Taxonomy for Biological Transformation Principles in the Manufacturing Industry

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Abstract. Industry and research are seeking answers to current demands in industrial value creation, like resilience of production, sufficient product quality and sustainability of products and processes. A novel line of thought, seeking the accomplishment of those is the Biological Transformation (BT). BT describes the interweaving of biological modes of action, materials and organisms with engineering and information sciences. The conflation of disciplines from natural, technical and social sciences yields in a heterogeneous field of activities with ambiguous technical terms. An ascertainment of principles of BT is required to classify yet undifferentiated patterns in nature-based production, facilitating their systematic implementation in aiming for sustained solutions on current challenges. With increasing research in biomimetic, attempts arise to capture nature-based activities in manufacturing through schematic classifications. Yet, basic semantics representing the effective principles of BT in the manufacturing industry is lacking.

The goal of this publication is to introduce a taxonomy of Biological Transformation in manufacturing based on its core principles Bio Inspiration, Bio Integration and Bio Interaction. Within the research project BioFusion 4.0, the taxonomy was developed and applied to classify technology innovations. The paper presents the taxonomy, its development and application in use cases.

Keywords: Biological transformation · Manufacturing · Sustainability · Taxonomy · Biomimicry · Use cases

1 Introduction

Industrial companies are in constant progress, moved by trends and long-lasting conversion. Increased public awareness of sustainability issues, increasing political constraints for environmental protection, resource scarcity and supply chain shortages characterize today's market. Mastering these challenges while ensuring product quality with new industrial technology solutions is perhaps the most crucial task of the present time. The internet of things, artificial intelligence, big data or digital twins are promising innovations for that matter [1]. On multiple levels in industry and research digitalization and

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Industrie 4.0 are being demonstrated to offer the potential to fundamentally improve various aspects of production such as quality, costs, and sustainability [2, 3]. To this regard, Biological Transformation (BT) is an emerging development in the field of Industrie 4.0. When applied in manufacturing this concept involves the systematic application of processes, principles and resources from biotic nature in technical systems by means of information technology [4]. Systematically applying knowledge about principles of BT in manufacturing is key to achieving promising effects like ecological stability, social well-being and economic resilience in production. This paper focuses on establishing a common language for and a clear definition of BT.

2 Biological Transformation in Manufacturing Industry

For the definition of BT in manufacturing, its historical development as well as the relevant fields of action, Industrie 4.0 and digitalization, are analyzed in the following.

Bioinspired Manufacturing. The transfer of biological forms and functions to technical application fields is first defined as bionics by J.E. Steele [5] and expanded by W. Nachtigall to include "aspects of the interaction of animate and inanimate systems as well as the economic-technical application of biological organizational criteria" [6]. As a scientific discipline, bionics is also termed *biomimicry, biometics, biomimesis*. In design and engineering in particular, databases of biological information sources, are already providing support via context-sensitive search with increasing prominence under the term *biologically inspired design* (BID) as a design movement for environmentally sustainable development [7, 8]. Evolving bionic ties in with new technical possibilities of nano-, bio-, information & communication technologies as well as cognitive sciences and artificial intelligence, which in the longer term is described as converging technologies [9]. In the context of technical innovations, Gleich [10] speaks of evolutionary generalizable optimization principles at the molecular level up to the ecosystem.

Industrie 4.0 and digitalization In Manufacturing. Focusing on the industrial manufacturing environment, the merge of the physical and virtual world marks the fourth industrial revolution, where production and information & communication technologies are converging. The vision of Industrie 4.0 describes a highly flexible, resource-saving and urban-compatible production. At the heart of Industrie 4.0 is the smart factory, where humans and machines work hand in hand, supported by intelligent assistance systems [11]. Technological progress and the accompanying digitization, in the sense of the process of introducing and using digital technologies [12], are leading to far-reaching transformation processes at the economic and social level.

