Towards the Concept of a Digital Green Twin for a Sustainable Product Lifecycle

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Abstract. Sustainability these days is required more than before. Resources are becoming rare goods, the pollution of air and water rises. Modern mechatronic systems consist of a high variety of components and materials and achieved high market penetration in recent years. As a result, the percentage of such systems of the total waste per year rises. The worldwide e-waste in 2019 made 53,6 million tons, an increase of 9,2 million tons, compared to 2014 (Global E-waste Monitor). That suggests that the problem of recycling gets more complicated and the risk of an increase of pollution will be higher in future. To handle this challenge, innovative concepts are required. The need of an efficient recycling must be considered much earlier than today. Lifecycle phases (Conceive, Design, Realize, Service, Reuse) show high efficiency in their procedures and tools, used to ensure quality and shorter cycle times. The aspect of sustainability today is not considered over the entire lifecycle. This paper highlights a concept, where different facets of a digital twin within the product lifecycle could create added value for the sustainability. A decomposition-simulation e.g., coming from development, supporting the recycling procedure, or a traceable data-model, including material-data of the product helping to identify the needed recycling steps. Therefore, the associated efforts of further facets in different steps of the lifecycle are compared to the benefit, given by a traceable application of a digital twin. This concept defines the Digital Green Twin, which is shown using consumer electronics industry as an example.

Keywords: Digital twin · Sustainability · Digital Green Twin

1 Introduction

Today the environmental and climate protection gets increasingly interesting for population [1, 2]. For two-thirds of humanity the climate and environmental protection is one basic challenge in future. The rising awareness for these topics is also reflected in

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legislation. One example is the directive for waste of the European Union from 2008 (directive 2008/98/EG) where the basics of product responsibility was defined. Accordingly, manufacturers are obliged to take back and dispose returned products after the use phase [3, 4]. Therefore, the need to design sustainable products over the entire product lifecycle arises in many companies to meet the increasing requirements of society and legislation.

At the same time, modern systems and products become more complex. Mechatronic and intelligent systems consist of different domain specific components like software, hardware or electronic. All components are integrated in these systems, so that the components of one single system already need to be recycled in different ways. Different plastics and metals e.g. must be recognized and separated. Different requirements, coming from user and market lead to a higher variety in modern products so that even one product has to be recycled in many ways regarding the varieties.

It is challenging to decompose the products and dissolve the materials in an efficient way. The recycled raw materials must be competitive with new materials regarding cost and quality. Recycling technologies need to be economically efficient to be attractive for companies [5]. The design of products and material compounds determine the complexity. Optimizing the recycling process is important to regain a large amount of the recyclable materials, such as metals and rare earths [6]. Due to the scarcity of resources, the raw materials become more valuable and the prices will increase. That makes it more important to close the loop for a sustainable circular economy [5]. However, the price development for recyclable materials is uncertain, which makes it difficult to calculate the recycling costs [7]. There is a huge potential for improvement in the development and optimization of recycling technologies [5, 7]. Beside the complexity of recycling processes, the amount of waste has to be taken into account. There are 2,01 billion tons of waste generated worldwide per year [8]. Innovative systems are characterized by mechatronic components. These systems belong to the electronic waste. The global E-waste monitor summarizes the total amount of waste each year [9]. For 2014, the monitor shows an amount of 44,4 million tons of E-waste, which made an amount of 6,4 kg per criteria. In comparison the amount of 2019 made 53,6 million tons of E-waste, which was 7,3 kg per criteria. It becomes clear, that the share of E-waste has increased by nearly 24% in the last years [9]. Furthermore, the monitor points out, that only 17,4% of this waste is recycled, what means, that 82,6% of the waste flows are not recycled or documented properly. The forecast shows an increase of the global waste amount with 74,7 million tons per year in 2030 [9]. Today's approaches and processes are overloaded by regarding these developments.

Summarized, there are different challenges to be faced. The rising complexity of systems, which goes along with variant materials and components, the rising amount of waste, and the actual recycling approaches should be reconsidered and thought in a sustainable way. As a first step, there is a need for transparency over the entire Product Lifecycle to identify sustainability potentials. This transparency is additionally demanded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [10]. Transparent product data should serve to optimize production, use and recycling of products in form of a digital product passport, which could represent a basis for a digital twin. The publication underlines additionally the need of innovative approaches for a holistic consideration of transparency in different phases of the product lifecycle. Therefore, this paper highlights the concept of the Digital Green Twin. Different facets of digital artifacts collectively form the twin, which creates added value for modern recycling processes. Based on the example of a refrigerator, these benefits are highlighted within a canvas for the Digital Green Twin. Different phases of the product lifecycle are considered, especially regarding the digital artifacts used within the phases.

