Digital Twins for Sustainability in the Context of Biological Transformation

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Abstract. Applying biological principles that are similar to those found in nature to product engineering and manufacturing offers new approaches to product and production systems and might lead to a significant contribution towards sustainability. By transferring materials, structures, and processes of natural to digital ecosystems industrial value creation can be optimized. A promising approach to establish a networked, self-regulating digital ecosystem represents a digital twin. The potential of digital twins within the context of biological transformation has not been researched yet. This paper attempts to provide a first entry into the research topic by identifying biological principles within the concept of a digital twin and analyzing its potential for biological transformation in the industry. As a main result, the paper presents a list of relevant principles of biological transformation based on a structured taxonomy. These are specified within the concept of a digital twin.

Keywords: Biological Transformation · Digital Twin · Sustainability · Biologicalization · Digitalization

1 Introduction and Research Approach

During the last two centuries, manufacturing systems have changed in shape and form innumerable times [1]. Up until now, the manufacturing industry is obliged to adapt due to emerging challenges such as demographic change, individualization, digitalization, the increasing scarcity of natural resources, and the growing demand for sustainability [2]. In response to many such demands, companies currently place their confidence in Industry 4.0 and digital transformation [3]. With regard to the fourth industrial revolution, the main items on the agenda are productivity gains, flexibility enhancements, and cost reductions, whereas sustainability commonly plays a subordinate role [4]. This is where Biological Transformation (BT) comes into play – a holistic approach to change industrial value creation towards sustainable optimized production systems, by an accelerating convergence of technical, digital, and biological systems in the manufacturing environment [5]. Embracing principles of nature by transferring materials, structures, and processes of natural to digital ecosystems harbors the great potential for sustainable and resource-efficient manufacturing [6]. The concept of a Digital Twin (DT) therefore represents a promising approach to establish a networked, self-regulating ecosystem

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whose stability and resilience are to be monitored and controlled with regard to ecological parameters. The potential of DTs for sustainability in the context of BT has not been researched yet. Hence, this paper attempts to provide a first entry into the research topic by presenting a conceptual framework and addressing the following research questions: "What are the relevant biological principles of a DT for sustainability? (RQ I)" and "How can these biological principles be integrated into a conceptual framework of a DT in the context of BT to foster sustainability in industrial value creation? (RQ II)".

In order to systematically answer these research questions, the state of the art of BT in manufacturing and DTs for sustainability will first be specified. As part of a systematic literature review on DTs in the context of BT, a more detailed understanding of the research area will be developed in order to deduce the research gap addressed within this paper. Starting from this gap, a conceptual framework will be derived that integrates biological principles into the concept of a DT for sustainability and serves as an initial provision of support. The result of the present paper must accordingly be regarded as a first basis that needs to be evaluated, specified, and applied in future research work.

2 State of the Art

2.1 Biological Transformation in Manufacturing

BT in general describes the holistic transformation from traditional industrial value creation towards sustainable value creation systems [7] by transferring principles, materials, functions, and structures from nature into technical systems [8]. The knowledge from nature is applied systematically in the context of BT in manufacturing [9] and pursues the aim of optimizing production systems regarding their societal and business challenges. In this context, a convergence of the bio- and technosphere is pursued [7]. The BT can be divided into three development modes [10], which include different levels of convergence of the bio- and technosphere [7]: *Inspiration* involves translating natural phenomena in the form of concepts (fluid dynamics, lightweight construction, biomechanics), processes of evolution (bio-analogue optimization techniques, swarm intelligence, neural networks), and principles of nature (resilience, self-organization, self-healing) into technical value creation systems [2, 7, 10]. *Integration* refers to the transfer of biological and technical processes to traditional value creation systems [7]. Examples include closed loops, the manufacturing of new products by using microorganisms to recover rare earth from magnets, extracting biofuel from CO_2 waste streams, and extracting methane from industrial wastewater [7, 11]. With digitalization and Industry 4.0, BT is experiencing a new dynamic. Beyond bio-inspired and bio-integrated approaches, current technological developments offer the possibility to foster sustainable value creation with the *interaction* of biological and technical systems by means of intelligent information systems such as the concept of a DT [8, 12]. The aim is to develop new and autonomous production technologies and structures [10].

