INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.163

A Method for the Support of the Design for Digital Twin Solution and Its Application on a Gearbox System

Y. Koch [1,✉], S. Husung [2], F. Röhnert [2], A. Mahboob [2], M. G. Frank [1] and E. Kirchner [1]
[1] Technical University of Darmstadt, Germany, [2] Technische Universität Ilmenau, Germany
✉ yanik.koch@tu-darmstadt.de

Abstract

The information from Real Twins are increasingly used to construct Digital Twins. Acquisition of information from the Real Twin or in other words performing measurements on the Real Twin may lead to effects in the working of Real Twin. For instance, the introduction of sensors may impair certain functions of a Real Twin. Therefore, it is important to analyse the effect of any change that is performed on the Real Twin for achieving the Digital Twin. In this paper, a method for Digital Twin solution is presented that address these aspects as well as its use is demonstrated by a case example.

Keywords: *design methods, design for x (DfX), product development, digital twin solution, sensing machine elements*

1. Introduction

During product development, the use of application or failure information of existing technical products that is based on measured data of these products incl. their components and their operational processes is becoming increasingly important. This information is relevant for the systematic implementation of different stakeholder goals (user, but also maintenance staff, etc.) and the realisation of associated use cases in the related product life phases. It may also be the case that stakeholder goals are thought out in advance in the context of innovation management. The usage of the information gathered from the existing product allows e.g. (see also (Jones et al., 2019; Schleich et al., 2017; Stark et al., 2020)):

- The interactive monitoring by continuous measurements of the product and, if necessary, the modification of the parameters of the product (here the stakeholders concern among others those persons from the customer who are responsible for maintaining the system with stakeholder objectives including reliability and product lifetime),
- The acquisition of application information as a basis for the development (further generation or ongoing development) of the product (see also figure 1, beside the product information, relevant information about the actors and environment is collected to define application scenarios (Mahboob, A. 2021)) or as a database for the evaluation of real usage scenarios (here the stakeholders concern among others. Product owner and product developers who need concrete requirements for the further development of the product, while considering stakeholder goals including the reliability of the information on the real usage of the system) or
- The development of new business models in the framework of cyber-physical twins (here the stakeholders concern among others product owners who want to develop new data-based business models, while considering stakeholder goals including the extraction of personalised information).

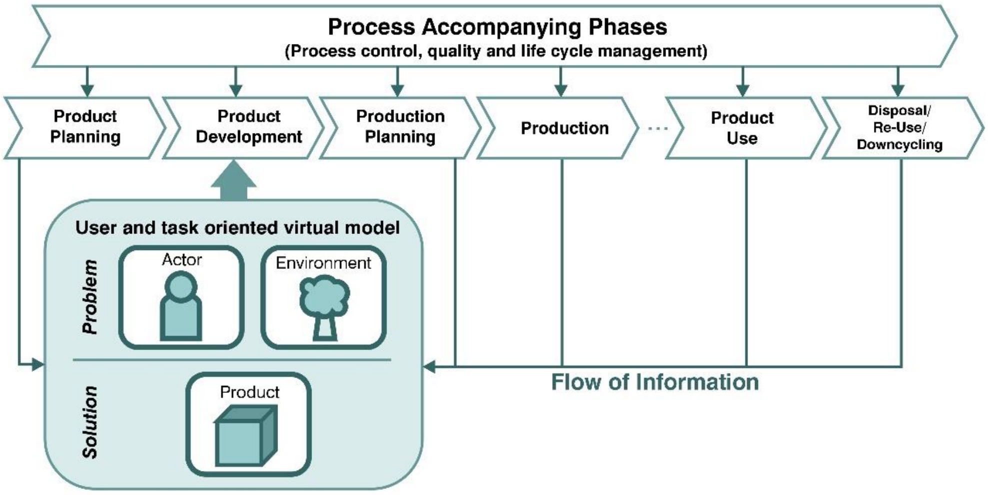

Figure 1. Information feedback from production, usage, etc. into product development (according to (Mahboob, A. 2021))

In order to realise the listed goals, as one option a so-called Digital Twin (Boss et al., 2020; Stark and Damerau, 2019; Trauer et al., 2020) is created for the processing of the information (see also figure 2), as a specific virtual instance representation of an existing technical product. The physically existing technical product is called Real Twin. This paper focuses on use cases where data is measured in the Real Twin and stored and analysed in the Digital Twin. The approach presented here can also be extended to use cases for interactive modification of Real Twins, often via parameters.

