Sustainable production and the role of digital twins–Basic reflections and perspectives

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Abstract
Sustainable production is essential for the future of the global economy. Despite the publication of its baseline vision over 30 years ago and the resulting diversity of interpretations and subdisciplines in engineering and social sciences, the progress of the approach in industrial practice remains marginal. This is mainly due to the fact that the discipline has not yet succeeded to realize the magnitude of the rethinking necessary of its very own perception as a whole. Existing definitions of sustainable production presented to date are thus only partly consistently derived from the baseline concept. Meanwhile, digitalization provides an increasing number of technologies that offer a new perspective on sustainable production. This especially applies to the concept of digital twins. Recent studies, thus, address their role in the context of sustainable production by analyzing its contribution to existing sustainability related methods as well as technical challenges on a microeconomic level (bottom-up approach). Although these approaches provide concrete requirements for technical deployment, it is highly questionable how they will contribute to sustainable production as a whole. In this paper, we choose a top-down approach to discuss the role of digital twins in the context of sustainable production. Based on fundamental reflections on the baseline concept of sustainability, we advocate a reorientation of production within the framework of planetary boundaries. Thereupon, we discuss the role of digital twins and digital threads and provide a number of requirements that future R&D needs to address for a future sustainability-oriented data-driven monitoring and regulation of production.

KEYWORDS
advanced manufacturing, sustainability

1 | INTRODUCTION

Sustainability is increasingly becoming the inherent challenge for future industrial production. Since the beginning of industrialization and the exponential population growth associated with it, the extraction of resources and the amount of greenhouse gases in the atmosphere have multiplied. In the last 30 years, global resource consumption has doubled, leading to an aggregated growth rate of 118%. A continuation of this trend will ultimately result...
in a further doubling by 2050.\textsuperscript{[3]} Due to the lavish resource usage of the past centuries since the first industrial revolution, many natural resources have already become short, e.g. silver, antimony.\textsuperscript{[4]} Pursuing this tendency will inevitably lead to an irresponsible exploitation of natural resources. Another example is climate change. Human impact has already caused global warming of about 1°C above pre-industrial levels.\textsuperscript{[5]} At current rates, global warming is likely to reach the 1.5°C limit agreed in the Paris Accord between 2030 and 2052.\textsuperscript{[6]} Consequently, the United Nations declared Sustainable Production and Consumption to be one of its 17 Sustainable Development Goals (SDGs) in 2016.\textsuperscript{[7]} Among others, this SDG12 aims to achieve sustainable management and efficient use of natural resources as well as a significant reduction in waste generation through prevention, reduction, recycling and reuse by 2030. It is therefore becoming increasingly important for companies to operationalize sustainability.\textsuperscript{[8–10]} This, however, represents a great challenge, among others due to the vague formulation of the guiding maxim by the Brundtland commission.\textsuperscript{[11,12]}

At the same time, industry is undergoing major changes due to digitalization and the mass integration of smart technologies.\textsuperscript{[13–19]} Such technologies bear the potential to make physical entities addressable, programmable, communicable, sensible, and traceable.\textsuperscript{[15,16]} Various authors thus stress their capability for the effective operationalization of sustainable production, for example, by increasing the availability of relevant data or improving the basis for decision-making.\textsuperscript{[20,21]} Especially the virtual representation of a physical entity within a manufacturing system, which is currently discussed under the term digital twin (DT), is considered to have significant possibilities. Consequently, a number of recent publications present analysis and use cases that primarily link existing methods and thought patterns that are commonly associated with sustainability to the DT concept and outline technical challenges of a microeconomic implementation. Recent examples of these bottom-up approaches include a DT-based life cycle assessment (LCA) framework,\textsuperscript{[22]} the conceptual basics of a DT concept for sustainability evaluation of railway station buildings,\textsuperscript{[23]} an implementation model applicable in the context of asset life cycle management,\textsuperscript{[24]} a method for DT-driven product design\textsuperscript{[25]} as well as a DT-driven green material optimal selection model.\textsuperscript{[26]} He and Bai present a substantial review of bottom-up-approaches related to DT-driven sustainable intelligent manufacturing and summarize their findings in a specific framework.\textsuperscript{[27]} In doing so, the authors assume a uniform understanding of sustainable production, which simply does not exist. Consequently, the principles and methodological toolkit assigned from this foundation can only reflect partial aspects, but not ensure to meet the primary goal of sustainability, i.e. environmental preservation. Yet, industrial standardization is currently beginning a process that is intended to transform these inadequate assumptions into new standards. For instance, the Industry 4.0 standardization roadmap of the German Standards Institute (DIN) requires the Asset Administration Shell (AAS)—a reference framework for DTs—to be suitable for containing sustainability data and to provide it at the end of a product’s life cycle for efficient disposal or recycling.\textsuperscript{[28]} DIN provides a similar concept in the form of a life cycle record for technical plants.\textsuperscript{[29]} Further standardizations that specifically address isolated aspects of sustainability (e.g. energy efficiency) in the field of Industry 4.0 are ISO 20140 and IEC 62832–3.\textsuperscript{[30,31]}

While bottom-up analysis on the role of DTs in the context of sustainable production are increasingly being published, a top-down-approach has not yet been presented. Therefore we conclude: Although sustainability represents a key factor of future production, it is not conclusively defined in order to be technically applicable. Existing (bottom-up) approaches assessing the contribution of DTs to sustainable production are therefore not considered comprehensively from a contemporary perspective. In order to navigate the technical development of DTs in an appropriate direction in the sense of sustainable production, a further (top-down) perspective is necessary.

2 | METHODOLOGY

This paper serves to complement the discussion on the role of DTs in sustainable production and to identify relevant focus topics for future research, development and standardization. Its core objective is to stimulate interdisciplinary scientific discourse by critically reflecting on the current primarily economic-technical focus of the research field and adding specific environmental aspects that mainly result from sustainability science. Instead of analyzing the contribution of DTs to existing sustainability related methods and thought patterns on a micro level (bottom-up approach), we choose a top-down approach (Figure 1), addressing three research questions:

1. How can an appropriate definition of sustainable production be derived from the baseline concept of sustainability?
2. Which basic requirements for DTs can be formulated from this understanding of sustainable production?
3. To what extent do recent publications, use cases and standardization initiatives address these requirements?

Therefore, we initially reflect on the baseline concept of sustainability in order to derive a sound understanding of sustainable production that goes well beyond existing
From this understanding we deduce overall requirements for an appropriate design and application of DTs. We then evaluate a number of existing DT approaches, use cases and standardization initiatives for congruence in order to identify recommendations for action for a future sustainability-oriented data-driven monitoring and regulation of production systems.

This paper exclusively focusses on the use of DT in production, not on the potentially adverse effects of the increased use of smart technologies in relation to various environmental and social impacts. We also exclude general issues of the technical implementation of DTs, which have already been sufficiently presented in other publications. Consequently, technical feasibility and economic efficiency are less in the focus of this investigation than the ecological requirements for sustainable production. This also allows the discussion of preferable states of industrial production, which may only become realistic in the distant future.