The biological transformation has different facets, basically inspiration, integration, and interaction. These can be expressed in various principles of nature. One way to describe and structure these principles is through taxonomies. The Biomimicry Taxonomy, for instance, covers various principles in eight major categories, which can be transferred in abstract form to the solution of technical problems [13].

2.2 Digital Twins for Sustainability

In general, DTs can be defined as "a digital representation of an active unique product [...] or unique product-service system (a system consisting of a product and a related service)" [14]. A DT consists of the interlinkage of Digital Master-data, which are models and information from the planning phase, and production, usage, or end of life data of an individual system instance, the so-called Digital Shadow.

DTs for sustainability are based on the definition of DTs with the specific aim to foster sustainability in the form of a minimized environmental impact [15, 16]. One specific approach in this context is the calculation of the environmental impact with Life Cycle Assessment as standardized in the ISO 14044 [17]. With the help of a DT with integrated LCA, an "As planned-LCA" for different product design variants and corresponding process alternatives can already be carried out during the design phase of a product and be stored within the Digital Master (see A in Fig. 1). With the start of the production phase, the product generates an individual CO_2 footprint ("As is-LCA") which is being captured along consecutive lifecycle phases via unique identifiers within the Digital Shadow (see B in Fig. 1). Through the linkage of master models and shadow data within the DT Core, lifecycle information such as data from production, usage, or end of life can be systematically made available and processed into valuable information. Thus, the comparison between "As planned-" vs. "As is-LCA" (see C in Fig. 1) may enable the provision of insights for future product optimizations (Feedback to Design). However, analysis and interpretation within the DT Core (see D in Fig. 1) can also be used to execute control commands via direct feedback to the physical system, for instance, to optimize product behavior with regard to CO_2 emissions.

2.3 Digital Twins in the Context of Biological Transformation

To analyze the state of the art of research on DTs in the context of BT, a systematic literature review was conducted. Limiting the search query to the terms biological transform* and digital twin* resulted in zero hits in the databases Scopus, Web of Science, and eLib. To broaden the data set for the literature review, more general keywords were used. The query, formulated as followed, retrieved 24 publications: TITLE-ABS-KEY (("biological transform*" OR "bio*inspir*" OR "bio*integrat*" OR "bio*interact*" OR "bio*intelligen*") AND ("digital twin*" OR "digitization" OR "digitalization" OR "digital technolog*")). After screening the results in full text, the respective publications were rated as high-, medium- and low-appropriate for the subject matter. Publications with low appropriateness for analysis either had no specific reference to BT or digital solutions or included case studies from other domains being too specific to be transferred to manufacturing. Papers of the subject area "manufacturing", that tended to consider the DT concept at a very high altitude or only as a marginal note have been rated with medium appropriateness. Publications with high appropriateness contained the term "Digital Twin" and will be described in more detail below.

Miehe et al. [10, 18] develop a framework of ten fields of action for BT of industrial value creation. According to their findings, the prerequisite for increased resilience of manufacturing systems are robust technologies constantly monitoring significant states of products, processes, and production systems. In the context of BT, the DT adopts the function of a genotype (genetic data) to its respective component state, the phenotype, and thus, may act as an enabler for optimized process transparency and planning. With the help of simulation and bio-inspired algorithms (e.g. swarm intelligence, ant algorithms) this ‘manufacturing gene pool’ will continue to expand [19, 20].

Bergs et al. [3] introduce projects applying BT in manufacturing. The project EVOLOPRO represents a bio-inspired approach for the utilization of biological principles (e.g. diversity of variants, facilitated variation) for optimizing complex self-adapting production systems with the help of DTs. Here, the DT evolving through learning and interaction analyzes and evaluates the difference between a targeted and an actual state of a manufactured product by using evolution-based algorithms and thus, helping the production system to perform better in future situations (increased fitness).

Miehe et al. [12] examine the transferability of existing DT architectures (Asset Administration Shell (AAS), RAMI4.0 Architecture) to biological systems. Therefore, Miehe et al. present a scalable model integrating structural and functional features of biological systems for the interoperability between process steps across company borders for both technological and biological assets.

In summary, literature on DTs in the context of BT is scarce. Recent publications in this field ascribe DTs significant potential for biological transformed value creation (e.g. enhanced process transparency and planning, optimized production systems), but lack a general contextualization of the concept of a DT within BT. By identifying relevant biological principles within the concept of a DT for sustainability, this paper attempts to provide a first entry into the topic and fill in the identified research gap.

