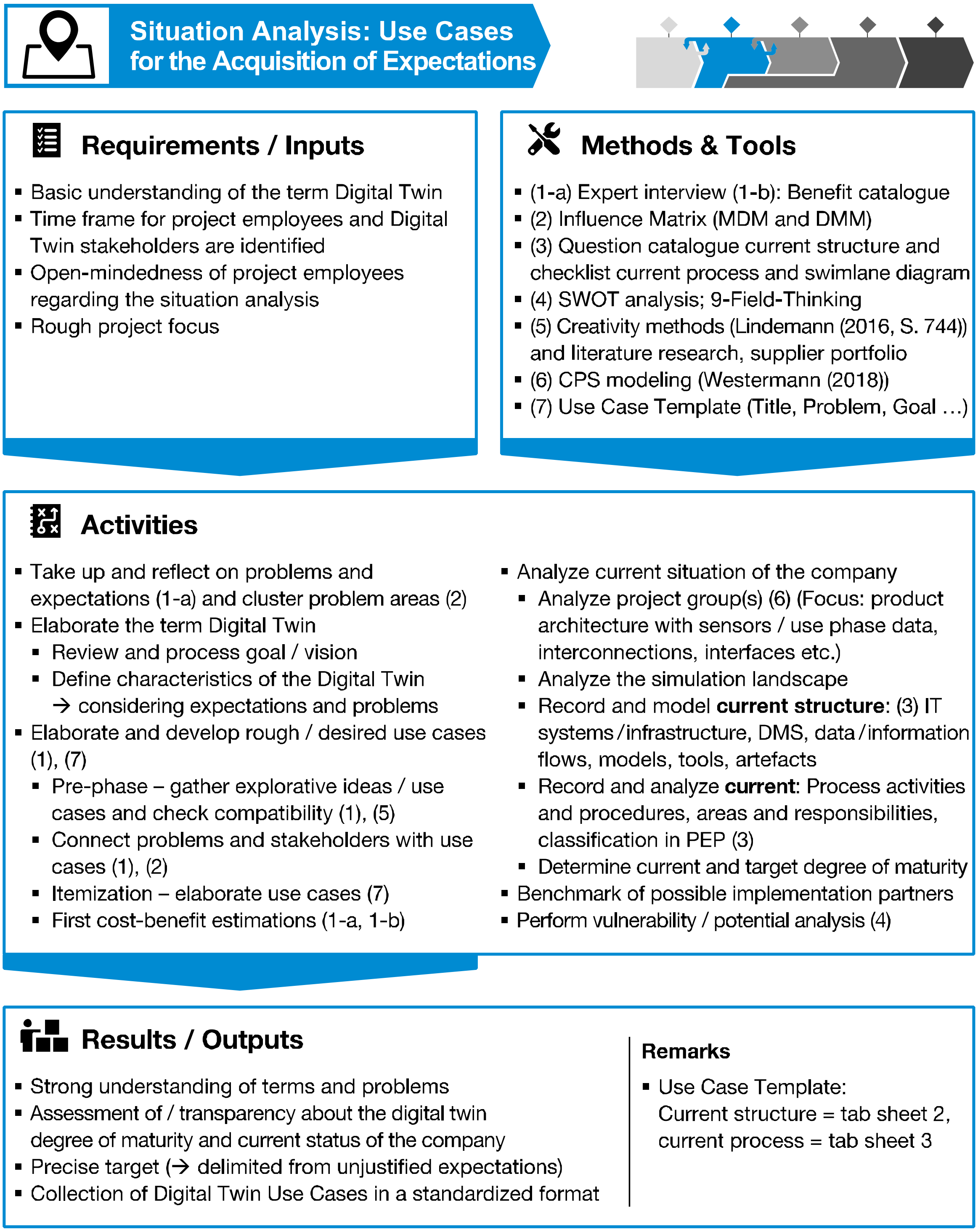

Figure 3. Overview of the second step *Situation Analysis*

4.4. Step 3: Target conception

The third step, target conception, is the main part in the procedure to conceptualize and implement a Digital Twin. Building on a detailed understanding of the current situation and some first insights from an initial vendor analysis, the target concept of the Digital Twin is derived in this step (cf. Figure 4).