For the determination of the information from the Real Twin, measurement capabilities (usually sensors) and associated asset administration shells (Anderl, 2016) in the Real Twin are needed. The necessary sensors may already be implemented in the product in order to fulfil the basic function of the technical product, or they must be additionally integrated into the Real Twin in order to determine the relevant properties for achieving the stakeholders' goals and implementing the use cases in the context of the Digital Twin. Especially when adding additional sensors to the technical product, the integration of the sensors must be planned, designed and implemented in a goal-oriented way. This integration is important for the creation of a purposeful and robust Digital Twin solution (meaning: Digital Twin + extension of the Real Twin (either exclusive extension for Digital Twin or adapted use of existing elements) that are needed for information provision) (see figure 2). The Digital Twin and Real Twin are concrete instances of the Digital Master, which is defined during product development.

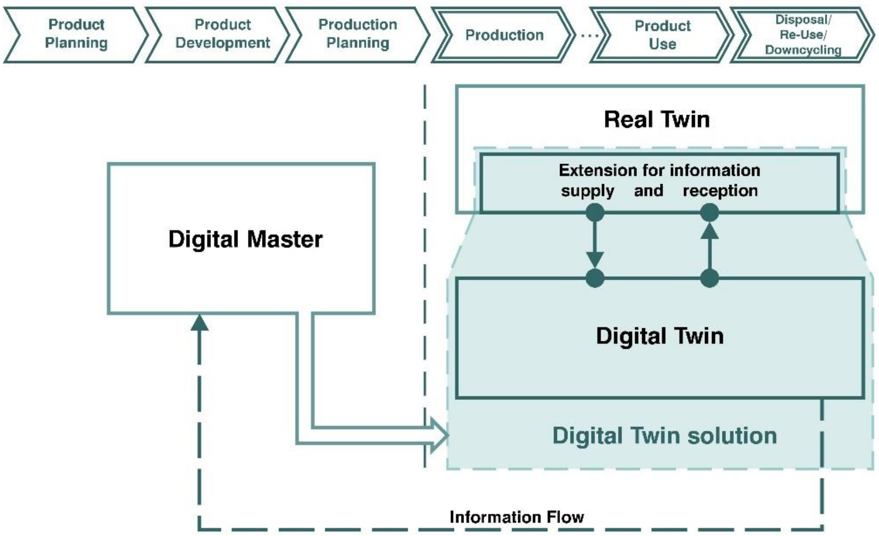

Figure 2. Digital Twin solution

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

During conception and design, it is particularly important that the measurement principles are chosen purposefully. The corresponding sensors must be determined at the targeted measuring positions in such a way that the functions and other properties of the Real Twin are not impaired by the integration of these sensors or through the use of the information gathered from these sensors inside the Digital Twin. The following steps are recommended by the authors for implementing a systematic approach that are further concretised in the following sections while considering the state of the art:

- Systematic analysis of stakeholder goals and comparison with existing solutions as a basis for deriving concrete measures for the Digital Twin solution,
- Holistic conception of the Digital Twin solution and its design (if necessary, building on the existing product), as well as
- Analysis of the Digital Twin solutions, especially the possible influences of the supplemented sensors on the Real Twin.

In this paper, a "Design for Digital Twin" method is discussed and demonstrated for a concrete example of a gearbox system. The method focuses on the mechanical and hardware aspects of the Real Twin. For data integration, the authors refer to sources such as (Moyne et al., 2020).

The paper is structured as follows: the state of the art is followed by an overview of the methodology, which is then applied using a concrete example.

2. State of the Art

2.1. Identification of Requirements for the Digital Twin

Many scientific papers deal with the identification of requirements for the management shell, the definition of the associated digital twin models and the processing of the information inside the Digital Twin and show approaches as well as solutions for the realisation (Schleich et al., 2017; Boss et al., 2020; Durão, Luiz Fernando C. S. et al., 2018; Moyne et al., 2020; Röhm et al., 2021). In this context, the interoperability, model quality, model exchange and extensibility as well as the processing of the information are discussed (Wilking et al., 2020). For the systematic determination of the relevant information from the Real Twin, there are still many open questions. Extending the state of the art, this paper focuses on the systematic conception and design of the mechanical and hardware aspects of the Real Twin.

2.2. Description of technical systems

The description of technical products can be done by means of different approaches (Eigner et al., 2017; Albers et al., 2019). For this paper, the description of technical products will be based on the system theory and the CPM/PDD approach (Weber, 2005; Köhler et al., 2008; Weber and Husung, 2011). With the separation of properties and characteristics, the CPM approach offers a good basis for describing the external required properties (here for the Digital Twin solution) and the necessary extension of the real twin derived from them as characteristics.