3 Concept of a Digital Twin in the Context of Biological Transformation

Based on the identified research gap, a conceptual framework for DTs for sustainability in the context of BT is proposed. The derived framework that is shown in Fig. 1 extends the current definition of Stark et al. [14] and Riedelsheimer et al. [15] to include the aspects of BT.

The DT accompanies its physical counterpart throughout its entire lifecycle [21]. Within this digital representation, selected characteristics, states, and behaviors of the product instance or system are reflected and models, information, and data are linked across lifecycle phases [14]. Along the lifecycle of a product, the DT uses enriched data sets on different product states, such as 3D models and product structures from CAD or PLM systems (“As designed”), manufacturing BOMs of the product instance from ERP or MES systems (“As built”), information on maintenance history (“As maintained”), or (real-time) data from the use phase (“As used”) [22].

Within this paper, BT in manufacturing is being referred to as a process of optimizing industrial value creation towards sustainability with concepts and technologies inspired by nature, integrating biological aspects, and operating in the interaction between digital and biological systems. The present framework is therefore primarily focusing on DTs for sustainability offering the opportunity to leverage existing data and optimize both the individual sustainability of the system and future product generations by means of an LCA (see Subsect. 2.2).

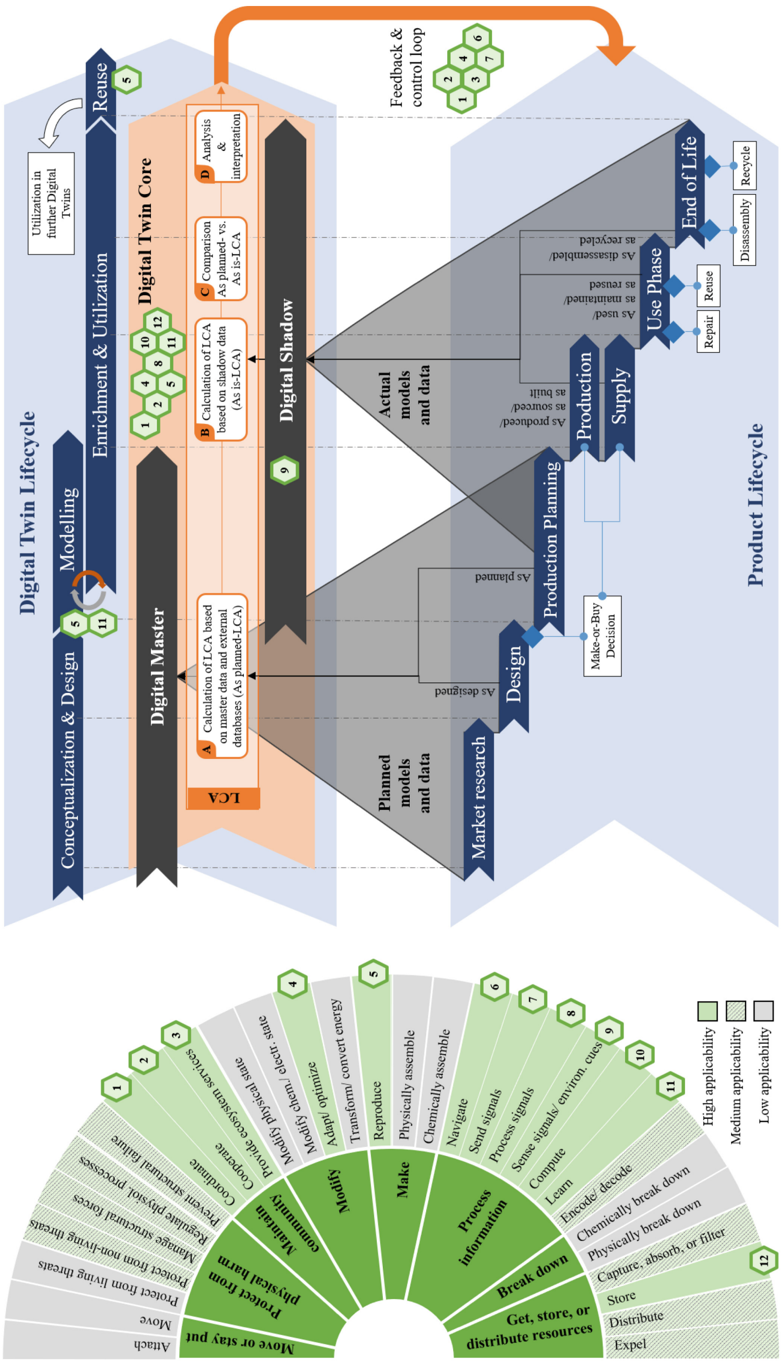

Fig. 1. Concept of a Digital Twin for Sustainability in the Context of Biological Transformation

