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"Towards shifted production value stream patterns through inference of data, models, and technology"

Shifting value stream patterns along the product lifecycle with digital twins

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Abstract

The concept of digital twins promises high potentials for product design, manufacturing, user experience and recycling. Thus, digital twins have received increasing interest in academia and industry. However, the actual benefits of digital twins remain in many cases unclear. This article aims to summarize selected recent developments in this field and demonstrate use cases from different phases of the product lifecycle. For that purpose, examples from the design, manufacturing, use and recycling phase are presented. In a subsequent discussion, ideas for new value stream patterns using digital twins are envisioned and research questions are derived.

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Keywords: Digital twin; Cyber-physical systems; Design; Manufacturing; Recycling

1. Introduction

Over the last 25 years information and communication technologies have shaped industrial production and drastically shifted production value stream patterns. For example, computers and simulation systems in product development and process planning have become state of the art. More recently, new and inexpensive sensors as well as almost unlimited data storage and processing capacities have unlocked new ideas for data retrieval from manufacturing and usage of products. In this context, the term "digital twin" is often used and connected to substantial promises regarding higher efficiency in product design, manufacturing, or user experience. A survey on Elsevier's Engineering Village reveals that the term has also received a drastic increase of attention since 2016 in academia. However, the actual benefits of such digital twins remain vague and only few actual use cases can be found. This observation is supported by an analysis on emerging technologies by Gartner [1]. According to the findings, digital twins are currently in a stage of inflated expectations. Thus, further research and development activities are necessary to establish a solid technological framework for digital twins. Moreover, business

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cases for digital twins must be developed and widely disseminated.

This article aims to highlight different research activities of the authors and discussions within the CIRP Research Affiliate Network regarding digital twins and their influence on future production value streams. For that purpose, selected definitions of the digital twin are reviewed and enabling technologies are briefly summarized at the beginning. Next, examples of the application of digital twins in different stages of the product lifecycle, e.g., design, manufacturing, usage and recycling, are presented. Subsequently, potential future use cases and emerging value stream patterns across the product lifecycle are discussed and open research questions are identified. While the reviewed literature in this article represents only a fraction of research activities around the world, the addressed aspects from different perspectives of the lifecycle and the drawn conclusions can serve as starting point for future research activities.

2. Definitions of digital twins

Enabled by the vast development of modern sensor, information, and simulation technologies, such as cyber-physical systems (CPS), high fidelity simulation models, the (industrial) internet of things, and driven by the need for reducing the product development lead-time and for increasing the product quality, digital twins have emerged as a key technology for modern design and production engineering workflows. In this regard, due to various application areas, different understandings and definitions of a digital twin have been proposed in research and industry.

The first definition was probably established by NASA, which has been adapted in [2]: *"A digital twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin"*. Sharing some similarity to the previous definition, Grieves et al. define a digital twin as *"a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level"* [3].

However, with the aim of bridging the gap between these partially diverging understandings, the International Academy for Production Engineering CIRP defines a digital twin as follows: *"A digital twin is a digital representation of an active unique product (real device, object, machine, service or intangible asset) or unique product service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions and behaviors by means of models, information and data within a single or even across multiple lifecycle phases"* [4]. In the following, we refer to this definition. In addition to that, a reference model for the digital twin has been proposed in [5].

3. Enabling technologies

The technology of the digital twin is closely connected to several emerging technologies. Especially, simulation systems, communication technologies and the concept of CPS can be considered as core enabling technologies for the digital twin.

CPS are a key concept of Industry 4.0 architectures and a technical evolution of mechatronic systems. Mechatronic systems combine elements of mechanics, electronics and computer science. Additionally, CPS are equipped with sensors to collect data, actuators to act on their environments and an embedded system. An embedded system is a microcomputer with computing power and an IP-address giving the CPS an identity and the ability to store and process data (see Fig. 1). Several CPS can be connected with each other via a data infrastructure – typically the internet – to communicate independently and coordinate themselves. By connecting several CPS in a production environment, so-called cyber-physical production systems (CPPS) are created [6]. A detailed description of CPS and CPPS can be found in [7] or [8].