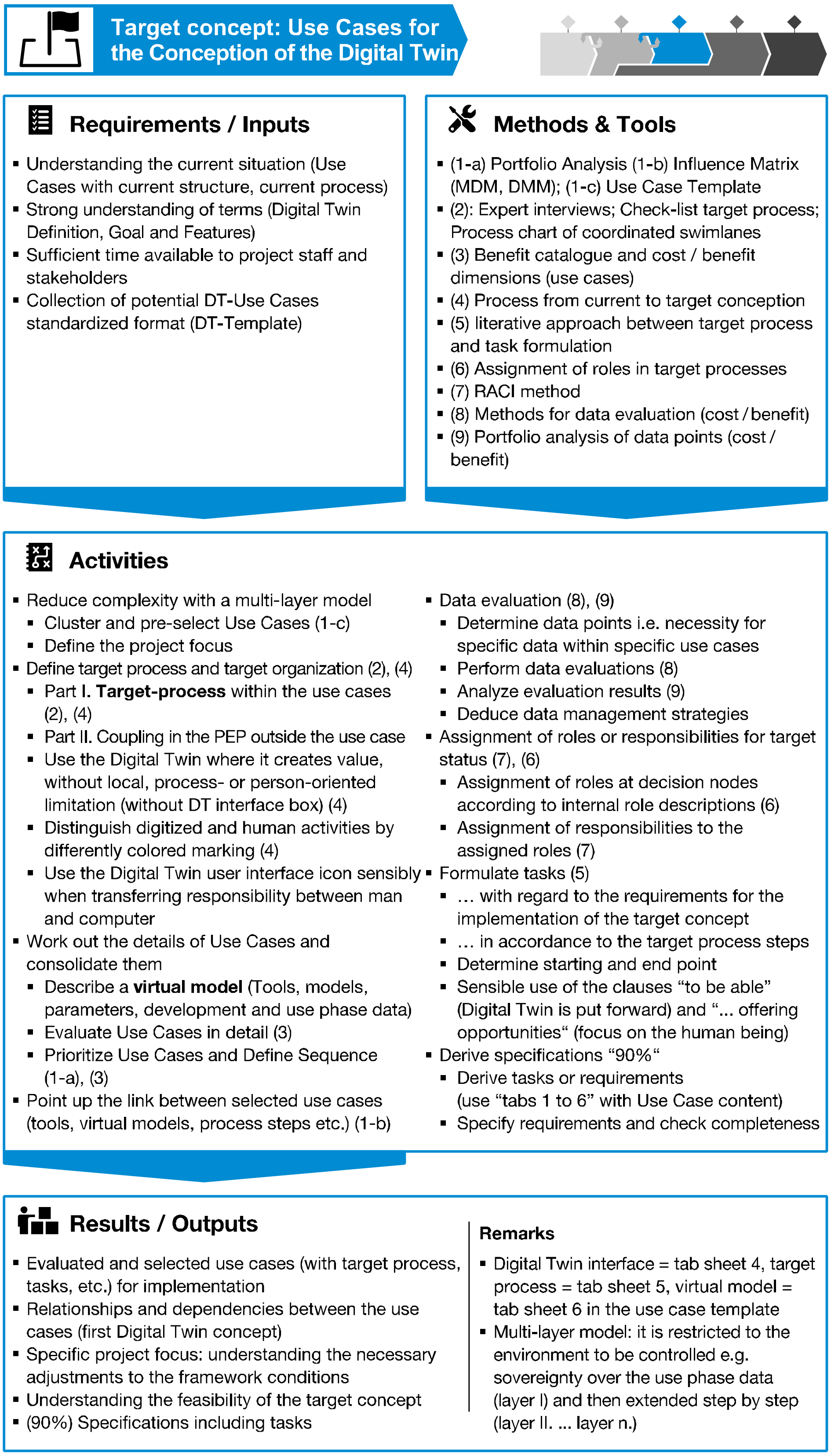

Figure 4. Overview of the third step *Target Conception*

As described before, the most important instrument to do that, are the use cases. In this case study, they are documented in a template that consists of six sheets: Overview, Current structure, Current process, Digital twin interface, Target process and Remarks (cf. Figure 5).

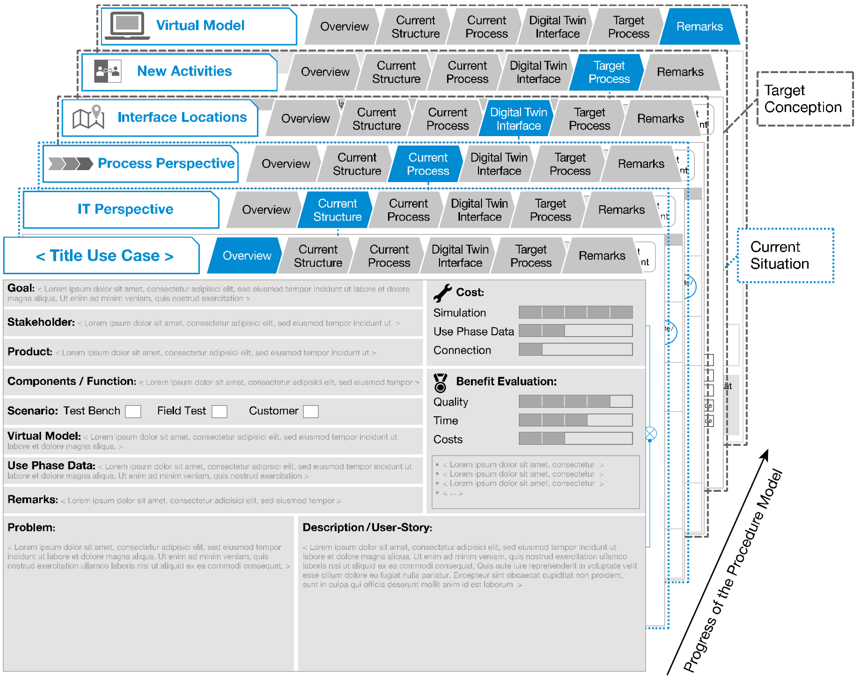

Figure 5. Template for the documentation of use cases in each step of the procedure model

4.5. Step 4: Vendor analysis

The vendor analysis can have different forms, depending on the specific situation of a company. While for some companies a vendor is already fixed as it provides the relevant PLM tools of a company, some companies might deliberately look for new vendors that add to their IT portfolio. The most time consuming part of this step is the transition of expectations and use cases to specific requirements that can be used in a bidding process. If some parallel vendor analysis has started during steps two and three, this will be of great benefit at this stage of the process. Some explanations of the company-specific definitions from step one and expectations from step two to the possible vendors are key elements here.