In order to systematically address RQ I, relevant biological principles of the Biomimicry Taxonomy [13] were assessed according to their applicability to the concept of DTs for sustainability. The result of the assessment is depicted in Fig. 1. Principles with low applicability address natural characteristics that relate to physical changes of the ecosystem (e.g. "Physically assemble", "Chemically break down") and were thus excluded from further considerations. Biological principles which are assignable to a general concept of a DT, but lack a certain transferability to DTs for sustainability were rated as medium-applicable (e.g. "Manage structural forces"). In response to RQ II, the remaining high-applicable principles are listed in Table 1 with corresponding examples within a DT for sustainability. As a digital ecosystem a DT inherents various biological principles itself but also serves as an enabler of biological transformed products by equipping it with characteristics inspired from nature to ultimately optimize its resilience, stability, and sustainability.

Table 1. Biological principles and examples within a DT for sustainability

Biolog. Principle	Examples within a DT for sustainability
Coordinate	e.g. Coordination of processes along the lifecycle to reduce CO_2 footprint: Monitoring of ecological parameters and identification of optimization potential
Cooperate	e.g. Intelligent linkage between master models and shadow data along the lifecycle (internally, across companies/industries)
Provide ecosystem services	e.g. Provision of insights for future product optimizations (Feedback to Design), execution of control commands via direct feedback to the physical system, for instance, to optimize product behavior with regard to CO_2 emissions
Adapt/optimize	e.g. Adaptation/optimization of physical system based on monitoring of CO_2 footprint
Reproduce	e.g. Provision of a physical system's copy and instantiation of DT along lifecycle and utilization for further Digital Twins (fleet, variants)
Navigate	e.g. Management of assets within production system with regard to ecological parameters for increased sustainability
Send signals	e.g. Visualization of "As planned-" vs. "As is-LCA" in dashboard
Process signals	e.g. Calculation of LCA based on master data, external databases, and shadow data as well as comparison of "As planned-" vs. "As is-LCA"

(*continued*)

Table 1. (*continued*)

Biolog. Principle	Examples within a DT for sustainability
Sense signals/environ. Cues	e.g. Data acquisition of operational, state, or process data in Digital Shadow (e.g. energy consumption)
Compute	e.g. Analysis and interpretation of "As planned-" vs. "As is-LCA"
Learn	e.g. Adaptation and optimization of DT itself based on historical data
Store	e.g. Storage of master models or shadow data with regard to ecological parameters

4 Conclusion and Outlook

BT as a holistic approach to change industrial value creation towards sustainable optimized production provides promising answers to current challenges such as resource scarcity, the reduction of ecological footprints, and climate change. A DT for sustainability offers the opportunity to optimize a product by impersonating the characteristics and functions of natural ecosystems. Leveraging and processing existing ecological data into valuable information along a product's lifecycle, with the help of DTs might ultimately lead to enhanced resilience, stability, and sustainability of the physical counterpart. Given the absence of theoretical foundations in recent literature, the objective of this paper was to develop a conceptual framework of a DT in the context of BT (RQ II) by identifying relevant biological principles of a DT for sustainability (RQ I). The main academic contribution of the present paper lies in its attempt to fill in the identified research gap and broaden companies' horizons towards the potential of DTs in the context of BT by providing a more holistic perspective. Given the diversity of DT use cases, the framework is deliberately kept general and therefore requires adjustments to individual project needs. Additionally, the potential to foster sustainability in manufacturing has not been quantified yet. In this connection, the impact and rebound effects of the DT on the ecosystem's CO_2 footprint should not be neglected in subsequent research. To this end, the developed framework shall be considered as a starting point and evolving concept, which needs to be further detailed with insights gained from evaluation, practical application, and future research.

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