2.3. Sensing machine elements

Enhancing machine elements with sensory functions to develop sensing machine elements is the current subject of application-oriented development, but also the basic research. The distinction of various types of sensing machine elements is described by (Vorwerk-Handing et al., 2020). However, the difference in the characteristics of the sensor concepts is relevant when seen from the point of view of a potential use of sensory machine elements for the process-related recording of as-is-properties (properties according to (Weber, 2005; Köhler et al., 2008)). Basic research (see, for example, the call for proposals for the DFG SPP "Sensor-Integrating Machine Elements as Pioneers of Comprehensive Digitalization") further aims to achieve the data evaluation in the machine element and still retain their standard interfaces. Examples descriptions of such concepts are still comparatively rare (Kirchner et al., 2019), for example, a timing belt with integrated sensor module including a Bluetooth transmission module (Welzbacher et al., 2021).

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

3. Design for Digital Twin Method

In section 3, the Digital Twin method is first explained, which is applied in section 4 using a concrete example of a gearbox system. Some explanations of the example are already going to be provided in section 3 so that the method can be explained more clearly later in this paper in section 4.
In the first step of the method, the concrete stakeholder goals and expected use cases must be concretised in such a way that the relevant product characteristics can be derived from them. Depending on the development and implementation status of the technical product, different levels of maturity of the relevant properties can be determined. Based on the identified relevant properties, an iterative process of conception, design and analysis is carried out (see figure 3). Details on the procedure are explained in the following sections.

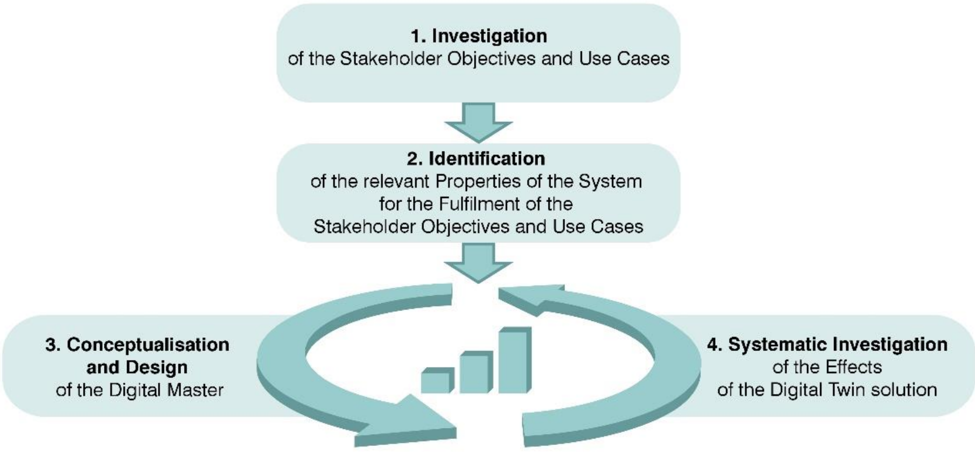

Figure 3. Overall approach

3.1. Investigation of the Stakeholder Objectives and Use Cases

Similar to the development of all products, the development of the Digital Twin solution first requires the identification of the concrete goals of the stakeholders and the associated use cases in the specific product life phases. The stakeholders and use cases can among other things be determined using systems engineering methods, e.g. based on (Weilkiens, 2016).The goals and use cases may originate from the same product life phase in which the Digital Twin and the associated Real Twin are located (e.g. during usage or maintenance). Furthermore, it is also possible that the goals and use cases are relevant in pre- or post-life phases (e.g. during product generation development (Albers et al., 2019)).
An example for both twins being in the same life phase is:

- Goal: Improving the reliability of the product
- Use Case: Monitoring of the as-is-properties of the product or component as a base for the detection of damage and/or its prevention (real-time information)

An example of different life phases is:

- Goal: Improving the predictability of required-properties of the product
- Use Case: Feedback of information on the as-is-properties into the ongoing or subsequent product development (consolidated information)

This distinction in terms of life phases is relevant because the use cases entail different requirements for the relevant properties and their processing (e.g. in the digital twin). For example, some use cases in the same life phase often require a specific performance when it comes to the processing of the information (e.g. for real-time monitoring of the product). In contrast, use cases originating from other product life phases often have requirements for the storage and consolidation of information (e.g. consolidation of product as-is properties collected over a long period of time).

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

3.2. Identification of the relevant Properties of the System for the Fulfilment of the Stakeholder Objectives and Use Cases

For the implementation of the use cases, information about specific properties of the Real Twin is required. These properties can be determined at the Real Twin from output flow variables (such as velocities, forces, etc.) or internal state variables (such as temperature, etc.) (see figure 4, the n-m relation comes from the fact that several flows or state parameters could be necessary for one property, and vice versa).