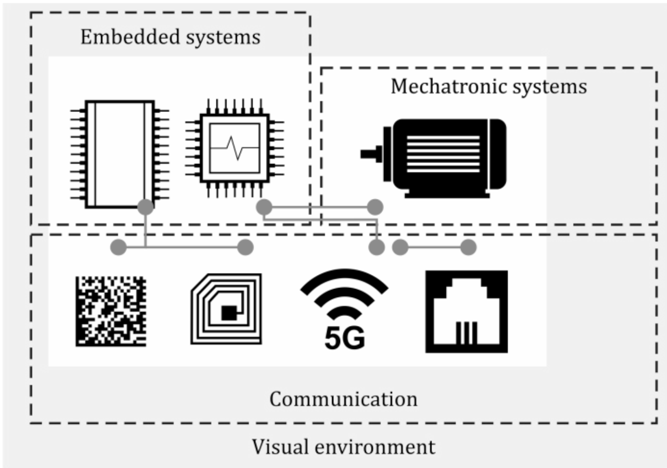

Fig. 1. Components of a cyber-physical system [9]

The decentralized data collection and processing by CPS is necessary to create a digital twin, which further processes the data – of several CPS – centrally [9]. Key problems are to acquire, transfer, store, protect and analyze relevant information. This requires a combination of dedicated hardware and software solutions. With respect to data transfer, 5G communication standard is expected to overcome current issues regarding bandwidth, latency, resilience and scalability to support multiple devices [10].

Based on the data provided by CPS, simulations can be run with a digital twin to test different scenarios [11]. This way, a digital twin assists in predicting the behavior of the CPS [12]. Moreover, it has been argued that *"from a simulation point of view the digital twin approach is the next wave in modelling, simulation and optimization technology"* [11].

Banks et al. define simulation as *"imitation of the operation of a real-world process or system"* [13]. In general, the evolution of physical quantities or entities of interest is simulated over time, but other physical domains are also possible. The simulation models express mathematical, logical, and symbolic relationships between the entities, or of interest for a specific system. These models are an idealized representation of the physical reality and therefore strongly depend on the intended use of the simulation model [14].

With respect to the product lifecycle, different stages can be distinguished (see section 4) and a vast amount of different simulation technologies has emerged for each of these stages over the last decades. In this regard, the fidelity of the simulation tools steadily increases, which enables a deeper understanding of the effects of product and process design decisions on the product behavior in use. However, it is widely acknowledged that the digital twin is not one complete model, but a set of linked operation data artefacts and simulation models, which must be chosen of suitable granularity for their intended purpose and evolve throughout the product lifecycle [15]. Consequently, simpler models may be used for deciding about the product concept, while sophisticated simulation models support the actual product design or manufacturing.

The amount of data generated by digital twins is huge and requires powerful methods of data processing. A promising approach are models based on artificial intelligence (AI). While many methods in AI, like neural networks, are known for quite some time, more computing power has given the technology a boost. AI models can be part of cloud/distributed computing or directly be embedded in robots, vehicles and other physical objects to ensure security and local processing of private data. In the distributed systems, it is important to assure that the data cannot be compromised. Data protection can for example be achieved with blockchain technology [16]. Besides, digital twins may benefit from other advantages of blockchain, such as traceability of events recorded during the entire lifecycle, smart contracts (small software snippets) automatically executed to invoke, for instance, maintenance or supply chain transactions.

4. Use cases of the digital twin over the product lifecycle

This section focuses on specific use cases and resulting benefits of the digital twin along the product lifecycle. The section is structured following the three phase product lifecycle model [17]. This systematic is commonly used in the engineering domain and splits the overall lifecycle in three distinct phases: Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL) [18, 19, 20] (see Fig. 2).

For the focal topic of this paper, digital twins, we decided to split the BOL phase in two sub-categories – the design (section 4.1) and the manufacturing (section 4.2) phase – because there are distinct differences, when it comes to applications of the digital twin and potential benefits. Furthermore, there is an increased interest in industry to utilize digital twins in these areas. Although manufacturing includes a wide range of different processes, we will focus mainly on machining operations. The MOL phase is reflected in section 4.3. Section 4.4 concludes the chapter with a discussion about the use of the digital twin in recycling (EOL).