Biological Transformation. From a production engineering perspective, the BIOTRAIN study defines "biointelligence" as the interaction of technical, biological and IT systems [13]. Generally, BT is understood as the transfer of principles of natural systems to technical materials, structures and processes, aiming for sustainable value creation [14]. Key concepts of BT are inspiration, integration and interaction [15]. On international level, the white paper "Biologicalisation: Biological transformation in manufacturing" describes these concepts from a production technology perspective [16]. Based on the state of the art in literature, the following definition is derived:

Biological Transformation in manufacturing is a holistic approach to change industrial value creation towards sustainable optimized product and production systems, by an accelerating convergence of technical, digital, and biological systems in the manufacturing environment. BT proceeds in three complementary developmental modes: (1) the integration of biological materials, structures, organisms, processes and functionalities, (2) the inspiration by nature and the transfer to the design of products and manufacturing technologies as well as (3) the interaction of the bio- and technosphere by means of information technology.

Existing classification schemes in scope of BT make biological information accessible to engineers and product designers for innovation processes [8, 17]. As a recognized approach the *Biomimicry Taxonomy* supports the inspiration from nature by classifying its functions by a terminology, comprehensible for non-biologists [8]. However, it does not fully capture the integration of biological into technical systems or the interweaving of biological, technical and IT systems. Following the given definition of BT and the potentials of a synergetic convergence of BT with Industrie 4.0, the herein presented taxonomy of Biological Transformation in manufacturing is addressing this research gap, by giving a systematic and more comprehensible overview of effective principles of BT. Providing this knowledge base is the first and essential step in enabling sustainability in manufacturing by means of the Biological Transformation.

3 Taxonomy Development and Presentation

3.1 Methodological Approach

A methodology widely established in information science to develop taxonomies was created by R. Nickerson [18]. The taxonomy of Biological Transformation in manufacturing was developed using an updated version of this methodology, ensuring that outcome and process are easily understood by a wide range science groups [19].

The deductive methodology was chosen following the basic subdivision of BT in the principles Bio Inspiration, Bio Integration and Bio Interaction by Bauernhansl [13]. The first taxa were chosen accordingly. Pre-collected characteristics were classified into the taxonomy and additional taxa were deductively derived. Subcategories of Bio Inspiration, Bio Integration, and Bio Interaction were fanned out to modes of action. Bio Inspiration was divided through concepts that describe how and in which forms natural functionalities can be adopted. Herein, the subcategory resilience was further divided by concept of J. Benyus [20]. The subcategory principles of circularity derived from [21, 22, 23]. The subcategory self-x was divided by concepts of Speck et al., Gleich et al., Müller-Schloer et al. and Gausemeier et al. [24–26, 26]. The subcategory functional morphology was divided by concepts of W. Nachtigall [28] and subcategory biomimetic information modelling and processing by a concept described in VDE Norm 6225 [29]. Categories in Bio Integration derivated from Matyushenko et al. [30] followed by a broad literature research on principles in biotechnology. Bio Interaction was divided into subcategories, on basis of the IPO-model [31] known from computer sciences, and with Input of the German Standardization Roadmap on Artificial Intelligence, the High-Level Expert Group on Artificial Intelligence [32, 33]. Herein, biological intelligent information processing and biointelligent communication were divided by concepts of W. Wahlster [34], biohybrid actuation following the work of Ricotti et al. [35].

3.2 The Taxonomy of Biological Transformation in Manufacturing

The taxonomy is organized hierarchically by the three core principles Bio Inspiration, Bio Integration and Bio Interaction, visualized in the following Fig. 1.

Within the core principle of Bio Inspiration 28 operating principles are organized into the five groups resilience, principles of circularity, self-x, functional morphology and biomimetic information modeling and processing. The core principle Bio Integration comprises the six groups biosynthesis, biosubstitution, biodegradation and decomposition, bioenergetics, biotherapeutics and biomodification. Within these, 18 effective principles are classified. Nine principles can be divided under the core principle Bio Interaction, which are grouped into biosensors, biological representation, biointelligent information processing, biohybrid actuation and biointelligent communication. This results in a total of 55 taxa, the principles of Biological Transformation in manufacturing, which are currently included in the taxonomy.