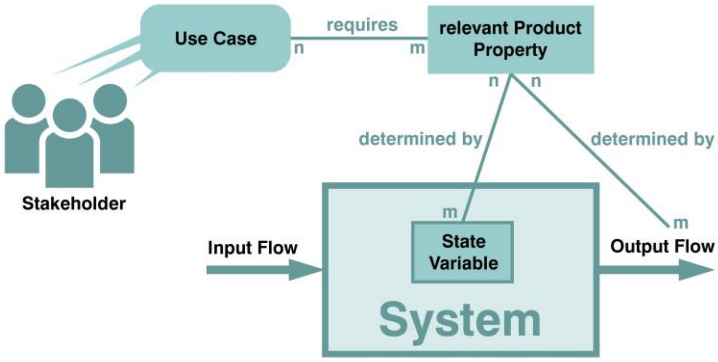

Figure 4. Relation between use case, relevant product properties and product output flow or state variables

The concretisation of the properties depends on the respective specification level and the level of detail of the Digital Master (term according to (Stark et al., 2020) - this refers to the product description during development). In the early phases of development, when only initial concept decisions on the Digital Master are available, the relevant properties can only be formulated in general or abstract terms. This is because their detailing depends on the development decision, e.g. the solution principles. The relevant properties for the Digital Twin are therefore iteratively detailed together with the concretisation of the Digital Master (already running synthesis/analysis loops according to the CPM/PDD model (Weber, 2005)). For instance, if according to the stakeholders' goals, the reliability of the overall ”gearbox system“ is to be improved, this property can be further concretised once the concept has been established (see section 4.1).

The approaches used to determine the specific properties depend on the level of system specification and detail of the Digital Master. Most commonly, approaches from use case analysis or system analysis (Darnieder et al., 2018) or ”experiential knowledge“ based on solution patterns are used (Weber and Husung, 2016). By means of the use case or system analysis, acceptance criteria are identified that must be met in order to evaluate the implementation of the use case or system functions. The relevant properties are then derived from these criteria. The reliability of the overall ”gearbox system“ is achieved, as an illustrative example, when torque and speed are transmitted with a small transmission error, low vibrations and a high degree of efficiency over the whole product life cycle.

In addition to the properties required for the current objectives and use cases, this approach also provides the opportunity to think ahead to potential objectives, use cases and related necessary properties in the context of innovation management. For these properties, solutions do not have to be fully developed and implemented by means of step 3 (see figure 3), but it should be examined what needs to be provided in the conceptualisation for a possible later extension.

3.3. Conceptualisation and Design of the Digital Master

Based on the analysis from step 2 (see figure 3) and the concretisation of the Digital Master, the relevant properties that need to be measured and consolidated by means of the Digital Twin (directly or indirectly) are determined (based on cause-effect relationships). The further conception of the Digital Master, especially the selection and representation of the relevant measurement principle and the sensors, is basically done from the outside in along the chain of effects. The search for suitable

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

measurement concepts and positions thus begins at the external interfaces and proceeds to the specific components.

For measurement positions that are further away from where the relevant properties occur, a comprehensive understanding of the elements along the functional chain is required. This understanding is required because the functional chain must be partially modelled to determine the relevant properties based on the measurement information. For instance, in the case example of the gearbox system, the consideration of reliability (as a relevant property) requires modelling (in addition to measurement) to describe the dependencies between the concrete measured properties up to the relevant property of reliability (see section 4.3).

3.4. Systematic Investigation of the Effects of the Digital Twin solution

The modification of the Real Twin through extensions with sensors for the Digital Twin solution can also lead to further effects on other properties of the Real Twin. Therefore, a comprehensive impact analysis is necessary for every change occurrence on the Real Twin. An essential prerequisite for the impact analysis is the existence of a system model that contains relevant functions, system components, their relationships and specific associated parameters (Husung et al., 2021). Further explanations of the analyses that had to be skipped here due to the scope of the article, can be found among others in (Kleiner et al., 2017; Biggs et al., 2019; Albers et al., 2003).

4. Digital Twin Method for Gearbox System

The following sections present an application of the aforementioned methodology to an industrial case example of a gearbox system. At the beginning of the Digital Twin conception, stakeholders' goal collection takes place (explained here only in excerpts). Here the foundation for the identification of stakeholder objectives and use case is laid, which is essential for the requirement derivation. Once the basic requirements are derived and formulated, the necessary parameters and properties for the newly developed sensory technology can be isolated and analysed in deeper detail. Based on these isolated properties, a detailed presentation of the integrated sensors is designed. Finally, the overall influence on the Real Twin as well as the Digital Twin through the sensor integration is investigated.