**3 REFLECTIONS ON THE BASELINE CONCEPT OF SUSTAINABILITY AND ITS INTERPRETATION IN PRODUCTION**

While its roots date back to early antiquity and 18th century European forestry, today's commonly accepted definition of sustainability was formulated in 1987 by the Brundtland Commission. It describes sustainable development as one that enables the present generation to meet its needs without depriving future generations of this possibility. Yet, the Brundtland report only specifies two aspects of the definition: the term needs is to be understood as basic human needs, while the guiding principle essentially seeks two primary goals, intergenerational (future generations) and intragenerational (global) equality. Therefore, sustainability is a purely anthropocentric approach that subordinates the natural environment to the purpose of human existence. Its preservation thus serves only the welfare of society. However, it remains unclear what state of the natural environment needs to be preserved in order to meet this requirement. In the context of the optimal use of the natural ecosystem, two partly contradictory interpretations have developed: strong and weak sustainability. The basis of this dissent is the legitimation of the exchange of natural, human and physical capital, for which the Brundtland Report does not mention specific regulations. Strong sustainability is understood as a demand, not only to preserve but also to revitalize the remaining fund of natural capital. The substitution of natural, human and physical capital is severely limited in this interpretation. Economy is perceived as a subsystem of the biosphere. This interpretation is also known as the priority model, as its primary objective is environmental protection. In comparison, the second interpretation, weak sustainability, assumes a general substitutability of capital, which is reflected in the triple-bottom-line model (economy, ecology, society). The term sustainability is interpreted as the preservation of the sum of all capital. With the help of integrative optimization, an ideal value between the three pillars should be realized. Although the interpretation has become particularly widespread in business practice, it is often criticized from a scientific perspective.
perspective. On one hand, it allows different actors to assert their positions and interests at will. On the other hand, the simultaneous consideration of three pillars leads to a complexity that can hardly be controlled. However, both interpretations have to be considered critical. Weak sustainability is not sufficient to preserve nature, whereas strong sustainability is too restrictive to be practicable. Despite over 30 years after the publication of the baseline concept, a few examples, however, indicate that today's practice is still far from meeting either one of these interpretations. The SDGs adopted by the United Nations in 2016, which are intended to decisively shape the global sustainability strategy until 2030, only include 3 of 17 goals with a clearly ecological orientation (SDG 13, 14, 15). All other goals are assigned to the economic or sociological dimension. Of the total budget of the Federal Republic of Germany for 2020, roughly 1% is reserved for environmental protection, while just under 50% is spent on labor and social affairs alone. Thus, an equal weighting (weak sustainability) or even prioritization of ecology (strong sustainability) is in no way implemented at present. Figure 2 illustrates the difference between priority model and triple bottom line according to Brand et al and Behlau in comparison to the qualitative image of the state of today's practice.

Other attempts at interpretation focus on the requirement of inter- and intragenerational equality. Here, the goal of sustainability is viewed as the preservation of the world's productive capacity over time, which could be directed towards the critical limits for each type of natural capital. While for a long time there was no clear agreement on the productive capacity of the earth, Rockström et al presented the concept of planetary boundaries (PB), which is now widely understood as the most promising option. Figure 3 illustrates the concept of planetary boundaries according to Rockström et al. In their approach, first published in 2009, which has since been continuously expanded with additional categories and insights, they identify nine Earth-system processes that are crucial to maintaining today's ecosystem services (climate change; rate of biodiversity loss [terrestrial and marine]; interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; chemical pollution; and atmospheric aerosol loading). Based on latest findings from the environmental sciences, the study also determined thresholds, which, if crossed, could generate unacceptable environmental change, and calculated the degree of utilization by today's economy. By taking a conservative, risk-averse approach, considering the large uncertainties surrounding the 'true' position of various thresholds, the framework enabled a holistic, quantifiable view of the natural environment worthy of preservation ('safe operating space') as well as an identification of the most pressing problems, that is those for which the current status has already exceeded ecological limits (climate change, loss of biodiversity, nitrogen cycle) or is or is about to exceed it (global freshwater use, change in land use, ocean acidification and interference with the global phosphorous cycle). On this basis, Griggs et al advocate a modification of the baseline concept of sustainability by emphasizing the preservation of planetary stability as the fundamental condition of all endeavors, clearly referring to the priority model. Likewise, Rockström sketches the necessity of a great transition toward the priority model, whose limits must the PBs. Although recent publications indicate that these categories should be considered in life cycle engineering or as constraints of industrial production, it is practically impossible at present to determine the individual contribution to the respective planetary

![Figure 2](image-url)
boundary categories on the micro level (companies, households, etc). On the one hand, separate basic approaches exist, especially LCA, IPAT equation and the science based targets initiative (an initiative that breaks down scientifically calculated targets for various environmental categories into microeconomic entities, SBTI), that have the potential to actually facilitate such a process. This, however, presupposes that many currently existing methodological weaknesses are overcome and that a standardized procedure is established globally. Assuming, however, that these barriers are overcome, another one follows, the partly contradictory strategies for transforming the current into a sustainable state. Typically, sustainability science mentions three basic strategies: efficiency, consistency and sufficiency.

The concept of efficiency in particular has inherited a special role in the sustainability debate and exists today in combination with a wide range of dimensions, including energy, material, resource, eco- and socio-efficiency. Various authors, however, show that increasing the efficiency of any technical system usually induces a more feudal consumption of the same or other goods, also known as the rebound effect. A further effect that goes hand in hand with efficiency in the context of sustainability is the failure to consider the entire life cycle or the interactions with other systems. Decisions based on the assumption of a too narrow system boundary or temporal frame of reference mostly lead to a shift of the problem into precisely those areas that are not considered (phases of the life cycle, regions, etc.). In literature, this phenomenon is referred to as the leakage or spillover effect. Last, but not least, efficiency is a relative figure. An increase does not necessarily lead to an improvement in the absolute use of the environment. In the case of non-renewable resources, the strategy can only achieve an extension of availability, but not permanent access. In literature, this phenomenon is referred to as the quantity effect. A solution to the environmental problem through a microeconomic increase in efficiency is therefore not possible.

In contrast, the concept of effectiveness or consistency refers to an adaptation of human actions to nature, which from a technical perspective is also the aim of biomimetic. In production, the consistency strategy seeks an adaptation of the industrial to the natural material cycle, which is predominantly discussed in the field of industrial ecology. Its overall concept is the circular economy. A consistent action is characterized by not exceeding the natural regeneration and absorption capacity of the environment. Like the efficiency concept, this strategy cannot be recognized without contradiction as a path to a sustainable economic form. On the one hand, there are no sound criteria in the context of sustainability that can attest the effectiveness of an action in the global context in advance. On the other hand, there are doubts about the general feasibility of the concept, which are supported, among other things, by the economic theory of entropy. The production of a good should never be seen as the creation of something completely new, but rather as a metamorphosis of
something that already exists. It thus becomes clear that an exclusive focus on the adaptation of human actions to nature lacks coherence.

While the concepts of efficiency and consistency are to be seen as adaptations of traditional economic approaches, the sufficiency strategy is a pure expression of the concept of sustainability. The concept identifies the rationalization of resources or needs as the central lever for sustainable development. The target state of the sufficiency strategy is a return to the satisfaction of real needs. The idea of purely quantitative economic growth is rejected. In literature, four measures are usually mentioned as concrete means of implementation: (1) Reducing the quantity of products, (2) increasing self-sufficiency, (3) regionalizing supply chains, and (4) decelerating consumption. Although from a purely ecological perspective the sufficiency concept has the most logical arguments for sustainable development, it is not free of deficits. On one hand, the approach contradicts conventional patterns of thinking geared to growth. Compared to the strategies outlined above, the sufficiency concept thus represents a fundamental modification of the socio-economic boundary conditions. Its real implementation seems to be confronted with insurmountable hurdles. Furthermore, the effects of rationalization and deceleration on Third World Countries, which can have adverse effects on global distributive justice, need to be examined. Abstinence can only occur in regions where consumption exceeds the satisfaction of real needs.

So the question arises: If the initial framework and its implementation strategies are ambiguous, then what is sustainable production and how can it be achieved? Attempts to define sustainable production on the basis of the above specified framework and implementation strategies are hardly to be surveyed by now. One prominent example is the Lowell Center interpretation of sustainable production as the fabrication of goods and services by applying processes and systems that are non-polluting, save energy and natural resources, are economically viable, safe and healthy for employees and consumers, and socially and creatively beneficial for all working people. Similar definitions are presented by O’Brien, Hauschild et al, Wiles and Watts, Lebel and Lorek, Velea and Ellenbecker, Krajc and Glavič as well as Pusavec et al adding various principles and methods that need to be addressed for an implementation at the micro level. Table 1 summarizes the most prominent principles and methods currently associated with sustainable production.