3.3 Validation of the Taxonomy with Industrial Use Cases

To investigate BT in the manufacturing environment and along a product's lifecycle, seven use cases are elaborated in the research project BioFusion 4.0. The use cases cover various industrial product and manufacturing solutions, ranging from digital twins in bio inspired product engineering, ecological intelligent services for production, intelligent recirculation of materials, biologically optimized process simulation of milling processes [36], bionic integration for networked production systems [37], additive manufacturing with biogenic and biodegradable polymers, up to biointelligent assistant systems for workers. These were used to validate the applicability of the taxonomy. For demonstration purposes the latter two are detailed in Table 1 and thereafter classified as per the taxonomy. With reference to the procedure for bionic design in VDE Standards 6226 and 6220 Part 2 [38, 39], the principles were allocated to the use cases in expert workshops via iterative analysis processes with methods of analogy mapping.

Use Case 1. An active exoskeleton responsive through physiological sensors fulfills the principle of *human-technology-interfaces* as part of *biointelligent communication.* Thus, the core principle *Bio Interaction* is applied. By suggesting less stressful postures and patterns to the workers, based on sensory ergonomic data, the workers are enabled to *self-optimization* of their ergonomic posture. Also, the enabling of information-driven adaptability of working modes leads to increased *resilience* of the production system as fewer absences due to health reasons result. Thus, the core principle of *Bio Inspiration* is brought into effect.

Use Case 2. Processing of disposed cooking oil by microorganisms into usable raw material is a principle of *biodegradation*, namely *bioconversion.* Simultaneously this