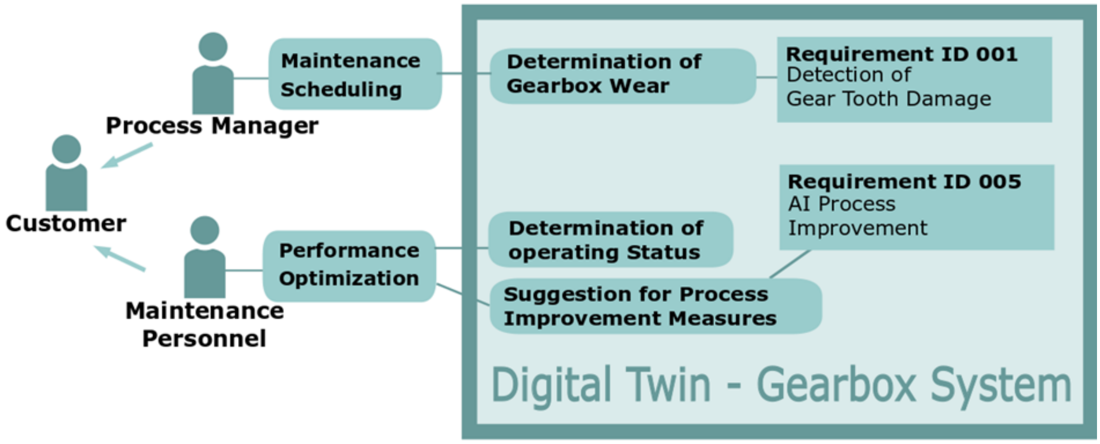

Figure 5. Example of Stakeholders' requirements

4.1. Investigation of Stakeholder

For acquiring the full scope of requirements, the product stakeholders' goals have to be investigated. In this example, two main stakeholders are possible: the product owner who is the developer of the gearbox system and at the same time is the owner of the Digital Twin, and the customer who is using (or going to use) the gearbox system in a process with the Digital Twin as a service. The analysis presented here concentrates on the customer and the determination of the goals of two stakeholders in detail, i.e. maintenance and process management. The maintenance stakeholder is mainly interested in scheduling the maintenance procedures based on reliable information. In this context, the gearbox

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

wear over time is of primary interest. While multiple parameters and factors influence the gearbox wear, the gear tooth damage is the most decisive to know (see requirement ID 001 in figure 5).
While the maintenance department concentrates on keeping the functionality of the gearbox alive, the process management focuses on optimizing the gearbox performance. Therefore, a constant process evaluation on the basis of the current operating status must be carried out as well as technical suggestions must be integrated. These suggestions are based on algorithmic process analyses, which require the involvement of Artificial Intelligence (AI) technology (see requirement ID 005 in figure 5).

4.2. Identification of relevant Properties to fulfil the Maintenance Scheduling Use Case

As discussed in the last sub-section, the gear wear is identified as the most relevant property, that the use case "Maintenance Scheduling" of the Process Manager can be fulfilled. Through analysis of physical effects, possible sensor concepts are derived (figure 6). Thereby, a cause effect chain similar to (Martin et al., 2018) is established. The end of each branch leads to physical sensor(s) that can measure the physical effect. As a next step, the discussion about the sensors is necessary to choose a feasible sensor for measuring gear wear.
Measurement of the surface deviation of a gear tooth is not feasible, because of the harsh operating conditions inside the gearbox. Especially, oil surrounding the gear wheel hides the surface deviation caused by the gear tooth damage from the measuring sensor.
However, the transmission error caused by the stiffness reduction and geometric deviation can be measured either by an angular encoder that is mounted onto the shaft or by using the gear wheel as a measuring scale. The integration of an angular encoder requires additional components that requires a design change. This change of the gearbox system will not be necessary when the gear wheel is used as measuring scale. Therefore, the gear wheel is used further as measuring scale and a sensor concept using magnetoresistive sensors (MR-Sensor) is developed to measure the angle.