Yet, the presented definitions do not sufficiently enforce the baseline concept of sustainability. In order to provide a satisfactory solution, it is primarily necessary to understand to what extent the baseline concept of sustainability questions the understanding of production as a whole. The concept of production is deeply rooted in the economic theories of the classic and neoclassical periods, usually being either interpreted as the process between purchasing and sales or as an act of value creation through appropriate combination of production factors. The harm a produced good causes to humans and the environment over its life cycle and / or the return and recycling of the

| TABLE 1 | Selected principles and methods currently associated with sustainable production |
| --- | --- |
| **Designation** | **Selected references** |
| **Principles** | 79–85 |
| - Life cycle thinking |  |
| - Corporate social responsibility |  |
| - Achieve transparency of material flows, energy consumption and emission generation |  |
| - Closing of material loop systems |  |
| - Return, reuse recovery and recycling of products |  |
| - Minimization or avoidance of waste and impact |  |
| - Amendment of non-recyclable products |  |
| - Minimization of transportation needs |  |
| - Minimization of hazardous substances |  |
| - Compliance with all relevant legislations and standards |  |
| **Methods** | 86–96 |
| - Life cycle assessment and costing (LCA, LCC), life cycle sustainability assessment (LCSA) etc. |  |
| - Design for environment (DFE), life cycle design (LCD) etc. |  |
| - Indicator systems (e.g. GRI) |  |
| - Integrated ECQFD, TRIZ, AHP design method |  |
| - Benchmarking (i.e. Best-in-class technologies and – system-designs) |  |
| - Resource criticality assessment |  |
| - Hazardous materials management |  |
| - Eco-design checklist |  |
| - Eco-Lean Management / Lean and Green |  |
| - Etc. |  |
products is negligible in the classical concept of production. Although these issues are addressed in the concept of sustainable production,[79–85] hardly any publications referred to the priority model for long. Accordingly, the concept of sustainable production would not set any limits to the overall use of natural sources and sinks. In addition, the preface 'sustainable' emphasizes the marginality of the concept in the entirety of production sciences. Should 'intelligent production' in today's world still be allowed to be unsustainable because the preface 'sustainable' is not explicitly stated? Obviously, the answer must be a clear no. Yet, this example illustrates the most striking problem of current interpretations of sustainable production: It allows that production (although depending on a multitude of ecosystem services) still views itself as an isolated unit, a fact that is continuously expressed in today's perception of the scientific discipline. A partial exception is the related discipline of LCE, which has recently addressed the link to PBs under the term 'absolute sustainability'. For instance, Hauschild et al propose a novel framework for LCE that outlines PBs as the overall limit (Figure 4).[56,57]

Although this represents a decisive reorientation of LCE, the approach still does not present a regulatory framework of impact limits to technology development and application. By simply assuming that the uncoordinated micro-level endeavors (e.g. by applying methods of life cycle design in product development) result in a global optimum, it fuels the notion of solving the environmental problem via microeconomic technical solutions. Identifying and reducing the environmental impact of a single product or enterprise along its life cycle as well as a large-scale closure of a single company's material cycles without a reference to all other subsystems of the natural overall system obviously do not suffice to achieve an overall sustainable production due to various effects (s. above). Ensuring production within PB clearly represents a regulatory concept, which largely implies a rejection of purely autonomous decision-making as well as uncontrolled technology development and application at the micro level.

If it is to be ensured that industrial production remains within the framework of PB, the general understanding of production must change. While early approaches in systems theory and biocybernetics, among others presented by Beer and Vester,99 100 had already outlined the factory and the product in the context of a superordinate system, whose optimization requires consideration of essential interdependencies, the recently developed concept of biointelligence (i.e. the rational utilization of natural resources in order to preserve the overall system)1101–103 represents a further step in this thought process. The concept differs between two perspectives. The technology convergence perspective views the information technological coupling of biological and technical systems as an innovative option to develop unique production technologies. The normative systems thinking approach is based on the fundamental principles of LCE and systems theory (and biocybernetics). It views the entirety of production as a self-contained organism and envisages controlled operations within the limited scope of planetary boundaries. While the former is thoroughly addressed in,1101–103 the
The term production is subsequently understood as a phase in a constant recirculation of matter. It occurs between the provision of input factors and the sales of products, thus includes all processes of manufacturing and remanufacturing of goods. Production is not a single economic act, but a self-contained organism whose natural basis (the planetary boundaries) must not be exceeded. This understanding of production presumes the existence of a globally acting controlling unit (or at least a uniform global policy) that acts as a regulatory authority involving each category of the PB concept (normative approach). It would have to monitor and control essential aspects of production (e.g. input factor type and provision, scope of factor combination, volume of goods in circulation). An authority of this nature would be indispensable to assess the current status of planetary stability at regular intervals, to calculate a safe-operating space for a certain period according to standardized procedures, to break down individual units (planetary budgets) into single economic units (companies, households) and to ensure that these are adhered to by means of monitoring and enforcement. Figure 5 illustrates the two perspectives of biointelligence (based on Miehe et al1101,102).

**FIGURE 5** Two perspectives of biointelligent production (based on Miehe et al1101,102)

The concept of the DT was first mentioned in 2003 in the context of product lifecycle management (PLM).[104] The term was adopted by NASA and defined as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.”[105] While the NASA definition primarily focused on the aerospace sector, it utilized Grieves’ approach by highlighting three major components of a DT: the real-world product, the virtual representation of it and a data flow that connects both. With the growing evolution of sensing, processing and communication technology in recent years, the DT concept has experienced increased attention. To date, the concept has been proposed for a large number of applications, including manufacturing.[106] Recent scientific literature thus provides a broad range of definitions of DTs as well as various descriptions of how to implement them.[107] Kritzinger et al present a...
comprehensive literature review of available DT concepts, resulting in a distinction of three stages of system integration\(^{108}\). The *digital model* (DM) represents a product virtually, while not exhibiting an automated flow of information between the product and the model. The second stage, the *digital shadow* (DS), differs from the digital model by the incorporation of an automated upload of information from the real-world product to the virtual one. Finally, the *DT* enables a bi-directional information flow in real-time between both systems (Figure 6).\(^{108}\)

To date, however, the three terms are largely used as synonyms.\(^{108}\) This applies in particular to the term DS and DT. From a manufacturing perspective, the DS can be understood as an accurate image of production, research and development as well as of adjacent processes (‘as good as necessary’).\(^{109}\) The DS is, therefore, primarily an instrument to transfer the real world into the virtual one.\(^{110}\) The DT, in contrast, aims to use simulations and process models to generate an image of reality that is as accurate as possible (‘as good as possible’). The DT, therefore, goes far beyond the mere simulation of a physical structure.\(^{111-113}\) As such, it contains a wide variety of information along the entire value chain that enables an autonomous production function, for example material composition, technical drawings, work plans, machining instructions, fasteners, parts lists, transport routes and/or emissions. Various authors, however, agree that the development of DTs has just started.\(^{106-108}\) While the term is quite well defined, data connectivity, which is an essential prerequisite for system interoperability, is currently seen as the most difficult hurdle for implementation. Further conceptual development and real-world use cases are required in order to establish sufficient data connectivity.\(^{107}\)

In order to overcome the data connectivity issue, the German Platform Industrie 4.0 and the German Electrical and Electronic Manufacturers’ Association (ZVEI) developed a standardized architectural model of a DT that is referred to as the asset administration shell (AAS).\(^{38}\) The model aims to guide companies in implementing DTs and to ensure interoperability between devices, components and applications across different business entities. The AAS is a virtual representation of any real-world asset that contributes to an I4.0 production task, e.g. items, software or documents.\(^{114}\) As such, it contains all available information on properties, status, parameters, functions and references of the asset, which are each stored in several AAS submodels. Each submodel is referring to a specific aspect, for example the ‘positioning mode’ of an axis, and may contain elements ‘position (0–2)’ and ‘average positioning error (mm)’. The submodels and their connections within the superior model layer are organized by a generic structure specified in the AAS metamodel. Submodel features may also have external references and references to local dictionaries.\(^{115}\) References may point to documents or websites that contain further explanation about the element, which is expected to help applications ‘interpret’ the given information semantically, enabling to apply the correct functions on the element.