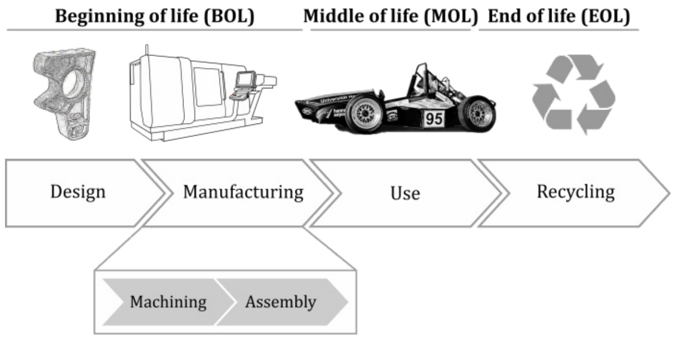

Fig. 2. Phases of the product lifecycle

4.1. Design phase

For product development, the concept of the digital twin exhibits new functionalities of data and information in which behavior (in its broadest sense) of an actual product can also be allotted to a virtual system [21]. In this context, the concept of digital twins strongly exceeds established virtual simulation and product presentation models by providing a bi-directional and entangled connection for data sharing between the virtual and the real product, system, or service [5]. This offers numerous opportunities to improve and optimize products and the corresponding manufacturing systems. Digital twins basically widen the set of tools and techniques for design and unremittingly connect digital representations of both product definitions and their manufacturing environments [22]. For product design and development, the added value of the digital twin is in this combination of various digital representations. Establishing the link between products, product types, production tools, environments, and processes, will render a coherent overview of the development cycles of products and production environments.

A distinction is made between digital representations of the actual and the desired situation. All digital representations, data and information that together shape a digital copy of the actual definition and status of the manufacturing environment are labelled as a digital twin. All information, data and virtual representations of the product definition express the desired status and are seen as the so-called digital master. Between the digital master and digital twin, a set of digital prototypes can be established that test or predict (from simulation to what-if analyses) the consequences of development decisions in a structured manner, for different levels of aggregation and for different stakeholders [23]. Here, different fields of expertise are integrated for conjoint, well-considered and well-underpinned decision making. This not only yields better products, but especially also more adaptive and effective (production) environments and a more flexible alignment of the two. Moreover, the development cycle in itself will improve by learning from the aggregate knowledge obtained. Likewise, the digital master/twin environment will serve as a learning factory in two ways: firstly, employees of the future can be trained/educated based on the real, but also on the digital model of the solution, but secondly, the solutions can learn (i.e., be improved) based on how they are used (either in reality or based on digital prototypes).

However, the most added value of using digital master/twin combinations, is that all stakeholders, from client, via developer to operator are supported with relevant, timely, tailored, purposeful and adaptive information with the appropriate perspective at the right level of detail/aggregation. This allows the employee of the future to understand and interact with the entirety of available information in a meaningful manner. Moreover, the digital solution that will be developed will present them with the design rationale of the development cycle, thus facilitating decision making. Moreover, the digital twin and its data and information backbone allow for product, system and service optimization with real-time feedback.

Essential in this is the development of adequate ways of presenting and accessing the large amounts of information that constitute the digital twin. This addresses the perspective-dependent representation of information, rendering (parts of) the information in a meaningful manner to the appropriate stakeholder. For this reason, the development of a structured way to establish a data analytics framework (also referred to as a 'virtual dashboard') is foreseen, enabling different stakeholders to be facilitated in multi-criterion and multi-stakeholder decision making and control by providing tailored yet adaptable and flexible insight in the information that underlies decisions [24, 25].

In tolerancing and geometrical variations management, which comprises all activities related to controlling geometrical part deviations and their effects on the product quality [26], digital twins have been identified as an enabler for exploiting vast efficiency potentials [27]. In this regard, a digital twin for real-time geometry assurance in individualized production has been proposed in [28], which is fed by inspection data [29] and allows quality improvements by different optimization approaches for example of welded components [30].

In order to integrate information from different phases of the product lifecycle into the design phase, the concept of technical inheritance was introduced by Lachmayer et al. [31, 32]. Therefore, assembled and verified information from production and application of a previous product generation are transferred to the next generation [33]. Thus, product requirements are concretized and the development and production are more efficient with every generation.

Other examples for the use of digital twins can be found in the design and reconfiguration of smart products [34]. Here digital representations using CAD, CAM and service models are integrated offering semi-automated reconfigurations of smart products. With enabling technologies such as big data and AI, the use of digital twins as enabler have been demonstrated in creating autonomous systems [11].