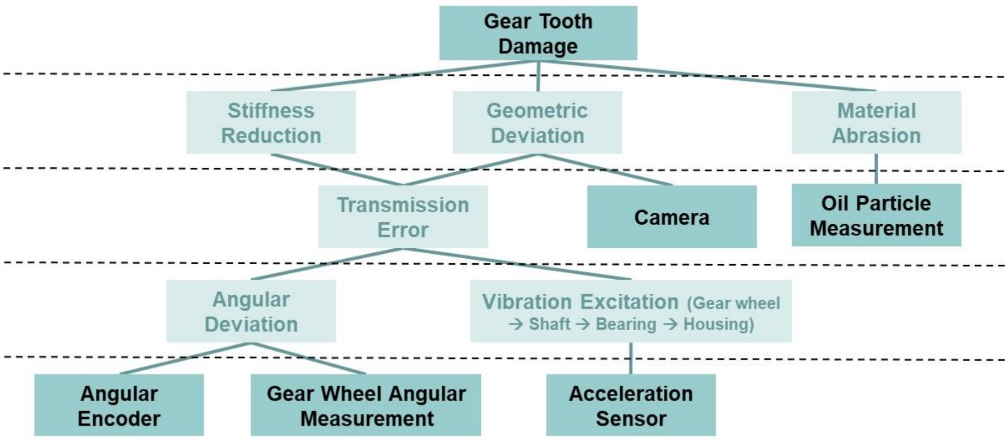

Figure 6. Derivation of sensor concepts to detect gear tooth damage

4.3. Sensor Concept of Gearbox System in order to identify the Gear Wear

In the last sub-section, a sensor concept is developed based on the stakeholders' requirements for plannable maintenance of the transmission and the associated gear wear. In this section, the integration of the sensor concept is described. The concept presented is a first draft for using a gear as a dimensional scale, and therefore the limitations are discussed below.
The developed sensor concept uses the gear wheel as a measurement scale, with the teeth acting as the partition segments of the measuring system. This measurement scale can be used, for example, with magneto-resistive sensors, which can be preloaded by a magnet and output a sine-like signal between two teeth by affecting the magnetic field (Slatter, 2019). The sensors can then be positioned above the gears, as shown in figure 7 for a two-stage gearbox of SEW-Eurodrive GmbH &Co KG. The sensors can be mounted on the gear housing using brackets attached to the gearbox housing. This integration

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

does not impact the actual function of the gearbox, as no change to the power transmission path is necessary. With this sensor concept, the instantaneous angular speed can be measured. If the tooth flank is damaged, changes in the transmission error will occur, which leads to a fluctuation in the instantaneous angular speed (Randall et al., 2019). That can be detected with the sensor concept. Since the measuring concept uses the gear wheel as a measurement scale, influences from changed power transmission must be considered as well and manufacturing imperfections of the gear wheel itself could superimpose the sensor signal. Furthermore, depending on the arrangement of the sensors, the working distance could change as a function of the torque. If this change is too high, the signal-noise ratio can worsen and the measurement concept will no longer work, but this dependence between working distance and torque can also be used to gather further information about the torque.

The presented sensor concept is highly linked to the gear wheel and thus contains a lot of information about the considered gear stage as well as the gear box properties. This information can be linked to models in a Digital Twin and new applications could be discovered by exploiting the data as well as further potentials for the customer could be explored. For example, more precise control can be achieved through more accurate knowledge of the process, in this example the torque. Since not only the drive data is available, but also specific information of the different gear stages.

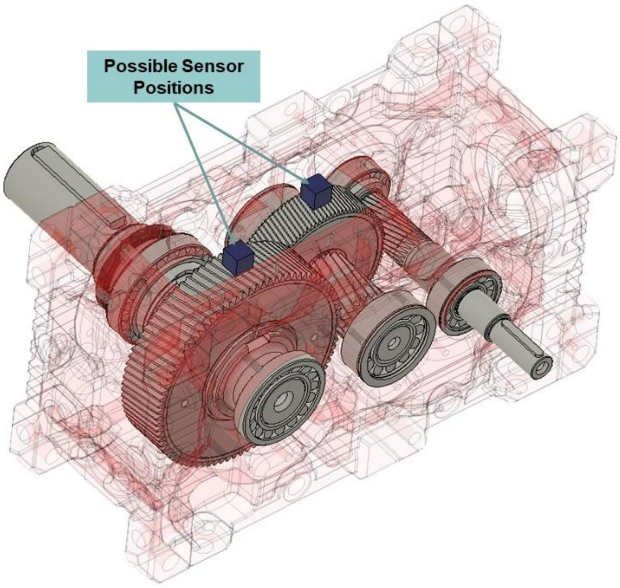

Figure 7. Integration of MR-Sensors for measuring the angular deviation

4.4. Influences of the Sensor Integration onto the Real Twin

The integration of the prescribed sensor concept requires changes to the gearbox housing. A first prototype uses a bracket screwed onto the housing and in this way, positions the sensor to the gear wheel. In further developed systems, the sensor housing could be integrated into the gearbox housing. In doing so, only those changes have to be made to the housing that do not influence the primary function(s). However, this will require an additional assembly step and the construction of the housing has to be changed as well. The additional component might also change the own frequencies and if attached with a screw could weaken the strength or stiffness of the gearbox housing. These changes might be little, but should be considered, when integrating new sensor technology. In modern high-developed gearboxes, the oil flow inside the gearbox is actively controlled by using the housing structure that facilitates the flow of oil towards the meshing gears. This controlled oil flow could be interrupted or reduced by the sensor and its housing, as the sensor needs to be in a working distance of a few millimetres from the meshing gears. Therefore, the oil flow might be redesigned, or the sensor housing should support a guided oil flow towards the meshing gears. Furthermore, the sensor concept is preloaded with a magnet that can also influence the functionality. During the operation of the gearbox, metal particles that are abrasively torn off the gear wheel start to accumulate inside the oil.

https://doi.org/10.1017/pds.2022.163 Published online by Cambridge University Press

The preloaded magnet in the sensor could attract these metal particulars that can interfere with the sensor signal and can thus lead to unforeseen changes in the information received from the sensor.