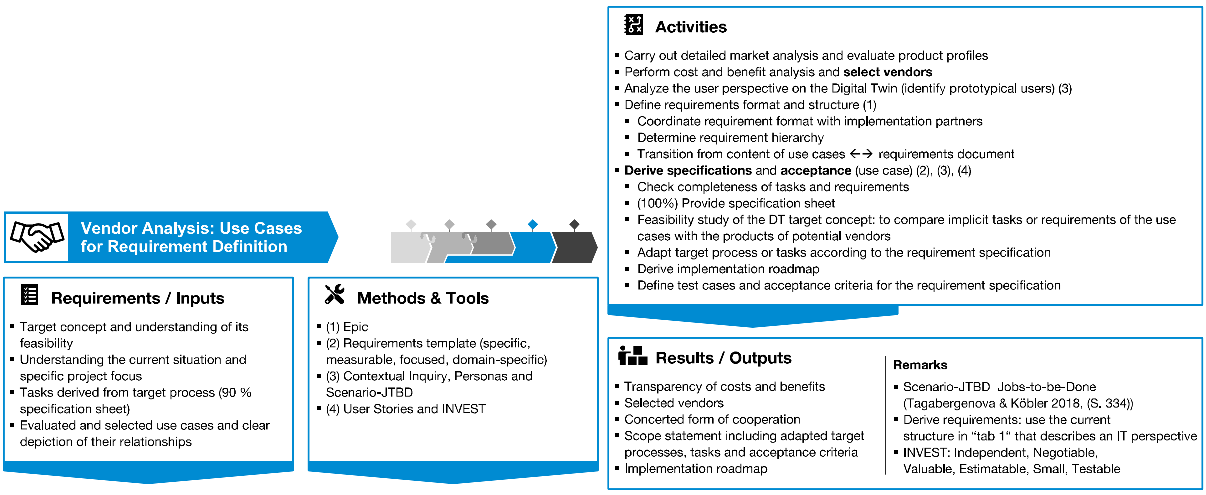

Figure 6. Overview of the forth step *Vendor Analysis*

4.6. Step 5: Implementation

Like step four, step five is highly dependent on the constellation of the specific boundary conditions of a company as well as the selected vendor. In many cases, this step of the procedure model will take more time than all of the previous steps combined. To reduce the risk of failure and loss of confidence of internal stakeholders, this procedure model suggests to start with an "easy" use case that might not even be dependent on data from the use phase but can be set up with internal data from test environments. Such a use case can be utilized to create a first proof of concept and further solidify the target state as well as the mode of collaboration with the vendor. This might result in a Digital Twin that can only be considered to be the twin of a certain, small part of a physical product, while it "grows" with every further use case that is implemented. As the Digital Twin will also result in many changes in the dimensions of people and processes, certain drawbacks and interactions are likely.