As exemplified in Figure 7, the combination of an asset and its AAS is referred to as an I4.0-component. It should be noted that both individual machines and entire device systems can be assigned an asset shell, depending on the hierarchy level at which the system is situated (see hierarchy levels in Figure 4). While AAS for assets of lower hierarchical levels, such as machines, or even sub-assemblies and individual parts, include specific attributes to their functionality, AAS for assets of higher hierarchical levels aggregate complex information relevant to the overall device system. The connection between the AAS displayed in Figure 7 is defined in a submodel called “topology model.” It connects the manufacturing device system to the AAS of the turning machine, but also to further devices such as control devices, milling machines, etc. This allows only the AAS of the manufacturing device system to be directly coupled to the I4.0 system, making it the single I4.0 component and reducing the overall implementation effort. The interconnection between I4.0 components and AAS at different hierarchy levels on the one hand and their respective assets on the other hand requires seamless communication. Hence, AAS enable information transfer via various communication channels and applications, forming the linkage between locally distributed real-world assets throughout the complete life cycle. AAS thus have to ensure interoperability by a number of characteristics leading to an AAS architecture model as presented by the German Platform Industrie 4.0 and the German Electrical and Electronic Manufacturers’ Association (ZVEI) (Figure 7).\(^{114-116}\)

In order to summarize and uniformly present data types as well as communication standards, the German Platform Industrie 4.0 and the German Association for
Electrical, Electronic and Information Technologies presented the hierarchical Reference Architecture Model Industrie 4.0 (RAMI 4.0). Figure 8 illustrates the RAMI4.0 model according to the German Platform Industrie 4.0 and the German Association for Electrical, Electronic and Information Technologies.117

The model distinguishes between three dimensions. The y-axis summarizes the different layers of IT representation, aiming to visualize the information flow within the IT-architecture. Assets such as machines, products or employees are connected to the IT system via an integration layer that gathers all the acquired data and makes it available for higher levels such as communication or information storage. The functional layer adds the possibility to automatically execute actions based on the incoming data. The z-axis represents various steps along the product life cycle and value streams based on IEC 62890. When the developed product is launched into production it changes from 'type' to 'instance'. On the x-axis, the hierarchical levels of the integration of ERP and control systems are derived from IEC 62264 / 61512. These levels represent the various functionalities that the assets may serve. The RAMI4.0 structural model and the I4.0 components form the core of a DT of a manufacturing system.

While the considerations listed above are primarily discussed in German-speaking countries, related models are documented in international literature in English and outline a variety of similarities of the DT concepts of Germany, United States, China and France.113

According to Seif et al the introduction of AAS to real-world manufacturing facilities requires a three-step approach.36 In a first phase, it is essential to deploy the AAS structure and integrate it into day-to-day business before actual advantages of DTs can be exploited. In this way, isolated solutions are avoided and the basis for communication capability and interoperability is ensured. In the second phase, after communication structure setup is completed, the functions can be extended to allow autonomous interaction of AAS without any central control and to enable the system to optimize on its own. The third phase comprises the deployment of the AAS via various implementations (OPC UA SDK, RESTful API, etc) of data bases, communication protocols and IoT integration. The final goal is to set up the communication between the real-world asset and the AAS. Use cases of AAS model deployments are documented by Kalhoff et al and Tantik et al.118 119

However, AAS standardization does not conclusively solve the data connectivity problem. In fact, the variety of information to be linked along the life cycle of a product presents further challenges that cannot be handled by the DT architecture alone. Consequently, the concept of the digital thread, which is intended to describe the communication framework along the entire lifecycle of a product, is increasingly being discussed in recent literature. This concept is based on the vision of a communication and data platform, which enables links to relevant information at any instance of time.120 The digital thread thus provides the DT with all information necessary to generate relevant submodels and functions. Figure 9 illustrates the approach of the digital thread as a mathematically describable decision problem along the life cycle of a product according to Singh and Willcox.121

According to the considerations above, we subsequently understand a DT as a digital representation of a physical object or system, which is capable of a bi-

**FIGURE 7** AAS architecture model (based on the German platform Industrie 4.0 and the German electrical and electronic Manufacturers’ Association (ZVEI)111–113
directional information flow between both systems in real-time. A DT is structured according to the AAS framework, maps all relevant links to other systems (e.g. databases), is capable of exchanging information with DTs of other physical entities and can be used for various applications demanding certain submodels and/or algorithms. Throughout the life cycle of a product, a DT constantly utilizes information provided by a specific communication and data platform, the digital thread.

5 | ROLE AND PERSPECTIVES OF DTS IN THE CONTEXT OF A SUSTAINABLE PRODUCTION

Taking into account the above reflections on sustainability and the further necessary reorientation of production, the role of DT is obvious: As a digital representation of any physical entity in a production environment, the DT must serve as the foundation of an IT-supported transformation towards a sustainable production by acting as an enabling technology for an improved execution of relevant strategies, thought patterns, methods and decisions. It is therefore essentially a tool that can support individual decisions or independently decide in terms of sustainability within a constant sequence of operations, as exemplified in Figure 10.

But how exactly can this be accomplished? In order to answer this question, it is necessary to summarize essential features of both bottom-up approaches (i.e. what is necessary to support approaches related to existing interpretations of sustainable production?) and the additional requirements resulting from the considerations outlined above regarding production as a self-contained organism within a normative framework (top-down-approach).

In any case, sustainable production requires the highest possible degree of transparency regarding the quantity and impact of the materials, substances and
energy used as well as the emissions and waste produced.\textsuperscript{122} This implies the necessity of standardized acquisition and storage of relevant data as well as semantic description. Sensor data for primary data collection and interfaces to relevant databases (for secondary data collection) serve as the foundation. However, no standardized data model has been developed to date that is capable of representing the diversity of already existing sustainability applications, for example:

- For \textit{compliance} with various requirements of environmental legislation (e.g. REACH, RoHS, Conflict Minerals), the material composition and supplier risk must be clarified and evaluated\textsuperscript{123,124}. This is usually done by checking relevant standards and databases, communicating with suppliers and assessing the risk using specifically developed models. At the same time, new legal requirements and changes in existing regulations (e.g. new substances on the SVHC list every 6 months, expiry of RoHS exemptions) have to be added and the compliance of processes and products constantly re-evaluated.

- For \textit{LCAs}, however, inventories of each entity involved (process step, machine, etc) are necessary in the sense of input–output balances in relation to a functional unit.\textsuperscript{87} However, since these can rarely be collected in their entirety, standard data sets have to be used. The evaluation is then carried out with regard to different impact categories (climate change, acidification, ecotoxicity, use of natural areas, human health etc), which in turn are assigned to different levels (midpoint and endpoint) and calculated using different methods (equivalence factors, environmental impact points, external costs etc).\textsuperscript{58,125}

- A \textit{material flow cost accounting} (MFCA) partly relies on life cycle inventories, yet allocates the costs occurring in traditional corporate accounting to the flows of raw and operating materials as well as the operations on the product using reasonable factors and production work. Likewise, various approaches and levels of detail exist here.