A Stakeholder initially neglected along with his requirements in Chapter 4.1 is the product owner. Through the systematic investigation, his requirements become clear. As the described solution for the use case “Maintenance Scheduling” (see figure 5) influences other use cases and objectives of the product owner as well. For example, the product owner is interested in a continuous development of his products. The newly integrated sensor technology opens up the possibility for the product owner to access data during the lifetime of the gear box, which he can use to optimize the product. This requires storage and consolidation of the acquired information, and could be integrated into the Digital Twin solution. This also shows the iterative nature of the method presented in Chapter 3.

5. Conclusion and Outlook

This paper has presented a method for the design of Digital Twin solution that bases on the combination of the Real Twin with the Digital Twin in a goal-oriented manner. The method emphasises on performing impact analysis for every change that has been made in the Real Twin for gathering information that is needed for the Digital Twin, for instance, the integration of a sensor in the Real Twin. This is shown by a case example of a gearbox system where the effect of the addition of a sensor into the Real Twin has been demonstrated by means of a cause effect chain. The choice of the sensor and place of integration must be carried out in such a way that the objectives of stakeholders are met and the working of Real Twin is not affected. This is first explained methodologically and later is applied to a real-world example of a gearbox system to demonstrate the effectiveness of the presented method.

As a next step, the presented method can be complimented by computer support that may allow the (semi) automatic evaluation of the effect chain. The use of Model Based Systems Engineering (MBSE) approaches might be a good candidate for this and can be explored next.

References

Albers, A., Matthiesen, S. and Ohmer, M. (2003) "An innovative new basic model in design methodology for analysis and synthesis of technical systems", *14th International Conference on Engineering Design.* Stockholm, pp. 147–148.

Albers, A., Rapp, S., Spadinger, M., Richter, T., Birk, C., Marthaler, F., Heimicke, J., Kurtz, V. and Wessels, H. (2019) "The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations", *22nd International Conference on Engineering Design - ICED19.* Delft, The Netherlands, pp. 1693–1702. DOI: https://doi.org/10.1017/dsi.2019.175.

Anderl, R. (2016) "Industrie 4.0 – Digital Transformation in Product Engineering and Production", *21st International Seminar on High Technology - Smart Products and Smart Production.* Piracicaba (SP), Brazil.

Biggs, G., Post, K., Armonas, A., Yakymets, N., Juknevicius, T. and Berres, A. (2019) "OMG standard for integrating safety and reliability analysis into MBSE: Concepts and applications", *INCOSE International Symposium*, Volume: 29, pp. 159–173. DOI: https://doi.org/10.1002/j.2334-5837.2019.00595.x.

Boss, B., Malakuti, S., Lin, S.-W., Usländer, T., Clauer, E., Hoffmeister, M., Stojanovic, L. and Flubacher, B. (2020) Digital Twin and Asset Administration Shell Concepts and Application in the Industrial Internet and Industrie 4.0. An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper, Industrial Internet Consortium (IIC) and Plattform Industrie 4.0.

Darnieder, M., Pabst, M., Wenig, R., Zentner, L., Theska, R. and Fröhlich, T. (2018) "Static behavior of weighing cells", *Journal of Sensors and Sensor Systems*, vol. 7, no. 2, pp. 587–600.

Durão, Luiz Fernando C. S., Haag, S., Anderl, R., Schützer, K. and Zancul, E. (2018) "Digital Twin Requirements in the Context of Industry 4.0", *Product Lifecycle Management to Support Industry 4.0: 15th IFIP WG 5.1 International Conference, PLM 2018, Turin, Italy, July 2-4, 2018, Proceedings.* Cham, 2018. Cham, Springer International Publishing, pp. 204–214.

Eigner, M., Dickopf, T., Schneider, M. and Schulte, T. (2017) "mecPro2- A holistic concept for the model-based development of cybertronic systems", *21st International Conference on Engineering Design (ICED 17)*, 21-25.08.2017. Vancouver, Canada, pp. 378–388.

Husung, S., Weber, C., Mahboob, A. and Kleiner, S. (2021) "Using Model-Based Systems Engineering for need-based and consistent support of the design process", *23rd International Conference on Engineering Design (ICED21)*. DOI: https://doi.org/10.1017/pds.2021.598.

Jones, D. E., Snider, C., Kent, L. and Hicks, B. (2019) "Early Stage Digital Twins for Early Stage Engineering Design", *22nd International Conference on Engineering Design - ICED19*. Delft, The Netherlands, pp. 2557–2566. DOI: https://doi.org/10.1017/dsi.2019.262.