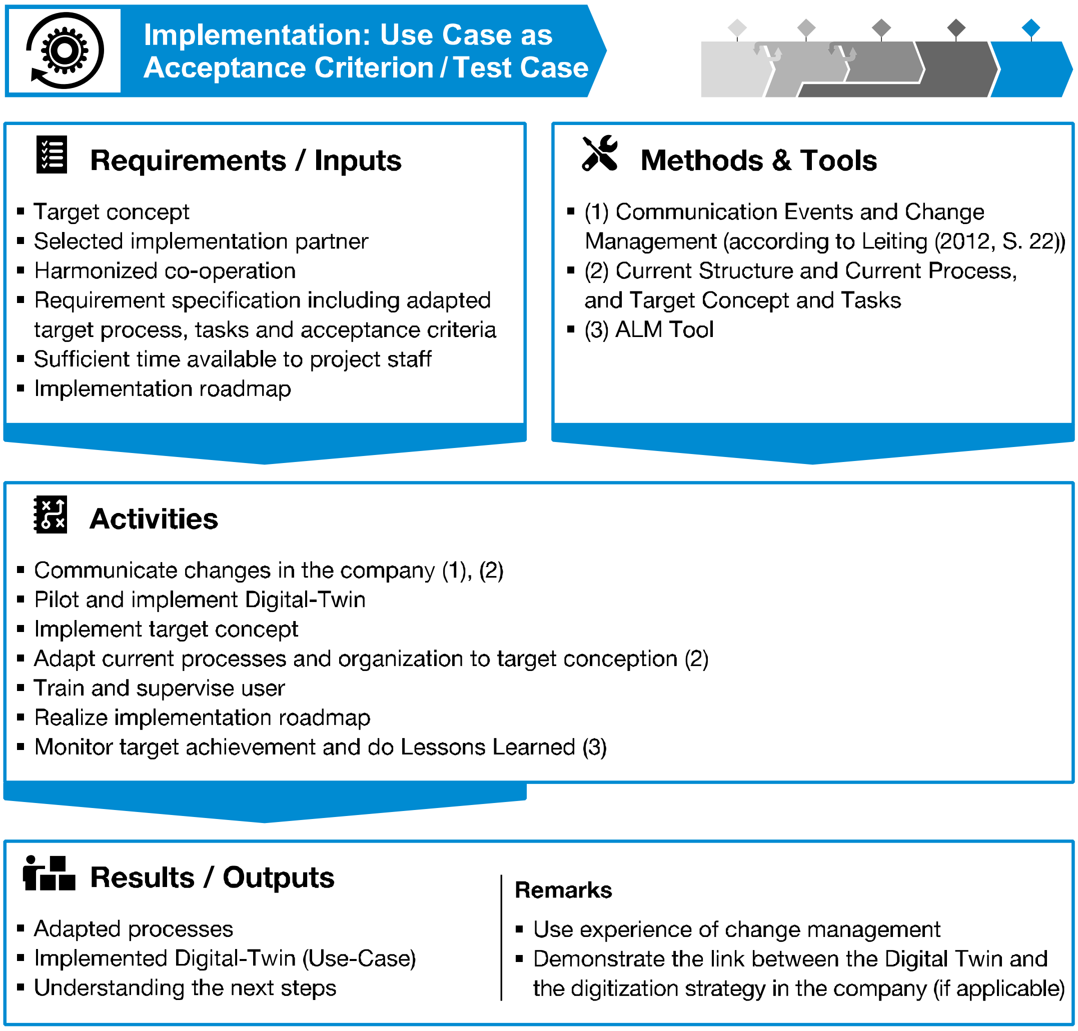

Figure 7. Overview of the fifth step *Implementation*

5. Implementation and evaluation at the industry partner

5.1. Implementation at the industry partner

While the main part of the procedure model is applicable to a broad range of companies, some adjustments reflect the specific situation of the case study partner. A lot of effort was invested, for example, into the translation of the use cases (output of step 3) into the format specified by the implementation partner. As the format for implementation requirements and specifications will differ to some extend dependent on the selected vendor, these activities will look different for other companies.

5.2. Evaluation

The evaluation of the case study focused on the procedure model rather than the specific use cases. It was carried out in workshops with one or two experts. Six experts took part in the evaluation coming from different groups: Head of Processes, Methods, and Tools; Head of Function Development; System

Engineer Function Development (x4). All of them were chosen either due to their overview over the current processes to be altered or their specific knowledge in the selected use cases. To obtain unbiased responses, the two experts involved in the development of the procedure model were not part of the workshops with the other four participants. After a presentation to summarize the achievements of the case study and explain the procedure model in detail, the participants were asked to separately fill out a questionnaire consisting of 19 closed questions concerning the approval to hypotheses measured on a five-step Likert scale plus an open question for final remarks at the end. Figure 8 shows the aggregated results in the three areas *theoretical context*, *practical application*, *methods*, and *overall assessment*.