2 Research Methodology and State of the Art

As part of the research methodology, the current state of the art was examined. In addition to a general literature review, first findings were identified using the literature database Scopus [11]. The first analysis shows that the Digital Green Twin is not yet a popular publishing field. In the last 20 years, no publication was found including «Digital Green Twin» in the search string (title, abstract, keywords). Only one publication from Fraunhofer IPK on a Sustainable Twin is to be mentioned. It deals with a «Life Cycle Sustainability Assessment by Means of Digital Lifecycle Twins» [12].

For this publication, a three-step approach was selected here. These results are shown in Fig. 1. In the first step, the results based on the search string «Digital Twin» were analyzed. This named term has to be included in the title, abstract or keywords. All publications entered in Scopus in the subject areas «Engineering», «Computer Sciences», «Energy», «Materials Science» and «Environmental Science» were examined. In total, more than 2700 publications on the topic «Digital twins» were published between 2000 and 2020. The number of publications has increased significantly, especially in the last three years (321, 912, 1324). 70% of these publications were in the subject area «Engineering».

In the second step, the analysis was carried out for the subject area «Circular Economy». More than twice number of publications (6765) were identified in the last 20 years. As for Digital Twin, there is also an increase but a smaller one in the last three years [1016 (2018), 1628 (2019), 2411 (2020)]. Only 37% of the publications were written in the subject area of «Engineering».

Of importance are publications that focus on both the «Digital Twin» and «Circular Economy» topics. The following word combinations were analyzed: «Digital Twin && Circular Economy» and «Digital Twin && Sustainability». The first publication on this word combination is found in 2017. Between 2017 and 2020, a total of 58 publications were published. 60% of these publications were placed in «Engineering».

The two essential aspects used in the analysis are the Digital Twin and Circular Economy. Therefore, the state of the art is examined in the following section.

Digital Twin: There is no unified understanding of the digital twin. Basically, the concept of a twin was first used by NASA, which used a twin-mockup of the rocket that flew to space. The twin was used to perform tests, based on the surrounding conditions of the rocket in space. The digital twin was defined by Grieves in 2003 at University of Michigan course on Product Lifecycle Management and published in various papers [13, 14]. Grieves defined the digital twin as a digital representation of tangible or intangible objects or processes, which are independent from the real object. This approach

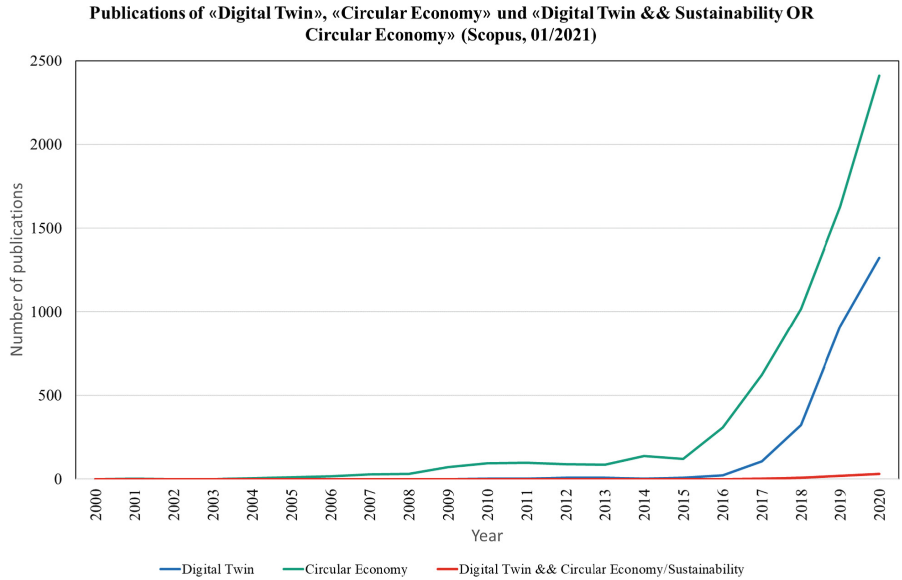

Fig. 1. Publications of «Digital Twin», «Circular Economy» und «Digital Twin && Sustainability OR Circular Economy» (Scopus, 01/2021)