Kirchner, E., Martin, G. and Großkurth, D. (2019) "Condition Monitoring with Sensor-Integrating Toothed Belts", *10. VDI-Fachkonferenz "Umschlingungsgetriebe 2019"*. Stuttgart.

Kleiner, S., Ricks, M., Engelmann, M. and Husung, S. (2017) "Model-Based Systems Engineering and Simulation for Automotive Systems Development at GKN Driveline", *NAFEMS World Congress NWC17*. Stockholm, 11.-14.06.2017.

Köhler, C., Conrad, J., Wanke, S. and Weber, C. (2008) "A Matrix Representation of the CPM/PDD Approach as a Means for Change Impact Analysis", *10th International Design Conference*. Cavtat, Dubrovnik, Croatia, pp. 167–174.

Mahboob, A. (2021) Modelling and use of SysML behaviour models for achieving dynamic use cases of technical products in different VR-systems (Dissertation), Ilmenau.

Martin, G., Vogel, S., Schirra, T., Vorwerk-Handing, G. and Kirchner, E. (2018) "Methodical Evaluation of Sensor Positions for Condition Monitoring of Gears", *NordDesign 2018: NordDesign 2018 : Linköping University, August 14-17, 2018*. Linköpings Universitet.

Moyne, J., Qamsane, Y., Balta, E. C., Kovalenko, I., Faris, J., Barton, K. and Tilbury, D. M. (2020) "A Requirements Driven Digital Twin Framework: Specification and Opportunities", *IEEE Access*, vol. 8, pp. 107781–107801.

Randall, R. B., Peng, D. and Smith, W. A. (2019) "Using measured transmission error for diagnostics of gears", in: *SIRM 2019 – 13th International Conference on Dynamics of Rotating Machines*.

Röhm, B., Emich, B. and Anderl, R. (2021) "Approach of simulation data management for the application of the digital simulation twin", *31st CIRP Design Conference*, Volume: 100, pp. 421–426. DOI: https://doi.org/10.1016/j.procir.2021.05.098.

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

Slatter, R. (2019) "Condition Monitoring of Gearboxes using Magnetoresistive Sensors", *VDI Berichte* 2355, pp. 229–244.

Stark, R., Anderl, R., Thoben, K.-D., Wartzack, S. and Krause, F.-L. (2020) *WiGeP-Positionspapier: „Digitaler Zwilling“*.

Stark, R. and Damerau, T. (2019) "Digital Twin", in: The International Academy for Production Engineering (ed) *CIRP Encyclopedia of Production Engineering*, Berlin, Heidelberg, Springer, pp. 1–8.

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K. and Zimmermann, M. (2020) "What is a Digital Twin? – Defintions and Insights from an Industrial Case Study in Technical Product Development", *16th International Design Conference (DESIGN 2020)*, pp. 757–766. DOI: https://doi.org/10.1017/dsd.2020.15.

Vorwerk-Handing, G., Gwosch, T., Schork, S., Kirchner, E. and Matthiesen, S. (2020) "Classification and examples of next generation machine elements", *Forschung im Ingenieurwesen*, vol. 84, no. 1, pp. 21–32 [Online]. DOI: https://doi.org/10.1007/s10010-019-00382-1.

Weber, C. (2005) "CPM/PDD - An Extended Theoretical Approach to Modelling Products and Product Development Processes", *2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes*, 07.-08.07.2005, Fraunhofer-IRB-Verlag, pp. 159–179.

Weber, C. and Husung, S. (2011) "Virtualisation of product development/design - seen from Design Theory and Methodology", *18th International Conference on Engineering Design (ICED 11)*, Volume: 2. Kopenhagen, 15.-18.08.2011, Design Society, pp. 226–235.

Weber, C. and Husung, S. (2016) "Solution patterns - their role in innovation, practice and education", *14th International Design Conference (DESIGN 2016)*, Volume: Design Theory and Research Methods. Cavtat, Dubrovnik, Croatia, pp. 99–108.

Weilkiens, T. (2016) *SYSMOD - the systems modeling toolbox: Pragmatic MBSE with SysML*, 2nd edn, Fredesdorf, MBSE4U. 9783981787580.

Welzbacher, P., Schulte, F., Neu, M., Koch, Y. and Kirchner, E. (2021) "An approach for the quantitative description of uncertainty to support robust design in sensing technology", *Design Science*, vol. 7.

Wilking, F., Schleich, B. and Wartzack, S. (2020) "MBSE along the Value Chain – An Approach for the Compensation of additional Effort", 2020 *IEEE 15th International Conference of System of Systems Engineering (SoSE)*, pp. 61–66. DOI: https://doi.org/10.1109/SoSE50414.2020.9130497.