Other applications, each of which requiring slightly different data and modeling, are DFE/LCD, energy monitoring, non-financial / EMAS reporting (e.g. GRI, materiality matrix etc), environmental management, Eco Lean Management, resource criticality and efficiency assessment of products and processes (e.g. according to the German VDI4800\textsuperscript{126}). In addition to the design documents (parts lists, technical drawings, etc) of the respective entity that need to be documented within a DT, harmonized data on energy and material consumption and losses would have to be collected at regular intervals and converted into models that allow evaluation with regard to sustainability applications (LCA, MFCA, reporting, environmental compliance etc). A DT must, therefore, have an interface and autonomous connection to existing databases such as GaBi, EcoInvent, iPoint, CDX, BOMcheck, and so forth. Yet, the amount of data is of secondary importance. Rather, it is a matter of generating the highest possible quality of information for the respective operational decision.\textsuperscript{100}

It is therefore primarily a heuristic task that must also be supported by appropriate submodels. Accordingly, DT must enable the holistic incorporation of submodels relevant for sustainability assessment (impact indicator models, characterization models, Monte Carlo simulations etc) as well as the constant tracking of their

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Digital twin (DT) as decision tool for sustainability within a constant sequence of operations}
\end{figure}
interference. As environmental impact does not occur in the here and now, but is determined in various stages of an entity’s life cycle by a number of factors, the impacts of production on the ecosystem (climate change, acidification, resource depletion and criticality, human and eco toxicity etc) are usually accompanied by a time lag of occurrence. In order to effectively analyze and avoid these undesirable effects, it is necessary to collect and share relevant data for each step in the supply chain respectively over the entire life cycle of a product, as well as to ensure interoperability of applied sustainability assessment models. Apart from the above described AAS architecture, the concept of digital threads represents a particularly promising approach, although its sustainability potential requires further research. This especially applies to the advanced concept of system-oriented life cycle thinking outlined above, which envisages the embedding of a single product in a constant recirculation process with different reuse and recycling options at different times and on different levels (system, product, element, molecule). The product's use and end-of-life phase (EOL) are, for example, largely neglected in the above sketched 'life cycle' of the RAMI4.0 framework. The life cycle outlined here, represents rather a traditional value chain (i.e. cradle-to-consumer), which is also a common practice in PLM, but does not include the use and EOL phase. An appropriate representation in terms of sustainability (i.e. cradle-to-cradle) would at least have to integrate the EoL phase as a step and allow parallel sequences of the development phase of products, since these must always remain combinable within a circular flow of matter (Figure 11).

The consolidation and provision of data relevant for a variety of sustainability applications (especially along the entire life cycle) within a standardized data model represents a security issue. A DT must therefore ensure that only the right people have access to the relevant content at the right time. The compatibility with technologies such as distributed ledger must be ensured in any case.

With these issues being addressed, DTs would still barely contribute to a normative systems-oriented interpretation of production. That has several reasons. First, the methods outlined above represent manifestations of current knowledge and approaches that are likely to change in the course of time. Current LCAs for example primarily calculate impacts on socially perceived problem areas at a given time (e.g. climate change). With new problems emerging, new impact indicators and characterization models will be developed. The Corona crisis is a current example. While the origin of the virus from animals is clear, debates are currently taking place about what could have been the trigger. One explanation is the ever-increasing exploitation of natural habitats by humans, which is pushing back wildlife. In evolutionary competition, the limitation of habitat leads to an increased spread of highly adaptable species, which usually carry extremely adaptable disease-causing agents. If this chain of effects from industrial patterns to an undoubtedly pressing social problem is scientifically validated, it may soon be embedded as a new impact category in LCA. Environmental compliance management, which is a highly discontinuous field. Compliance with the applicable environmental legislation for a product, for example, can only be achieved for a certain point in time in the form of a risk-
based approach. However, since the number and content of regulations is subject to constant change, compliance with products in development or already on the market must be evaluated at regular intervals, that is, it must be checked whether exemptions still apply or whether there are new regulated substances above a certain limit in the product etc. The applied DT submodels must therefore be adaptable and have a modular structure in order to integrate new functions and information.

While the previously discussed ideas are essentially derived from the bottom-up approach and have partly been discussed in recent papers, the normative systems thinking concept of sustainable production (top-down approach) requires further thoughts on a potential role of DTs. In this context, especially the development and implementation of innovative submodels represents a necessary consequence. This primarily concerns three areas of the DT and its real world asset: ensuring adaptivity through predictive submodels, mapping of the impact interrelationships between all subsystems (producing units, companies, supply chains etc.) of the overall system as well as assuring a collective impact assessment of the entirety of production regarding the framework of planetary boundaries. It is only when these challenges have been addressed appropriately that one or more regulatory authorities can be provided with an adequate data and decision basis for implementing the normative approach.

As discussed above, the consideration of the entire life cycle of an entity does not suffice for sustainability accounting and planning. In terms of biointelligence and in accordance with the cradle-to-cradle concept, the development and application of intelligent physical entities (products, operating resources etc.) means that it must be clear from the very beginning, how all substances used will be reused. At the same time, technological progress must be taken into account. It is difficult to estimate the technological level of a society at the beginning of a life cycle, especially in the case of very long-lived goods. While the physical structure of the real world product must ensure a high degree of flexibility in the recycling or composition of materials and substances, it is necessary to track technological progress by means of adequate submodels and develop recycling scenarios over the course of the life cycle. DT must therefore contain predictive submodels for the development of scenarios for the secondary use of all substances used at different points in its life cycle (exploitation options).

While a variety of political mechanisms (e.g. emission prizing and trading, compensation) and technical options (e.g. carbon capture storage, renewable energies, change of raw material basis, waste to energy processes, increased recycling) exist to address individual impact categories (a broad overview of climate change solutions is provided by Project Drawdown), a globally coordinated strategy is required to ensure that all approaches are deployed appropriately throughout the world in accordance with all PB categories. This again requires a globally acting authority that regulates the entirety of production (see chapter 3). From a contemporary perspective, the concept of a globally regulated integral production within the framework of PBs represents a hardly surmountable hurdle. On the one hand, empirical evidence shows that the independent deduction of science-based macro goals to individual companies alone represents a process of one person-year. In case current material, energy and impact balances have to be recorded, aggregated and reported independently over a certain period of time and assigned to the PB categories in a methodologically questionable way, the scope of non-value-added activity (which is already being utilized by various other issues such as compliance management and standardization) can simply no longer be justified for companies. On the one hand, although being urgently required (as most environmental problems cannot be solved by a single state), a consensus within the international community for the establishment of a globally operating regulatory authority seems hardly conceivable.

In the midterm, it is more likely that single state regulatory authorities will impose tighter transparency requirements on companies regarding impact of production. Consequently, only those measures can be successfully implemented that enable reliable provision of relevant information to one or more regulatory authorities, without incurring disproportionate expenditures for manufacturing companies. Thus, three distinct paths may be defined for the role of DT in the context of the normative system thinking approach to production, which can also be understood as steps with increasing sustainability contribution:

1. **Supply of information to one or more regulatory authorities via collective ecosystem impact submodel:** DT as enabling technology for collective impact assessment (of entirety of production) based on fully mapped impact interrelations between all subsystems of the overall system as well as the collective impact according to a standardized procedure model consisting, for example, of a combination of PBs, STBI and LCA.

2. **Active control of individual real world assets via AI-based ecosystem decision submodel:** AI-based DT submodels enabling independent decision on control,
application and exploitation of real world entity along its life cycle permanently considering the impact interrelations between all subsystems as well as their collective impact to the overall system.

3. **Independent, interlinked ecosystem control submodel:**
   DTs as active control units of a fully autonomously regulated organism-like entirety of all industrial production units, whose collective impact remains within the framework of planetary boundaries at any time. A DT exists for each entity, from the single substance to the entire ecosystem, while the regulation of production is realized by AI based algorithms.

Despite being much more complex, the foundation of the approaches 2 or 3 could be an algorithm, which works much like the envisaged control of an autonomous fleet of vehicles. The algorithm necessary for this can only move vehicles on designated roads (streets, entrances, etc) and does not lead them into areas not designated for their purpose (fields, sports fields, lakes, etc). In the same way constraints are formulated, which, similar to PBs, must never be exceeded.

As a result of the reflections, we derive three superior categories and 10 major demands for the role of DTs with regard to the normative systems thinking approach of production. While becoming relevant and/or technically feasible at different points in time, they remain equally crucial for future R&D.

1 Requirements regarding data interoperability
   1.1 Ensuring interoperability of relevant data, documents, models etc. via harmonized formats, design patterns and interfaces along the entire life cycle of an entity (including connections to existing databases such as GaBi, EcoInvent, iPoint, CDX, BOMcheck etc.) within a standardized, adaptable and modular structure.
   1.2 Definition of appropriate access rights in order to provide the required data to the relevant entity.

2 Requirements regarding the data itself
   2.1 Extensive compilation of all relevant data on substances, materials and energy (an/or metabolic pathways) used as well as emissions and waste generated along the entire life cycle of an entity.
   2.2 Transparency on chemical composition and physical design principles for the purpose of environmental compliance as well as disassembly, e.g. via technical documents, dismantling instructions and the like.
   2.3 Constant checking of standards and databases and linking them to material and substance composition model.