The potential of such rich representations and new use of software strongly extends the potential functionalities of traditional PLM. Moreover, its implications and possibilities of digital twins for design, manufacturing and service are investigated in [35]. The authors signal that many new technologies ranging from management and use of big data, flexible, agile and networked production and cloud computing find their way into PLM, but the possibilities of virtual representations are not yet available or integrated. With digital twins there is a growing need to support a full integration of new knowledge representations of the product definition [36].

4.2. Manufacturing phase

Increasing individualization of products and sophisticated manufacturing processes require efficient process planning. By collecting manufacturing data and predicting product quality, digital twins can improve decision making in the manufacturing phase. A classification of available literature on digital twins in manufacturing can be found in [37]. In the following, we highlight some additional applications of digital twins in machining and assembly.

4.2.1. Machining

Machining processes with CNC-machine tools are usually planned with CAM-systems. While most of these systems verify the planned toolpath in order to avoid collisions, they are not designed to predict process quality in terms of product quality. Thus, NC-simulations, which consider the actual dynamics of a machine tool, have gained more interest in academia and industry, recently. The information from the NC-simulation can be used to predict the machining result and to optimize the process before start of production. Fig. 3 shows an exemplary application of a virtual machining process in blisk re-contouring. Altintas et al. [38] reviewed several examples for the use of virtual machining for process optimization. However, the accuracy of virtual machining process is closely related to the quality of the digital twins of the machine tool and the applied tools. In this regard, Botkina et al. [39] presented a concept how to represent cutting tool data and exchange it based on ISO 13399 standard. With respect to the machine tool model, Luo et al. [40] stated that weak coupling between different virtual machine modules, insufficient interfaces and varying levels of detail lead to rather inconsistent virtual representations. In addition, static and dynamic process conditions or clamping failures affect the simulation accuracy.

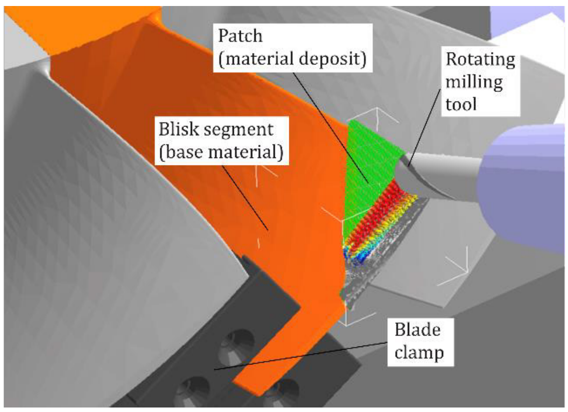

Fig. 3. Exemplary representation of the process simulation [41]

Despite careful planning, machining processes are characterized by variations, e.g., tool wear, varying cutting conditions or material properties. Moreover, axis interpolation and the actual dynamic behavior of the machine tool bring additional uncertainties into virtual machining processes. Consequently, there is often a difference between the product "as planned" and "as machined". The digital twin can help consolidate data from process planning, machining and quality control to improve manufacturing and enable a self-optimization of the machining process (Fig. 4).

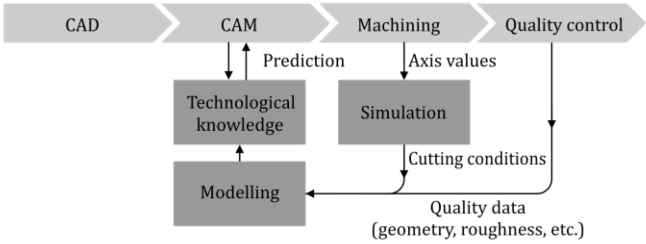

Fig. 4. Feedback loop for self-optimization of machining processes [42]

For that purpose, a digital representation of the workpiece is enriched with data from the process and quality control, like force measurements and geometry measurements. A process-parallel simulation allows connecting these measurements to locally resolved cutting conditions [43, 44]. As a result, an accurate representation of the cutting conditions and the machined workpiece is possible without a control model of the machine tool. An example for the application of virtual machining for online process control and monitoring can be found in [45]. Brecher et al. [46] applied a process-parallel machining simulation to carry out a digital quality control. Krüger and Denkena [47] calculated the surface roughness directly from process forces and a process model in end milling. In this way, an online quality control using a digital twin was achieved. Besides predicting the process result, the digital twin can also be used to close the feedback loop as shown in Fig. 4. Dittrich et al. [42] presented an approach for a self-optimizing process planning procedure in 5-axis milling. Besides optimizing process planning, the obtained production data can also be used to evaluate the product function. Haefner et al. developed an evaluation of the lifetime characteristics of high-precision gears based on measured production data using a functional product model [48, 49].