distinguishes between the real and the virtual space. The digital twin consists of interconnected data and models. Data could be represented as system parameters, test data or other data that refers to the system. Models could be software- or simulation models or in case of approaches like Model Based Systems Engineering any others. In case of model-based development of mechatronic systems there are several examples, e.g. [15]. The virtual space is linked to the real space by extracting data, but the presence of the real space is not mandatory. In case of a development process e.g., the conception of the later product is often performed by using simulation models, before a real prototype is built. The vision of a digital twin is, that all the models and data are continuously and consistent linked over a products lifecycle, so that transparency and traceability are given. Chatti et al. provide another definition of a digital twin, that represents a digital image of a product and contains virtual models and data from various product lifecycle phases [16]. Applications of a digital twin could be the simulation or, as given by Uhlemann et al., the optimization of a production process. The different steps of the production are simulated and forecasted, so that logistic actions could be planned more precisely [17]. Further applications of digital twins in design are shown by Tao et al. [18], like real time data-acquisition during manufacturing based on the digital twin. Summarized, there are lots of applications of digital twins to optimize different phases of a product lifecycle. Common to all is the digital link between the artifacts, which create transparency and traceability.

Circular Economy: The concept of a Circular Economy is based on the idea of finite and limited resources and was first mentioned in 1989 by Pearce and Turner [19]. The intention of a Circular Economy is to set up a restorative or regenerative industrial system, which eliminates the production of waste and focusses on a renewable concept. Maintaining the value of products, materials and resources is the key aspect of a Circular Economy compared to a traditional linear economy [20]. Therefore, materials and products are recycled, reused, refurbished, and repaired as far as it is possible [19, 20]. This can be accomplished by using regenerative energy resources and leads to a minimization of waste [20]. By implementing a Circular Economy based on the cradle-to-cradle principle, the transformation towards an overall sustainable, resource efficient economy can be achieved. This also benefits the environment, due to less pollution of the waste [20].

3 Definition of a Digital Green Twin

Today there is no specific approach or definition for a Digital Green Twin in the state of the art. In the context of this paper, the following definition for a Digital Green Twin is proposed and used in reference to existing definitions for digital twins [13, 14, 16]:

> *The Digital Green Twin (DGT) is a digital image of a product or service. It contains and connects virtual models and data that include all important environmental and sustainability aspects from various product lifecycle phases. The goal of the DGT is to transparently present sustainability potentials and to optimize recovery processes.*

Considering the initial situation presented above, the overall objective of the concept is to design a DGT canvas, that faces the challenges shown. These can be derived from the fields of action digital twin and sustainability. Basically, there are three fields and associated goals:

Subgoal 1 - Use Cases of a DGT over the Product Life Cycle: For the expansion of future market services, the diverse use cases of a DGT must be identified and structured based on existing applications of a digital twin. Legal requirements and guidelines must also be considered. Knowledge about the technical possibilities of a DGT enables the derivation of feasible use cases. The analysis should cover all phases of the Product Lifecycle and consider the essential, current regulations and guidelines. The individual use cases are to be evaluated in terms of their requirements for corporate structures.

Subgoal 2 - Design of a Canvas: Based on the structured use cases, an architecture for an overall solution will be developed, which corresponds to a reference architecture for a DGT. Requirements of and synergies between the use cases will be derived for the technical realization. Components of the reference architecture are e.g. a data model as well as the necessary IT infrastructure.

Subgoal 3 – Procedure Model: Based on the use cases and the canvas, a process model is to be made available to interested stakeholders. This process model enables systematic guidance on the integration and implementation of the DGT in e.g. corporate structures.

In summary, this will lead to a more efficient, sustainable product creation process as well as a green Product Lifecycle. In particular, the benefits for recycling should be emphasized here. The concrete experience gained in implementing and integrating the canvas of the DGT forms the basis for further integration of sustainability potentials in the Product Lifecycle Management landscape.