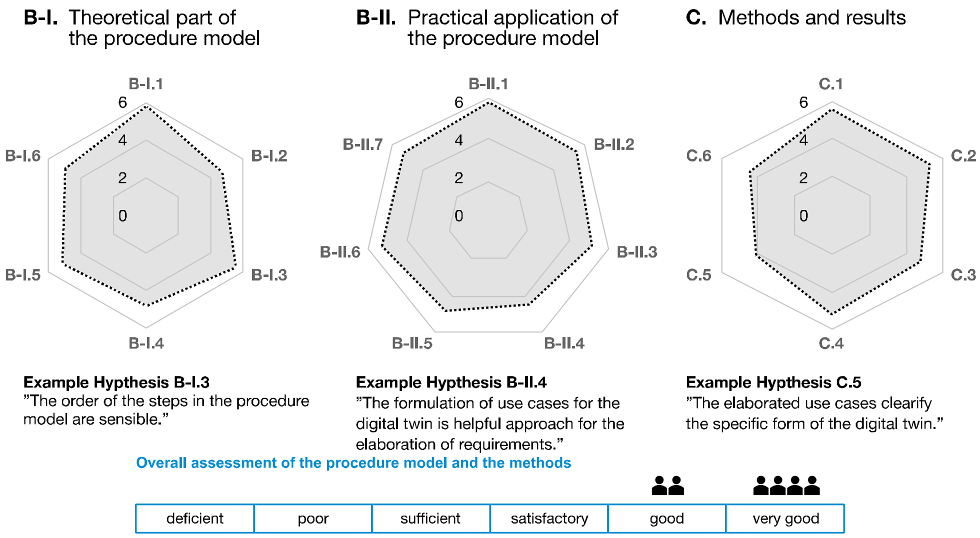

Figure 8. Results of the expert-based evaluation

The results of the evaluation are very positive, as four of six experts asses the procedure model as very good. Some improvement potential remains concerning e.g. the further specification of certain use cases or the efforts to gather the relevant data for each use case in the organization. The overall effort for the implementation were regarded as high, which forms a barrier for the application of the procedure model.

6. Conclusion and outlook

6.1. Discussion

The presented work results in an evaluated procedure model for the conception and implementation of a Digital Twin, so that companies under given conditions can access potential values of a Digital Twin.
There is a discussion in the scientific as well as the consulting community what to call a Digital Twin and what not (cf. Trauer et al., 2020). Some might argue that the approach presented here does not lead to a Digital Twin in their definition. In the definition of this paper, however, with a Digital Twin being a virtual dynamic representation of a physical system, which is connected to it over the entire life cycle for bidirectional data exchange, all use cases developed with this framework have such a twin as a target.

6.2. Outlook

The focus of this case study was technical product development. Therefore, the twin presented here can rather be regarded as an engineering twin, while other areas like production and operation are only minor parts of some use cases. This was done to form a starting point for the conception of a comprehensive Digital Twin. Further work will be done on integrating other aspects too, in order to build a more holistic Digital Twin concept. The procedure model presented here can also be used for these areas, though. At the point of time of publication of this contribution, the implementation of the Digital Twin at the case study partner is still in progress. This might result in minor changes in the procedure model, especially in steps four and five. The authors of this paper will be part of the implementation process to get a chance to further define certain activities in the procedure model.

Acknowledgements

The authors thank Bernd Stöhr, Louis Mahlau, and Murat Saygin for their extensive work in building this procedure model as well as Christoph Hollauer and Julian Wilberg for the fruitful collaboration in this case study.

References

Bottani, E. et al. (2017). "From the Cyber-Physical System to the Digital Twin: the process development for behaviour modelling of a Cyber Guided Vehicle in M2M logic", *XXII Summer School Francesco Turco Industrial Systems Engineering*, pp. 1-7.

Boer, L. and Donovan, J. (2012, June). "Provotypes for participatory innovation", In *Proceedings of the designing interactive systems conference*, ACM, pp. 388-397. https://doi.org/10.1145/2317956

Daniel, A. (2001), *Implementierungsmanagement*. Deutscher Universitätsverlag, Wiesbaden. https://doi.org/10.1007/978-3-322-89883-8

Eigner, M. and Stelzer, R. (2009), *Product Lifecycle Management*. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/b93672_3

Grieves, M. and Vickers, J. (2017), "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems", In: Kahlen, F.-J., Flumerfelt, S. and Alves, A. (Eds.), *Transdisciplinary perspectives on complex systems*, Springer International, Switzerland. https://doi.org/10.1007/978-3-319-38756-7_4

Jones, D.E. et al. (2019), "Early Stage Digital Twins for Early Stage Engineering Design", in *Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft*, The Netherlands, 5-8 August 2019. https://doi.org/10.1017/dsi.2019.262

Kreimeyer, M. et al. (2005), "Holistic integration of CAD and CAE: Analysis and combination of diverse current approaches", *The 9th International Research/Expert Conference Trends in the Development of Machinery and Associated Technology*, pp. 1081-1084.