4.2.2. Assembly

As an application of a digital twin in assembly, Lanza et al. [49] developed a digital twin to systematically analyze various production strategies by means of adaptive manufacturing and selective assembly based on real-time data. The application of digital twins opens up the possibility for individualized assembly of parts, thus, increasing the geometrical quality of assembled components and products. In this regard, an approach to individualizing locator adjustments of assembly fixtures employing digital twins has been proposed [50]. Beside this, Aderiani et al. [51] presented a digital twin for sheet metal assemblies. These works are built on an information and simulation framework [30] and a digital twin for real-time geometry assurance [28]. In order to use the potential of digital twins in assembly, the acquisition and integration of real-time data from the entire production system is crucial. These data are often gathered along with the quality control system of the production system. For this, various sensors are to be integrated in-line into both the assembly and the aforementioned machining processes. In order to horizontally connect these data, IT systems such as Manufacturing Execution Systems (MES) and Computer-Aided Quality (CAQ) systems can be used. Based on this, the current status of the real-world system can be evaluated. Feeding these data into the digital twin, the current system performance can be systematically analyzed, and various options for improvement can be simulated. Particularly, a functional model of the product can be even involved in these evaluations as shown by [48, 49]. Wagner et al. [52, 53] demonstrated how models of the production system and the product function can be integrated in a common digital twin to select optimal production strategies my means of adaptive manufacturing and selective assembly in a function-oriented way. To enable function-oriented analytics in real-time, suitable meta-model can be applied for this.

4.3. Product use phase

The maximization of equipment availability at a minimum cost is one of the key challenges in many industry branches, e.g., aerospace industry. Therefore, maintenance, repair and overhaul (MRO) operations have become crucial especially for high-value products. Some of the key challenges emerging are [54]:

- A range of requirements to sustain availability for a variety of complex tasks on a large variety of complex systems.
- Diagnosing the equipment health status proactively with minimal resources.
- Making sure that quality requirements are achieved.

In order to overcome these challenges, new ways of communication and gathering data must be found, avoiding the current issues encountered in the MRO industry. Digital twins are emerging as an enabler for these. In the age of globalization and digitalization, many industries have evolved from a physical space information flow towards a two-way communication between virtual and physical space. The literature is increasingly paying attention to how a virtual system can adjust itself to the constantly changing conditions of the physical space of information that influences the operation dynamics of the MRO requirements [55]. There are multiple uses of digital twins at various points in the product lifecycle to help develop, design and certify a product. Some of the advantages given by [2] for the in service phase of the product are as follows: life cycle management (e.g. evaluation of modification effects), health management and predicting or extending the use phase.

Health management looks at the remaining life of the asset and determines when the asset will fail [35]. This system collects, and correlates data obtained from sensors all over an asset and provide predictions (e.g. the remaining life of components before failure). For example, Quirico et al. presented in [8] an approach to evaluate the condition of a product based on lifecycle data and fatigue modelling. Another example is given by Cerrone et al. [56]. They discuss the creation of Finite Element Modelling (FEM) to more accurately predict cracking on specific components. Also, they looked at ways of specifically modelling and simulating as manufactured components and how cracks can propagate.

The digital twin can also support the assembly and disassembly processes in MRO as shown by Grieves and Vickers [3]. They demonstrate how a digital twin can be used to overlay an existing physical product in order to locate specific assemblies and components and then bring up a series of menu options. It then provides instructions on how to use the product, how to maintain it, and how to troubleshoot faults. This also achieved with animations to aid instructions overlaid onto a physical product.

Although some example already exist in recent literature, the use of digital twins during a product's use phase is still in its infancy and further research is needed in a number of areas. One area is related to the implementation of intelligent digital twins, which implies autonomous twins that do not require human input (autonomous). Another area is the application of digital twins for multiple complex products, which refers to utilizing digital twins for multiple objects rather than a single object (scalable). For example, a digital twin could be used to monitor a whole fleet of aircrafts. Data from each individual aircraft can be used to identify faults early and determine which of the other aircrafts may experience similar problems. Thus, reducing time and risk of manually assessing all aircrafts within the monitored fleet. The gained insights can also be used to improve the product design or its manufacturing process. Furthermore, using a digital twin to monitor large-scale processes such as a supply network and monitoring assets within the supply network can be beneficial to improving all areas of a company. There is also a need to enhance research in predictive analytics, as well as augmented reality applications that are integrated with the digital twin.