3 Requirements regarding specific submodels
   3.1 Submodels and simulations relevant to environmental impact assessment (e.g. characterization models, life cycle impact models, Monte Carlo simulation etc.) within the framework of existing impact categories.
   3.2 Predictive models for the development of scenarios for the secondary use of all substances used at different points in the life cycle (exploitation options).
   3.3 Predictive sensitivity models to anticipate and incorporate previously unknown relationships and impacts with and on people and the environment.
   3.4 Collective ecosystem impact submodel of the ‘organism production’ to conclusively map impact interrelations between all subsystems of the overall system as well as the collective impact to PBs according to a standardized procedure model.
   3.5 Active control of individual units and/or entirety of production via AI-based independent, interlinked ecosystem control submodel(s)

6 | STATE OF RESEARCH AND STANDARDIZATION

The extent to which research and standardization are already addressing these demands of sustainability is demonstrated by a comparison with a selection of recent publications (Table 2). The approaches discussed below are based on a literature review using a search matrix. The research was conducted in relevant databases for a total of 57 word combinations that explicitly link the terms DT or AAS with relevant sustainability concepts (environment, recyclability, life cycle etc). Thereby the focus was on use cases with a concrete technical implementation and/or standardization initiatives that propose a uniform approach to this implementation.

The number of relevant case studies is still limited. In contrast to a variety of use cases that primarily focus on the demonstration of interoperability, root cause analysis, product quality monitoring and service-oriented business models, Barni et al developed a DT-based LCA framework that represents a semi-modular, modular, and scalable sustainability assessment and optimization tool. While the authors clearly focused on interoperability of sustainability performance data, collection of relevant data and LCA assessment, the approach did not address the other requirements of sustainable ecology-oriented industrial production. Nevertheless, the authors note that research in this field is only just beginning and outline three essential steps to bring DT and sustainability together:
intensification of automated sustainability data collection, DT data management and smart sustainability service analysis. In addition, since feedback is not possible in this approach, it needs to be noted that it rather represents a DS than a DT. Kaewunruen and Xu apply conceptual basics of the DT concept for the sustainability evaluation of railway station buildings by extending a 3D Building Information Modeling (BIM) with additional dimensions that address additional building information such as cost estimations, carbon emissions from construction process and renovation simulations. Although the approach provides important elements of DT design, it represents a link between databases and models rather than a real-time-capable DT. Besides, interoperability was not a focus of this work. Thus, the approach is rather to be considered an extended DM. Altamiranda and Colina present a comparatively far-reaching approach by developing a framework and a road map for a DT architecture and implementation model applicable in the context of asset life cycle management. Although the approach provides important elements of DT design, it represents a link between databases and models rather than a real-time-capable DT. Besides, interoperability was not a focus of this work. Thus, the approach is rather to be considered an extended DM. Altamiranda and Colina present a comparatively far-reaching approach by developing a framework and a road map for a DT architecture and implementation model applicable in the context of asset life cycle management. However, the term life cycle (i.e. life time management for e.g. maintenance) is not used in the sense of sustainability (i.e. cradle-to-grave). The model thus does not enable an appropriate LCA. The same applies to Tao et al, who present a new method for DT-driven product design, manufacturing and service. By also focusing on the use of DT for PLM, they found an increased potential for identification of inefficiencies. While the study presents novel approaches to solve the problems of data in product life cycle and illustrates practical applications of DTs in three phases of a product life, the life cycle approach used here is not in line with the sustainability interpretation. Kannan and Arunachalam present a DT approach for a grinding wheel as a product-integrated and web-based knowledge sharing platform that integrates data collected in each phase of the grinding wheel’s life time from the manufacturing to the conditioning phase. Within the analysis, a case study with a special focus on productivity and efficiency was conducted resulting in a 14.4% energy and resource efficiency increase. While the publication clearly addresses aspects of sustainability, it leaves a number of questions unanswered. In addition to the approach of energy and resource efficiency calculation, this is particularly the origin of the data from the real entity. It does not become sufficiently clear how interoperability should be realized. Nevertheless, the linkage to the predictive model depicts an essential basis for further system theoretical developments in the context of sustainability. Xiang et al develop a DT-driven green material optimal selection (GMOS) model that is supposed to enable sustainable manufacturing. While the model contains indicators of environmental impact, basic aspects of sustainability (system boundaries, life cycle, recyclability) are not taken into account here. Another approach, developed by Wang and Wang, uses DT for compliance with the waste electrical and electronic equipment (WEEE) directive. Thereby, information about product design, product status, logistics and recovered materials or components is integrated in the DT framework throughout the entire life cycle of a product.

| Existing studies and/or standards | Basic requirements |
|----------------------------------|--------------------|
| Kalhoff et al\textsuperscript{118} | ++ + + + + + + + + + + + + + + |
| Koerner et al\textsuperscript{119} | ++ + + + + + + + + + + + + + |
| Dettner and Eigner\textsuperscript{120} | ++ + + + + + + + + + + + + + |
| Barni et al\textsuperscript{122} | ++ + + + + + + + + + + + + + |
| Kaewunruen and Xu\textsuperscript{23} | ++ + + + + + + + + + + + + + |
| Altamiranda and Colina\textsuperscript{24} | ++ + + + + + + + + + + + + + |
| Kannan and Arunachalam\textsuperscript{25} | ++ + + + + + + + + + + + + + |
| Tao et al\textsuperscript{130} | ++ + + + + + + + + + + + + + |
| Xiang et al\textsuperscript{126} | ++ + + + + + + + + + + + + + |
| Wang and Wang\textsuperscript{131} | ++ + + + + + + + + + + + + + |
| DIN 77005–1:2018\textsuperscript{29} | ++ + + + + + + + + + + + + + |
| ISO 20140\textsuperscript{30} | ++ + + + + + + + + + + + + + |
| BS EN IEC 62832–3\textsuperscript{21} | ++ + + + + + + + + + + + + + |
| RAMI4.0 framework\textsuperscript{117} | ++ + + + + + + + + + + + + + |

Note: ++ = fulfilled, + = partially fulfilled, – = not fulfilled.
In doing so, the authors extend the DT framework by the further phases of service, collecting and recycling/recovery. However, the approach represents a specific and isolated use case for a single directive. Besides improving the recycling in the context of WEEE, the authors do not suggest further applications. Upon a substantial literature review, He and Bai present a framework of digital twin-driven sustainable intelligent manufacturing that is intended to ensure interoperability and to integrate different sustainability methods. Yet, a use case implementing it in practice is not provided. Other related fields examined here do not provide further insights. While a number of publications in the fields of smart technologies, digital sustainability and digital artifacts intend to formulate requirements for digital resources/artifacts from a sustainability perspective or for data acquisition using RFID chips, they do not present a specific application or reviews of existing approaches. At the same time, the requirements formulated here can only be insufficiently transferred, since the objects under investigation (smart technologies, digital resources/artifacts) represent a significantly wider spectrum than the comparatively close examination of DS, DT, and AAS. In addition to scientific publications, individual standards partly address the requirements defined here, although primarily focusing on ensuring interoperability and collection of data (requirements 1 and 2).

The discussion of the present focus of R&D in the context of DT and sustainability exemplified by recent publications and standardization initiatives again proves that the discipline mainly views production as an isolated unit, which severely opposes the primary goal of the baseline concept of sustainability. Merely ensuring interoperability and providing information for existing methods of an inadequately defined concept of sustainable production will not suffice to ensure that production remains within planetary boundaries.

Figure 12 sketches the role of DTs in the context of the normative systems thinking approach as well as essential features in the sequence of growing contribution to sustainable production and the current status of research.

7 | SUMMARY AND OUTLOOK

Digital twins are regarded as central building blocks of a digitalized industry. Since their development is still in its very beginnings, it is necessary to integrate the elementary requirements of sustainable production now in order to encourage researchers and developers in relevant areas.
(e.g. information technology, production engineering, business administration) to address them well in advance and implement them appropriately. After a number of recent publications, industry associations and standardization bodies have proclaimed sustainability as a main pillar of digital twin development. In this paper, we reflected on the general concept of sustainable production and discussed perspectives of digital twins. Other than recent studies that provide valuable use cases for isolated aspects of sustainability (bottom-up approach), we took a top-down perspective in order to paint the big picture.