4 Canvas and Procedure Model of Digital Green Twin

Based on the previously presented definition of the DGT, the following chapter shows a canvas of the DGT. For this canvas, existing approaches from the field of the digital twin, e.g. [21], are combined with sustainability aspects. Presented in Fig. 2, the individual processes or stages of a typical product life cycle form the basis of the canvas. The processes were selected based on ISO 24748-1 [22]. Existing IT systems and tools that are typically used in the individual Product Lifecycle stages in engineering are listed under these processes [23]. Thus, e.g., authoring tools such as a specific requirements management tool are used in the product design stage. The IT systems and tools described are used to generate results or outputs in the form of artifacts during the activities in the individual Lifecycle processes. For the requirements management example, a requirement list in Excel could be an artifact. In the final part of the DGT canvas, sustainability potentials are presented that extend the classic canvas of a digital twin. The sustainability potentials result from the consistent use of the virtual models and data of the individual product lifecycle stages. The specific potentials are documented in the form of fact sheets, in which single use cases are also described. A sustainability potential for the example of requirements management is, for example, the use of substance compliance data during the creation of requirements. Already in this early development stage, it can be ensured that only materials and substances are used that fulfill substance compliance guidelines.

Physical simulation, as part of the model-based development, is an effective approach for development processes. Within this approach there are physical models built from the system of interest. In case of this paper, the simulation of the refrigerator is performed by modeling e.g. the compressor of the heat pump, the thermal simulation of the cooling behavior or the logical simulation of the control software. All these sub-models are simulated within a system-simulation, to analyze the interactions of the different components of the refrigerator. These physical models, as part of the digital twin already contain system parameters and material properties of the refrigerator, which could create added value for the recycling process and shorten the recycling steps The refrigerant e.g. does not have to be identified before recycling, when adding the simulation models to the Digital Green Twin. Some of these models must be enriched with further information. This could evoke additional effort in the development phase, but simultaneously optimize the recycling. The effort of adding information to simulation models is slight, compared to the benefit for recycling, and most of the information is already included. In this example, the simulation models from the development process already contain material data and fluid data, which could be used without additional effort. Using this information e.g. saves the time for the recycler to find out which material used.

Further aspects of the DGT are artifacts of the integration phase. Verification and validation deliver a lot of test data, which could enhance the DGT. The refrigerator is

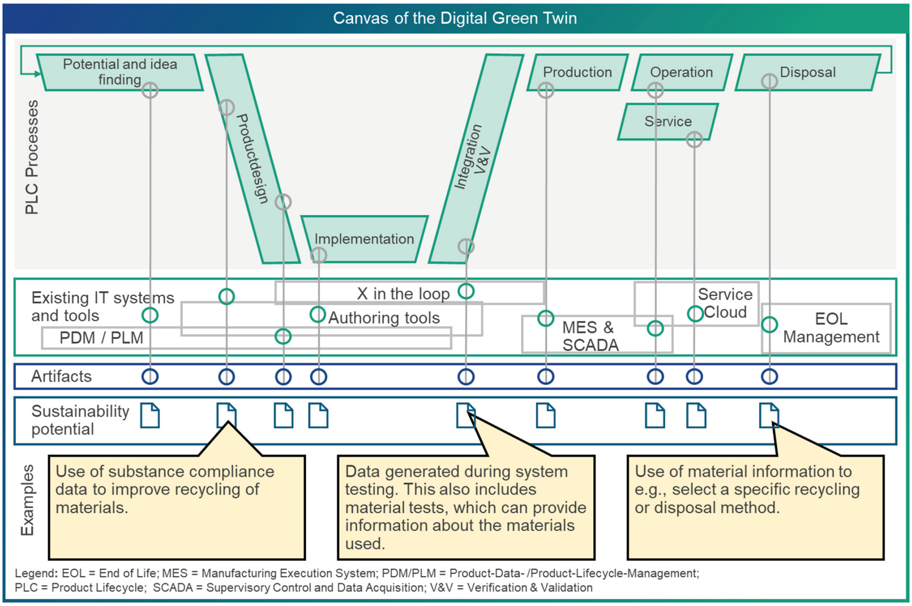

Fig. 2. Canvas of Digital Green Twin based on [20]

subjected to different tests. Mechanical tests, where the mechanic parts like the movement of the door and the handle are tested. Mechatronic tests also deliver a lot of data, like a Hardware-in-the-Loop test [24], which could be used. Furthermore, the materials are tested, often in form of long-term tests und various conditions. These tests and results provide information, which could be integrated in the DGT. Material data is, as said, the most beneficial information for recycling and simplifies the process. When producing modern products, the bill of materials (BOM, mBOM, xBOM) often is used to describe the parts, which have to be assembled. These lists and the assembly instructions of the products are further artifacts, which bring time-benefit for recycling by adding them to the DGT. Today there are assembly simulations, used to simplify the assembly. These simulations often originate from design phase, based on the product structure. In case of the refrigerator the mounting of each component could be simulated and visualized. These simulations could also be used beneficially in recycling. The model enables to perform disassembly-steps, so that the refrigerator could easily be disassembled into the different components, the compressor, the door, the insulation etc.