Kritzinger, W. et al. (2018), "Digital Twin in manufacturing: A categorical literature review and classification", *IFAC-PapersOnLine*, Vol. 51 No. 11. https://doi.org/10.1016/j.ifacol.2018.08.474

Leiting, A. (2012), *Unternehmensziel ERP-Einführung*, Springer Fachmedien, Wiesbaden. https://doi.org/10.1007/978-3-8349-4462-7_4

Lindemann, U. (2016), "Kreativität in der Produktentwicklung". In: Lindemann U. (Ed.): *Handbuch Produktentwicklung*. Carl Hanser Verlag, Munich, pp. 743-758. https://doi.org/10.3139/9783446445819.026

Michels, J.S. (2018), "Industrial Connectivity and Industrial Analytics, Core Components of the Factory of the Future", In: Sendler, U. (Ed.), *The Internet of Things: Industrie 4.0 unleashed / Ulrich Sendler*, editor, Vol. 2015, Springer Vieweg, Berlin, pp. 247-270. https://doi.org/10.1007/978-3-662-54904-9_15

Reicheneder, J. (2015), "15 Years SPDM@BMW", *Proceedings of NAFEMS European 'Simulation Process and Data Management' Conference*, Munich, Germany, December 2-3, 2015, NAFEMS.

Riesener, M. et al. (2019), "The Digital Shadow as Enabler for Data Analytics in Product Life Cycle Management", In: *Procedia CIRP*, Vol. 80, S. 729-734. https://doi.org/10.1016/j.procir.2019.01.083

Schlenkrich, M. (2015), "Handling the Constant Evolution of Simulation with SPDM Solutions", *Proceedings of European Simulation Process and Data Management Conference*, Munich, Dec 2-3, 2015, NAFEMS.

Schweigert-Recksiek, S. and Lindemann, U. (2018), "Improvement Opportunities for the Collaboration of Design and Simulation Departments - An Interview Study", *The international Design Conference on Engineering Design*. The Design Society, Zagreb, pp. 905-916. https://doi.org/10.21278/idc.2018.0393

Sommer, M., Stjepandić, J. and Stobrawa, S. (2019), "Automatic Generation of Digital Twin based on Scanning and Object Recognition".

Tagabergenova, D. and Köbler, F. (2018), "Human Centered Design – Personas, Customer Journeys und Informationsarchitektur", In: Wiesche, M., Sauer, P., Krimmling, J. und Krcmar H. (Eds.): *Management digitaler Plattformen*, Springer Fachmedien Wiesbaden, Wiesbaden, (Informationsmanagement und digitale Transformation), S. 331-345. https://doi.org/10.1007/978-3-658-21214-8_22

Trauer, J. et al. (2020), "What is a Digital Twin? - Definitions and Insights from an Industrial Case Study in Technical Product Development", *DESIGN 2020 17th International Design Conference*, Dubrovnik, Croatia. (accepted)

Westermann, T. (2018), *Systematik zur Reifegradmodell-basierten Planung von Cyber-Physical Systems des Maschinen- und Anlagenbaus. PhD Thesis*. Heinz-Nixdorf-Institute, University Paderborn.

Wilberg, J. et al. (2017), "Big Data in product development: Need for a data strategy", *Proceedings of the PICMET '17: Technology Management for Interconnected World. Portland: International Center for Management of Engineering and Technology*. https://doi.org/10.23919/PICMET.2017.8125460