Based on a comprehensive discussion of the baseline concept of sustainability, we first note that its scope has not yet been adequately addressed in production science. We conclusively argue that existing interpretations of sustainable production do not suffice to meet its intended core objective (environmental preservation). We then present a normative systems thinking interpretation of production, which is subsequently referred to as biointelligence (i.e. the rational management of natural resources). A production of this kind operates as a holistic, complex organism whose limits correspond to the planetary boundaries. Prerequisites for the implementation of the concept in industrial practice are the resolution of existing methodological hurdles (especially in sustainability science), an extensive, intelligently designed data exchange between producing units as well as collective impact assessment and a controlling unit of the entirety of production. This controlling unit would be responsible for the determination of the current status of planetary stability at regular intervals, to calculate a safe-operating space for a certain period according to standardized procedures, to break down individual units as (planetary budgets) into individual economic units (companies, households) and to ensure that these are adhered to by means of monitoring and enforcement.

In a further step, we discussed the role of digital twins and digital threads within this concept. A digital representation of a physical entity must serve as the foundation of an IT-supported transformation towards a sustainable production by acting as an enabling technology. As a result of the reflections, we derived 10 major demands for the role of DTs with regard to the normative systems thinking approach of production. Apart from requirements mainly resulting from existing publications (interoperability, security, adaptability, submodels for existing methods etc.), we outlined a far-reaching vision. Therein the control unit is envisaged as an independent cerebral intelligence, in which DTs would act as the synapses of an organism-like entirety of all industrial production units. Further needs arise from this, especially for the submodels to be integrated in digital twins (predictive sensitivity models, collective impact models, autonomous ecosystem decision models etc.). The comparison of these demands with recent publications in the field reveals that only three out of 10 demands have already been addressed by individual initiatives or examined in case studies. These are the insurance of data interoperability and appropriate access rights, the compilation of environmentally relevant data as well as the incorporation of environmental impact models. We conclude that future digital twin research should increasingly address transparency issues of chemical composition and physical design principles. This serves environmental compliance as well as disassembly. A constant autonomous checking of relevant standards and databases and their linking to material and substance composition models is required to assure accordance with the ever changing regulatory requirements. Extensive further research is required for the development and implementation of specific sustainability-relevant submodels, among others including collective predictive models for the secondary use of all substances used at different points in the life cycle of an entity, ecosystem impact as well as AI-based independent, interlinked ecosystem control submodel(s).

The core objective of the paper was to stimulate interdisciplinary scientific discourse by critically reflecting on the interpretation of sustainable production and the role of digital twins. We are aware that with this paper we are addressing some aspects in the context of sustainability that may only become feasible in the distant future or may never be implemented, whether due to technical or political hurdles. Nevertheless, we are convinced that the perspective presented here can serve as a basis for an appropriate technology development and application in production sciences.

**AUTHOR CONTRIBUTIONS**

**Robert Miehe:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; visualization; writing-original draft; writing-review and editing. **Lara Waltersmann:** Formal analysis; writing-original draft; writing-review and editing. **Alexander Sauer:** Resources; supervision. **Thomas Bauernhansl:** Resources; supervision.

**DATA AVAILABILITY STATEMENT**

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

[1] R. Miehe, T. Bauernhansl, M. Beckett, C. Brecher, A. Demmer, W. G. Drossel, P. Elfert, J. Full, A. Hellmich, H. Hinßlage, J. Horbelt, G. Jutz, S. Krieg, C. Maufroy, M. Noack, A. Sauer, U. Schließmann, P. Scholz, O. Schwarz, M. ten Hompel, P. Wryczka, M. Wolperdinger, J. Manuf. Syst. 2020, 54, 50.

[2] Sustainable Europe Research Institute [Ed.]. Global resource extraction by material category; 1980–2011. http://www.materialflows.net

[3] Fischer-Kowalski, M., von Weizsäcker, E., Ren, Y., Moriguchi, Y., Crane, W., Kraussmann, F. et al. Decoupling natural resource use and environmental impacts from economic growth: Report of the Working Group on Decoupling to the International Resource Panel. Paris; 2011.

[4] Zukunftsfakademie Oberösterreich [Ed.]. Endlichkeit der Rohstoffe Ressourcenvorräte von A bis Z. Linz; 2013.

[5] Intergovernmental Panel on Climate Change [Ed.]. Global warming of 1.5°C – Summary for policy makers. IPCC, Switzerland.

[6] European Environment Agency. Energy and climate change. Kopenhagen. 2017. https://www.eea.europa.eu/signals/signals-2017/articles/energy-and-climate-change

[7] United Nations [Ed.]. Take Action for the Sustainable Development Goals. New York, 2020. https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[8] M. J. Epstein, M. J. Roy, Long Range Plann. 2001, 34, 585.

[9] S. Engert, R. J. Baumgartner, J. Cleaner Prod. 2016, 113, 822.

[10] C. Wijethilake, J. Environ. Manage. 2017, 196, 569.

[11] M. Hauff, A. Jörg, Oldenburg Wissenschaftsverlag 2012.

[12] J. Kopfmüller, Ökologisches Wirtschaften. 2007, 1, 16.

[13] R. N. Langlois, Ind. Corp. Change 2003, 12, 351.

[14] R. Merrifield, J. Calhoun, D. Stevens, Harv. Bus. Rev. 2008, 86, 72.

[15] Y. Yoo, Mis Q 2010, 34, 213.

[16] Y. Yoo, O. Henfridsson, K. Lytinen, Inf. Syst. Res. 2010, 21, 724.

[17] M. G. Guillemette, G. Paré, Mis Q 2012, 36, 529.

[18] J. Kallinikos, A. Aaltonen, A. Marton, Mis Q 2013, 37, 357.

[19] D. Cerri, S. Terzi, Comput. Ind. 2016, 81, 47.

[20] G. Beier, S. Niehoff, B. Xue, Appl. Sci. 2008, 8, 219.

[21] A. Keenso, Big Data and Environmental Sustainability: A Conversation Starter, Smith School of Enterprise and the Environment, Oxford, UK 2015.

[22] barni, a. Fontana, a. Menato, S. Sorlini, M. Canetta, L. Exploiting the digital twin in the assessment and optimization of sustainability performances. International Conference on Intelligent Systems (IS); 2018; 706–713.

[23] S. Kaewwrunrue, N. Xu, Front. Built Environ. 2018, 4. https://doi.org/10.3389/fbuil.2018.00077.

[24] E. Altamiranda, E. Collina, OCEANS 2019, 1. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8867187.

[25] K. Kannan, N. Arunachalam, J. Manuf. Sci. Eng. 2019, 141. https://doi.org/10.1115/1.4042076.

[26] F. Xiang, Z. Zhang, Y. Zuo, F. Tao, Proc. CIRP 2019, 81, 1290.

[27] B. He, K. J. Bai, Adv. Manuf. 2020, 9, 1.

[28] Deutsches Institut für Normung and Deutsche Kommission Elektrotechnik [Ed.]. Deutsche Normungssroadmap Industrie 4.0 Version 3, 2018.

[29] Deutsches Institut für Normung [Ed.]. DIN 77005–1:2018, Lebenslaufakte für technische Anlagen—Teil 1: Strukturelle und inhaltliche Festlegungen, 2018.

[30] International Organization for Standardization [Ed.]. ISO 20140 Automation systems and integration — Evaluating energy efficiency and other factors of manufacturing systems that influence the environment.

[31] British Standards Institution [Ed.]. BS EN IEC 62832–3 Industrial-process measurement, control and automation. Digital Factory framework. Part 3. Application of Digital Factory for life cycle management of production systems.

[32] N. Nikolakis, K. Alexopoulos, E. Xanthakis, G. Chryssolouris, Int. J. Comput. Integr. Manuf. 2019, 32, 1.