These examples given already show, how different artifacts could offer added value for recycling. To reach a holistic approach for integrating a DGT, the canvas for the DGT offers a structure to gather the necessary information and elements. Furthermore, to implement the DGT, a procedure model is required. This procedure model supports the detection of potentials and the implementation of a DGT.

The procedure model for the development and integration of a DGT is shown in Fig. 3. It consists of four phases in a sequential order with specific tasks and a defined result in every phase. This procedure leads to a DGT, which can be approached step by step.

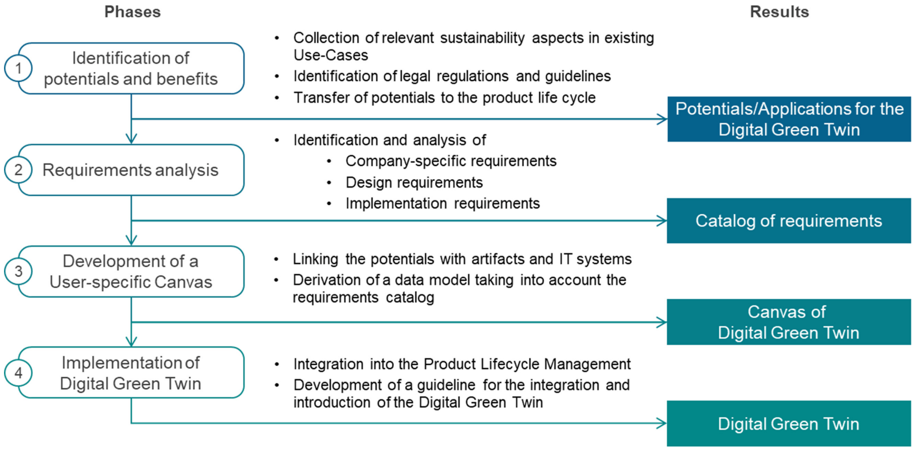

Fig. 3. Procedure model for development and integration of Digital Green Twin

Phase 1 – Identification of Potentials and Benefits: The process starts with the identification of potentials in existing use cases and benefits, where future applications, operations and values of the DGT are considered. The relevant sustainability aspects are collected, and all legal regulations and guidelines must be identified in the first phase. The potentials are transferred to the Product Lifecycle and as a result the applications of a DGT are defined.

Phase 2 – Requirements Analysis: In the next step a requirement analysis is done by identifying and analyzing the company-specific requirements, the design requirements and the implementation requirements, which result in a catalog of several requirements.

Phase 3 – Development of a Canvas: Afterwards a canvas of the DGT is developed by linking the applications with artifacts and IT Systems. A data model is derived with consideration of the requirements catalog.

Phase 4 – Implementation of Digital Green Twin: The DGT is implemented in the final phase, where it is integrated into the Product Lifecycle Management. Besides a guideline for the integration and introduction of the DGT is developed. By going through the whole process, the DGT can be obtained, considering all relevant features in all phases.

5 Summary and Conclusion

The paper introduces the Digital Green Twin as a concept to optimize future processes with. The main idea of the DGT is to regard the entire lifecycle of products and especially the digital artifacts being used within the different phases. These artifacts are analyzed regarding their added value for recycling. Furthermore, the paper delivers a guideline in form of a canvas for the DGT and a procedure model for the development and integration of the DGT in existing processes. With the help of the canvas, data and information from the existing artifacts can be identified and used for sustainability purposes. They could be represented as parameters, test data or simulation models. These artifacts enhance the recycling process, without generating a lot of further effort. The canvas could be used to analyze and visualize the different potentials in the actual Lifecycle and to develop a company-specific canvas, which shows the DGT for a specific Lifecycle. The procedure model supports the implementation of the DGT, defined within the canvas. All these aspects provide a fundamental basis to optimize modern Product Lifecycles with regard to recycling, which gets more important in today's products and systems. Further work could be focused on the implementation of single use cases, where the aspects of effort and benefit are each quantified in detail. This could exemplarily be shown within a simulation of a decomposition process, where simulation models from the development process are used.