4.4. Recycling phase

The EOL phase describes the final part of the lifecycle when a part or product can no longer be used as intended by the user. While recycling is a major aspect of EOL applications, there is a distinct hierarchy of actions with regard to their sustainability with reuse/ remanufacture, and recycle at the top and disposal/landfill at the very bottom [57]. Reuse/remanufacture and recycling operations are fundamental for a functional circular economy and in reality are often used in a cascading structure, either on the product/system- or part-level [58]. Over the full term of a product's lifecycle, there may be several cascade levels, where selected parts remain at certain levels for lifecycle iterations, other parts enter alternative lifecycles [58]. We have to keep in mind that when we look at the critical decision of reusing or recycling a product or part, this is most likely product dependent [59]. This is a key aspect for digital twin applications during the EOL, the item-level access to information and data over the whole use history of the product or part. This enables not only the better decision whether or not a part or product can be reused as is or remanufactured, but also to identify alternate uses in another cascade level. While to the authors' knowledge, digital twin applications during the EOL are still rare, we will briefly illustrate to potentially value adding cases describing how digital twins can enable a more sustainable use of resources in a circular economy sense.

First, when we think of a complex system such as an automobile with several components that are individually worn during the use phase depending on a variety of factors, e.g., climate (winter or desert), main mode of use (highway or city), etc. Today, this is posing a problem when it comes to reuse decisions for some of the parts. While suspension control arms for example can be remanufactured and reused well [58], other components, especially with electronics are more difficult, and costly, to evaluate. Furthermore, the access to the information and data is directly dependent on access to the physical asset. This makes it harder to access for an efficient marketplace that is required to make reuse and remanufacture economically feasible. In this regard, the digital twin could help to reduce warranty and liability issues in re-manufacturing. A digital twin of the car could potentially address these issues and enable a higher percentage of high-level EOL operations, contributing to the sustainability goals of all major markets. Additionally, an added benefit of a sophisticated digital twin model, is that it will provide access to the components materials used and bill of material (BOM) as well. While a digital twin is probably an overkill for such an application by itself, it nevertheless will most likely enable more effective recycling decisions and operations.

A second problem is set in the heavy machinery industry but is most likely applicable in machine tools or special machines domain as well. Heavy machinery have generally a very long lifecycle and are often used in a variety of applications and used by different owners/users. Over the lifecycle, they might come in contact with materials that pose a contamination threat. An extreme example may be an excavator that operated in a uranium mine. For effective and safe reuse of such systems and their parts, having a seamless history of use and part origins via digital twin may enable a better management of these equipment.

5. New value stream patterns across the product lifecycle

Driven by the developments of different core enabling technologies, the increasing entanglement of (sensor) data from the real world with simulation models from the virtual world offers significant potentials in various applications and use cases along and across the product lifecycle. Based on the technologies and use cases presented in chapter 4, we attempt to envision new value stream patterns for the different stages of the product lifecycle individually, but also across the entire lifecycle as a whole.

During the beginning of live, in the design phase, the development of digital twins for assets, services, and products is a novel business opportunity for engineering departments or specialized service providers, thus offering and selling adaptive information carriers to asset operators. Moreover, the need for knowledge transfer regarding digital twin development, digital twin standards (such as planned IEEE and ISO initiatives), and digital twin operation structures (see sec. 3 on enabling technologies) will lead to new value streams in consulting, training, and education and beyond. New business models that integrate formerly internal functions such as design and manufacturing with customer facing functions are enabled through digital twins, impacting the customer order decoupling point. On the other side, this offers opportunities in form of earlier lock-in of customer and reduction in overhead when it comes to managing customer driven changes in requirements.

The use of digital twins in manufacturing offers several opportunities for process optimization and new value streams. While machine tool manufacturers already sell virtual machines for process simulation, new business models may arise from using the digital twin as soft sensor in manufacturing. By this, additional data, which cannot be measured directly or only at high cost, such as workpiece temperatures in machining or cutting conditions, can be obtained and utilized for process optimization and advanced predictive hybrid analytics models. Moreover, new value streams can for example arise from selling the operations data to machine tool manufacturers and/or tooling companies to enable product optimization based on accumulated real usage data of their products.