[33] G. E. Modoni, E. G. Caldarola, M. Sacco, W. Terkaj, Proc. CIRP 2019, 79, 472.

[34] A. Rasheed, O. San, T. Kvamstdal, IEEE Access 2020, 8, 21980.

[35] H. C. Carlowitz, Sylvicultura Oeconomico oder haufwirthliche Nachteile und Naturgemäße Anweisung zur Wilden Baum-Zucht, Johann Friedrich Braun, Leipzig 1713.

[36] U. Grober, Die Entdeckung der Nachhaltigkeit: Kulturgeschichte eines Begriffs, 3rd ed., Kunstmüntn, München 2010.

[37] World Commission on Environment and Development [Ed.]. Our Common Future: Report of the World Commission on Environment and Development: United Nations, 1987. Available: www.un-documents.net/our-common-future.pdf

[38] H. E. Daly, Popul. Develop. Rev. 1990, 16, 25.

[39] B. G. Norton, M. A. Toman, Land Economics 1997, 73, 553.

[40] E. Neumayer, Weak versus strong sustainability: Exploring the limits of two opposing paradigms, 2nd ed., Edward Elgar Publishing Ltd, Cheltenham, UK 2003.

[41] J. Hartwick, Am. Economic Rev. 1977, 67, 972.

[42] R. Costanza, H. E. Daly, Consen: Biol. 1992, 6, 37.

[43] Pearce, DW, Howarth, A. Technical Report on Methodology: Cost Benefit Analysis and Policy Responses. Blithoven, 2000. http://ie.europa.eu/environment/envanco/priority_study/pdf/methodology.pdf

[44] R. Döring, K. Ott, Zeitschrift für Wirtschafts- und Unternehmensethik 2001, 2, 315.

[45] K. Ott, R. Döring, Theorie und Praxis starker Nachhaltigkeit, 2nd ed., Metropolis, Marburg 2008.

[46] Brand, KW, Jochum, G.Der deutsche Diskurs zu nachhaltiger Entwicklung, 2000. http://www.sozialforschung.org/wordpress/wp-content/uploads/2009/09/kw_brand_deutscher_nachhaltigkeit.pdf

[47] K. M. Meyer-Abich, Zeitschrift für Wirtschafts- und Unternehmensethik 2001, 3, 291. http://www.soor.info/soor/bitstream/handle/document/34.

[48] E. U. Von Weizsäcker, A. Wijkman, Come on!. Berlin

[49] Janson, M. Der Bundeshaushalt 2020. Statista. Statista

[50] Karlsruhe

[51] J. Jörissen, J. Kopfmüller, V. Brandl, et al., Unternehmensethik

[52] J. Rockström, W. Steffen, K. Noone, et al., Feature 2009, 461, 472.
Industry 4.0 asset administration shell and the digital twin during the life cycle of a plant. 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2017:1–8.

[112] A. Seif, C. Toro, H. Akhtar, Proc. Comput. Sci. 2019, 159, 495.

[113] Hankel, M. Reference Architecture Model for Industry 4.0 and International Collaboration: OPC Day Finland 2017. Finish Society of Automation. 2019. https://www.youtube.com/watch?v=_7XnF6K_OY

[114] Plattform Industrie 4.0. The asset administration shell: Implementing digital twins for use in Industrie 4.0: Making Industrie 4.0 components interoperable. Berlin, 2019. https://www.plattform-i40.de/Pl40/Redaktion/DE/Downloads/Publikation/verwaltungsschale-im-detail-pr%C3%A4sentation.html

[115] Plattform Industrie 4.0 Die Verwaltungsschale im Detail - von der Idee zum implementierbaren Konzept. Berlin, 2019. https://www.plattform-i40.de/Pl40/Redaktion/DE/Downloads/Publikation/verwaltungsschale-im-detail-pt%C3%A4sentation.html

[116] Plattform Industrie 4.0. Details of the Asset Administration Shell: Part 1 - The exchange of information between partners in the value chain of Industrie 4.0 (Version 2.0). Berlin, 2019. https://www.plattform-i40.de/Pl40/Redaktion/DE/Downloads/Publikation/Details-of-the-Asset-Administration-Shell-Part1.html

[117] Plattform Industrie 4.0. Diskussionspapier Verwaltungsschale in der Praxis: Wie definieren ich Teilmodelle, beispielhafte Teilmodelle und Interaktion zwischen Verwaltungsschalen (Version 1.0). Berlin, 2019. https://www.plattform-i40.de/Pl40/Redaktion/DE/Downloads/Publikation/2019-verwaltungsschale-in-der-praxis.html

[118] Kalhoff, J, Löwen, U, Manger, T, Schneider, K. Open Source Projekt openAAS – mit offenen Standards Industrie 4.0 umsetzen. 2017. https://www.zvei.org/fileadmin/user_upload/Verband/Fachverbaende/Automation/Open-Source-Projekt-openAAS-mit-offenen-Standards-Industrie-4.0-umsetzen.pdf

[119] E. Tantik, R. Anderl, Proc. CIRP 2017, 64, 363.

[120] T. D. West, A. Pyster, Insight 2015, 18(2), 45.

[121] V. Singh, K. E. Willcox, AIAA J. 2018, 56(11), 4515.

[122] L. Waltersmann, S. Kiemel, I. Bogdanov, J. Leitgen, R. Miehe, A. Sauer, J. Mandel, Proc. Manuf. 2019, 39, 685.

[123] R. Miehe, S. Mueller, R. Schneider, S. Wahren, M. Hornberger, Int. J. Precision Eng. Manuf.-Green Technol. 2015, 2, 289.

[124] Deutsches Institut für Normung. DIN EN 50581: Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances.

[125] M. A. Curran Ed., Life cycle assessment handbook: a guide for environmentally sustainable products, John Wiley & Sons, Hoboken, New Jersey 2012.

[126] Verband Deutscher Ingenieure, Ressourceneffizienz - Methodische Grundlagen, Prinzipien und Strategien, Düsseldorf 2016.

[127] R. Miehe, Methodik zur Quantifizierung der nachhaltigen Wertschöpfung von Produktionsystemen an der ökonomisch-ökologischen Schnittstelle anhand ausgewählter Umweltprobleme, Fraunhofer Verlag, Stuttgart 2018.

[128] Project Drawdown. The World’s Leading Resource for Climate Solutions. https://www.drawdown.org/

[129] Detzner, A., & Eigner, M. (2018). A digital twin for root cause analysis and product quality monitoring. In DS 92: Proceedings of the DESIGN 2018 15th International Design Conference 1547–1558

[130] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, F. Sui, Int. J. Adv. Manuf. Technol. 2018, 94, 3563.

[131] X. V. Wang, L. Wang, Int. J. Prod. Res. 2019, 57, 3892.

[132] K. Bradley, Library Trends 2007, 56, 148.

[133] P. Seele, Sustainability Sci. 2016, 11, 845.

[134] D. Chen, S. Heyer, S. Ibbotson, K. Salonitis, J. G. Steingrimsson, S. Thiede, J. Cleaner Prod. 2015, 107, 615.

[135] Stürmer, M. Characteristics of digital sustainability. Proceedings of the 8th International Conference on Theory and Practice of Electronic Governance. 2014, 494–495.

[136] Bradley, K. Digital sustainability and digital repositories. 2008. https://openresearch-repository.anu.edu.au/handle/1885/46784

[137] B. Jickling, Environ. Educ. Res. 2001, 7, 167.

[138] G. Chowdhury, J. Doc. 2013, 69, 602.

[139] M. Steuern, G. Abu-Tayeh, T. Myrach, Sustainability Sci. 2017, 12, 247.

[140] Dalmolen, S, Cornelisse, E, Stoter, A, Hofman, W, Bastiaansen, H, Punter, M, Knoors, F. Improving sustainability through intelligent cargo and adaptive decision making. E-Freight Conference. 2012.

How to cite this article: Miehe R, Waltersmann L, Sauer A, Bauernhansl T. Sustainable production and the role of digital twins—Basic reflections and perspectives. Journal of Advanced Manufacturing and Processing. 2021;3: e10078. https://doi.org/10.1002/amp2.10078