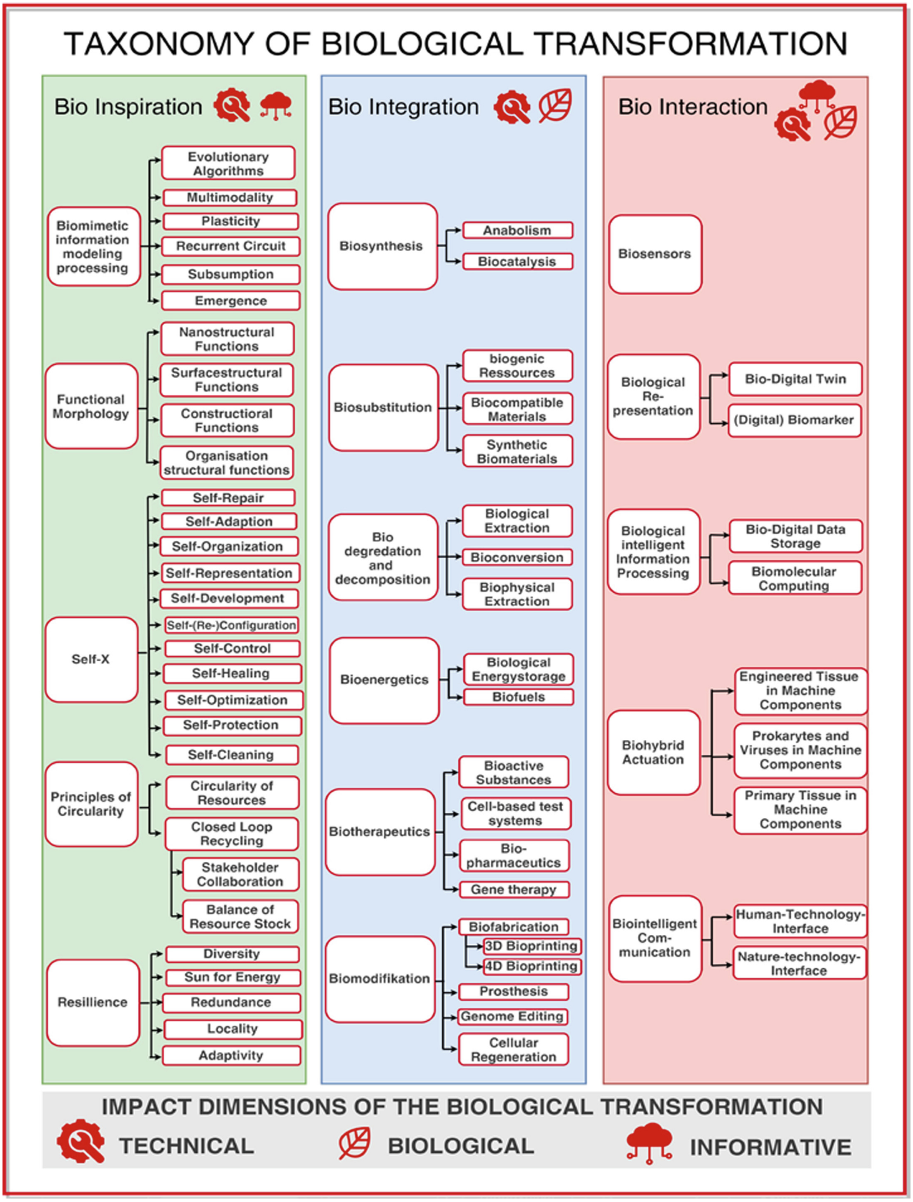

Fig. 1. The taxonomy of Biological Transformation in manufacturing (authors own illustration)

establishes the principle of *anabolism* in *biosynthesis*. The following utilization of the produced biopolymer in 3D printing instead of fossil polymers realizes the principle *biogenic resources* and because the biopolymer is nontoxic when handled by humans the principle of *biocompatible materials* is met in the use case. Thereby the core principle of *Bio Integration* is applied. The reuse of biogenic waste as a raw material establishes a

Table 1. Use cases and technological solutions for biological transformation

Use Case 1: Biointelligent assistant systems for worker	
Challenge	Physiological stress for worker during manual work in production environment; unclear impact on workers' health, unclear progress of manual tasks
Solution	Supporting worker during manual tasks with exoskeleton, equipped with sensors; monitoring of physical burden and work progress
Core functions	Data collection with sensors; support with actors; optimization of work mode
Context of use	Wearing during manual assembling by worker to monitor health indicators and work progress at the same time
Application Scenario	Assembly of automotive components, i.e. module for electric batteries as a high stress operations on health state of workers
Added Value	Increased ergonomics; reduced chronic physical overload; increased transparency on assembly quality
Use Case 2: Additive manufacturing with biogenic and biodegradable polymers	
Challenge	Limited resources; linear value creation; high amount of waste while still high need for new components and products
Solution	Usage of waste to produce bio based material for 3D-printing
Core functions	Processing and combination of material; creation of physical systems
Context of use	Printing of components for temporary usage that are biodegradable
Application Scenario	Disposed cooking oil is microbiological converted into biopolymer PHB, which is employed to 3D print consumable parts of tools in industrial production or disposable medical device, like orthosis
Added Value	Reduced resource use; Increased recycling quota

bioinspired *principle of circularity*, namely the principle of *circularity of resources*. The symbiosis is an important part to ensure circularity in ecosystems. The collaboration within the use case exists between producers of food waste, (communal) collectors of recyclable materials and recyclers, processors of polymers, and industrial companies, resulting in a *closed loop recycling* of materials. The primary raw materials, taken from nature for the production of edible oil, are ultimately returned to it through biological treatment of the bioplastic. The principle *balance of stock* takes effect.

4 Conclusion

The presented taxonomy for Biological Transformation in manufacturing provides a systematic overview of relevant principle effective in the interfaces of nature, technology and information technology. As technology is further evolving opportunities arise to facilitate BT in manufacturing, which requires a constant update of the taxonomy to make it a useful instrument for this progression. Particularly, the research on artificial intelligence and bionic information processing is evolving rapidly, setting new standards to be aligned within the taxonomy. As the ultimate goal of BT in manufacturing is sustainability, a necessity exists provide enabling means to industry stakeholders to identify and apply principles of the taxonomy in sustainable innovation processes.

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