References

1. Umweltbundesamt: Environmental awareness in Germany. https://www.umweltbundesamt.de/en/topics/sustainability-strategies-international/environmental-awareness-in-germany. Accessed 17 Jan 2021
2. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU): Umweltbewusstsein in Deutschland 2018 - Ergebnisse einer repräsentativen Bevölkerungsumfrage, Berlin, May 2019
3. European Union: REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC, European Union (2006)
4. European Union: DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on waste, European Union (2018)
5. Stolle, T.: Zukünftiges Abfallaufkommen von Photovoltaikmodulen. Materialfluss- und Reifegradanalyse für das Recycling, pp. 80–83. Diplomica Verlag, Hamburg (2016)
6. Kausch, P., Bertau, M., Gutzmer, J., Matschullat, J.: Strategische Rohstoffe — Risikovorsorge, pp. 164–168. Springer Spektrum (2014)
7. Hoyer, C.: Strategische Planung des Recyclings von Lithium-Ionen-Batterien aus Elektrofahrzeugen in Deutschland, pp. 71f. Springer Gabler (2015)
8. Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F.: What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development. World Bank, Washington, DC © World Bank. License: CC BY 3.0 IGO (2018). https://openknowledge.worldbank.org/handle/10986/30317

9. Forti, V., Baldé, C.P., Kuehr R., Bel G.: The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam (2020)
10. Kammerer, F., Schäfstoß, N., Röw, M.: Digital Policy Agenda for the Environment. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) Division for Public Relations, Online Communication and Social Media, February 2020
11. Scopus abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings. https://www.scopus.com/search/form.uri?display=basic&zone=header&origin=#basic. Accessed 15 2021
12. Riedelsheimer, T., Neugebauer, S., Lindow, K.: Progress for life cycle sustainability assessment by means of digital lifecycle twins – a taxonomy. In: Kishita, Y., Matsumoto, M., Inoue, M., Fukushige, S. (eds.) EcoDesign and Sustainability II, pp. 329–346. Springer, Singapore (2021)
13. Grieves, M.: PLM-Beyond lean manufacturing. In: Manufacturing Engineering, vol. 130, p. 23. SOC MANUFACTURING ENGINEERS (2003)
14. Grieves, M.: Digital Twin – Manufacturing Excellence through Virtual Factory Replication (Whitepaper). LLC (2014)
15. Holtkötter, J., Michael, J., Henke, C., Trächtler, A., Bockholt, M., Möhlenkamp, A., Katter, M.: Rapid-control-prototyping as part of model-based development of heat pump dryers. In: 4th International Conference on System-Integrated Intelligence (2018)
16. Chatti, S., Tolio, T.: CIRP Encyclopaedia of Production Engineering. The International Academy for Production Engineering, pp. 5–18. Springer, Berlin (2020)
17. Uhlemann, T.H.-J., Lehmann, C., Steinhilper, R.: The digital twin: realizing the cyber-physical production system for industry 4.0. In: The 24th CIRP Conference on Life Cycle Engineering. Procedia CIRP **61**, 335–340 (2017)
18. Tao, F., Liu, A., Hu, T., Nee, A.Y.C.: Digital Twin Driven Smart Design. Academic Press, Elsevier (2018)
19. Delchet-Cochet, K.: Circular Economy: From Waste Reduction to Value Creation, pp. 3–5. Wiley (2020)
20. Mavropoulos, A., Nilse, A.W.: Industry 4.0 and Circular Economy: Towards a Wasteless Future or a Wasteful Planet?, pp. 75–78. Wiley (2020)
21. Rasor, R.: Der digitale zwilling: anwendungsbereiche, architektur und technologien. In: OWL VIPROSIM E.V., 14. Fachtagung Virtual Prototyping and Simulation, Paderborn (2020). https://www.owl-viprosim.de/veranstaltungen-viprosim/fachtagungen/fachvortraege-der-14-fachtagung-virtual-prototyping-simulation/. Accessed 26 Jan 2020
22. ISO/IEC/IEEE 24748-1:2018: Systems and software engineering - Life cycle management - Part 1 - Guidelines for life cycle management (2018)
23. Eigner, M., Koch, W., Muggeo, C.: Modellbasierter Entwicklungsprozess cybertronischer Systeme. Springer, Heidelberg (2017)
24. Millitzer, J., Mayer, D., Henke, C., Jersch, T., Tamm, C., Michael, J., Ramisch, C.: Recent developments in hardware-in-the-loop testing. In: Conference & Exposition on Structural Dynamics (2018)