With respect to digital twins of produced workpieces, one can think of digital quality control as a new product offerings for manufacturers of measuring instruments. The digital workpiece twin enables also a more sophisticated process chain control. Assuming an individual digital twin for each workpiece at the shop floor, all upstream process information could be included for process planning of the next manufacturing process. An example for this is the process chain in additive manufacturing. Usually, these processes require post-processing to ensure high quality requirements. A digital twin of the workpiece as built supports process planning of a subsequent machining process and reduces planning uncertainties. Similarly in a subtractive process, such as 5-axis milling, the as-planned time differs in most cases from the actual production time true to differences in actuators, servos, etc. Provided the digital twin communicates the current state in real time, the MES system can be updated in real time to provide a more accurate prediction of the completion time.

In usage and operation, digital twins foster the shift towards the operator model by allowing condition monitoring and health management and thus a more accurate availability prediction of assets. New non-ownership business models depend on access to data of the asset and thus require a form of digital twin as their raison d'etre.

Beside this, new value streams will emerge in recycling and remanufacturing making use of the seamless product history stored and made available in digital twin information packages.

Figure 5 summarizes the discussed applications of the digital twins and potential benefits. While the discussed applications focus mostly on a single stage within the product lifecycle, a fully integrated digital twin would allow to determine its current state and predict its functionality at every stage in the product lifecycle. In accordance to the actual product, the digital twin would evolve over time to different stages, which could be named "as planned", "as built" and "as used" (Fig. 5). Thinking beyond the lifecycle of one product, the obtained data can then be used to optimize future product generations or processes.

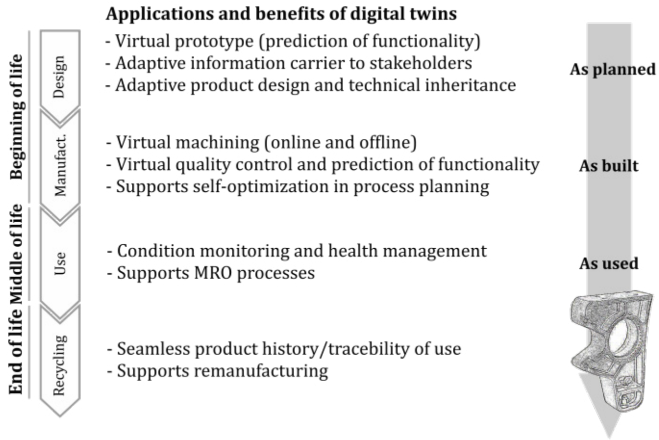

Fig. 5. Applications and benefits of the digital twin at different stages of the product lifecycle

In order to create new value streams from using the digital twin, we postulate some research challenges for design and production engineering:

- The development and application of holistic digital twins requires the work and expertise of many actors along the product lifecycle. These different experts must move towards each other and work in interdisciplinary teams to fully exploit the potentials of digital twins. This is, in fact, not only a technical, but also an organizational challenge.
- The connection and crosslinking of data and information from all stages of the product lifecycle requires sophisticated data formats or data packages, which allow a coherent transfer of all kinds of information through standardized interfaces. For example, enhanced CAD models could help to transfer information on the required surface integrity or tolerances to manufacturing.
- A higher level of sensor integration is necessary to monitor the product condition more closely and update the digital twin continuously.
- In order to ensure fast computation, combinations of different simulation techniques (hybrid modelling) as well as adaptive and scalable simulation methods must be further developed. In this context, it is also necessary to investigate the required granularity of modelling.
- In most cases, optimization has been limited to separated stages of the product lifecycle. In order to fully exploit the potential of digital twins, optimization procedures, which integrate all stages of the lifecycle and allow identifying global instead of local improvements, must be developed.

6. Conclusion

The concept of digital twins has received increasing attention recently. Though, actual use cases in industry are rare. Based on a brief discussion of different definitions and emerging enabling technologies we presented selected examples of digital twins and their usage in different stages of the product lifecycle. The presented use cases reveal that a broad range of applications based on digital twins can already be found in the literature. However, actual business cases are still rare. Thus, we discussed some ideas for applications that might create additional value streams at different stages of the product lifecycle, e.g., design or manufacturing. From our point of view, the boundaries between the stages of the lifecycle must be overcome in order to unleash the full potential of digital twins. The derived research questions can be seen as a starting point for future research in this direction.

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