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The biological transformation of the manufacturing industry – envisioning biointelligent value adding

Robert Miehe[a]*, Thomas Bauernhansl[a], Oliver Schwarz[a], Andrea Traube[a], Anselm Lorenzoni[a], Lara Waltersmann[a], Johannes Full[a], Jessica Horbelt[a], Alexander Sauer[a]

[a]*Fraunhofer-Institute for Manufacturing Engineering and Automation (IPA), Nobelstr. 12, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49(0)711/970-1424; fax: +49(0)711/970-1002. E-mail address: Robert.Miehe@ipa.fraunhofer.de

Abstract

Since the first industrial revolution manufacturing systems have been considered well-defined socio-technological entities that extract resources from the natural environment in order to create goods for the satisfaction of human needs. Productivity gains stimulated by technological innovations such as electricity and computers are inherent to the system. Whilst digitization depicts the latest paradigm, other technology leaps have virtually been neglected in traditional manufacturing science: biomimetics and biotechnology. In this context, we present the concept of a biointelligent industry outlining the vision of a naturally consistent subsistence strategy. Future industrial activities are expected to no longer extract resources from the environment but apply nature as a manufacturing utility. From a scientific point of view many issues, however, remain unanswered. In this paper we thus present fundamentals of a biological transformation from a manufacturing standpoint based on recent research. Thereby we define this novel field of research, discuss its impact on traditional patterns of thought, provide a selection of technology, process and system examples, and present 10 fields action in terms of future research, industrial investment, policy initiatives, and societal involvement. The paper sets the basis for extensive further research and discussion within the manufacturing community.

Keywords: Digitization; sustainability; biological transformation

1. Introduction

A sustainable transformation of traditional industrial value creation is essential for both society and economy [1]. The challenges that companies and individuals face in this context are manifold. In addition to demographic change, globalization, individualization, and digitization, assurance of continued resource availability as well as minimization of environmental impact (e.g. climate change, air pollution) are crucial. In the past 30 years global resource extraction has doubled [2]. Although humanity consumes more resources annually than earth is capable of providing since 1970 [3], a further doubling of resource consumption by 2050 is to be expected under current circumstances [4]. While some resources are already considered scarce today, an increase of this trend is just a matter of time. Simultaneously, climate change threatens large parts of the world as a result of drastically changing climatic and weather impacts. External costs for damage caused by air pollution account for roughly one trillion Euro p.a., only in Europe [5].

In order to overcome these problems, visions of a complete circuitry of the industrial metabolism (circular economy) and/or a renunciation from fossil based to renewable resources (bio-economy) have been subject to great attention in the recent past. Therefore, digitization of manufacturing is widely viewed as a vital approach. Many authors argue that the transition from a pipeline to a platform economy enables sustainable value creation [6]. A prominent example quoted in this context is car

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sharing that when extrapolated leads to the idea of a shared economy, a cornerstone of a circular economy.

Recent studies and discussions in both science and practice, however, abandon the dominant role of digitization as a solution approach and rather classify it as an enabler of change [7]. While solutions and enablers are well-established, principles of a sustainable transition are not. In this context, a convergence towards biological processes depicts a future trend in research and industries with a potential of drastically changing the face of traditional value creation. In this paper, we thus outline a biological transformation from a manufacturing standpoint and present preliminary fields of action based on recent research.

2. State-of-the-art

To date, several authors have presented definitions and approaches for the generic concept of a circular economy, i.e. Cradle-to-Cradle, Industrial Ecology, Performance Economy, Biomimicry, Regenerative Design, Natural Capitalism, and Blue Economy [8-14]. The currently most widespread definition has been presented by the Ellen MacArthur Foundation. Thereby, the goal of decoupling resource use and growth is understood as a constant level value preservation of products, components and materials over time. This is to be achieved by a circulation of different goods. A distinction is made between a technical and biological cycle [15]. A related concept is the image of a bio-economy, which was decisively shaped by the former EU Research Commissioner Janez Potočnik [16]. It describes the transformation of an economy dependent on fossil fuels to an economy based on renewable raw materials [17-19]. The goal of the bio-economy-concept is not necessarily the holistic closure of cycles, but the production and use of biological resources to provide products, processes and services in all economic sectors within the scope of a sustainable economic system [20]. Thereby, biotechnology is often viewed as the enabler [16,21]. In order to describe the process of a convergence of traditional manufacturing towards biological processes, few authors have introduced the term biologicalisation. On one hand Kremoser understands the term as the use of biotechnology as a platform to drive a variety of innovations in industries [22]. In this sense the biological transformation is viewed as a parallel process to the digital transformation. Patermann has provided a broader definition by characterizing the biological transformation as a systematic use of knowledge about nature by incorporating the potential of accompanying or supporting new technologies, such as information, communication or nanotechnologies [23]. Examples from the chemical and pharmaceutical industry show that a large-scale addition and/or replacement of traditional with bio-based technologies is already feasible today.

Although the convergence of traditional manufacturing towards biological processes may partly target similar visions as a circular and/or bio-economy, it may simultaneously lead to significant improvements in a traditional business sense, e.g. via holistically improving a product's functionality during its use phase or adaptive industrial processes and systems. This in turn may create novel business models and enable access to new markets. As such the biological transformation may have severe impacts in the future, as it may not only be viewed as a sound transition to a sustainable future but also a business opportunity.

3. Defining a biological transformation of industrial value creation

As a simple focus on the use of biotechnology seems too narrow for the process of a biological transformation, we define the term in dependence on Patermann [26] as a systematic application of the knowledge of nature and/or natural processes aiming at optimizing a manufacturing system regarding its societal and business challenges by seeking a convergence of bio- and technosphere [Figure 1].

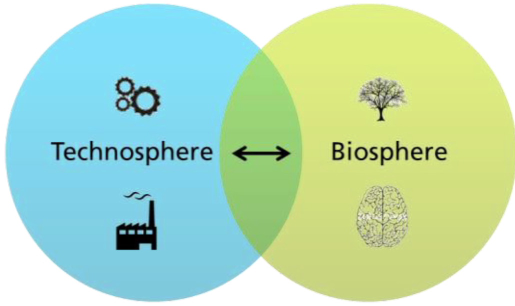

Figure 1 Integration spheres of the biological transformation

As such it is understood as a process towards a sustainable industrial value creation. Thereby, we differ between three modes of development that depict different steps of converging bio- and technosphere: 1. the *inspiration* in terms of a transfer of natural phenomena (biomimicry, biomimetics) enabling a bioinspired value creation, 2. the *integration* of technical and biological processes (i.e. biotechnology) in traditional value creation environments, e.g. to close cycles or to produce novel products, and 3. the *evolvement* of bio- and technosphere. While traditional manufacturing systems have been considered well-defined (isolated) socio-technological entities, single solutions have been presented that initiate a convergence in form of both inspiration and integration. Evolvement, however, depicts an entire new approach seeking a complete mergence of bio- and technosphere in form of a thorough cross-linking of bio, manufacturing, and information technology. Driven primaryly by technical advancements in digital networking and biotechnology, its goal is to create completely new, self-sufficient (biointelligent) value creation technologies and structures to enable autonomous and ad hoc adaptation of the system architecture to the optimal solution of a value creation task. Figure 2 illustrates the process and modes of development of a biological transformation of the manufacturing industry.

Inspiration

This development mode is defined as a transfer of natural phenomena in form of a process of analysis, abstraction and technical realization. As such it has been present for years in biomimetics, although mostly being reduced to individual aspects of manufacturing.

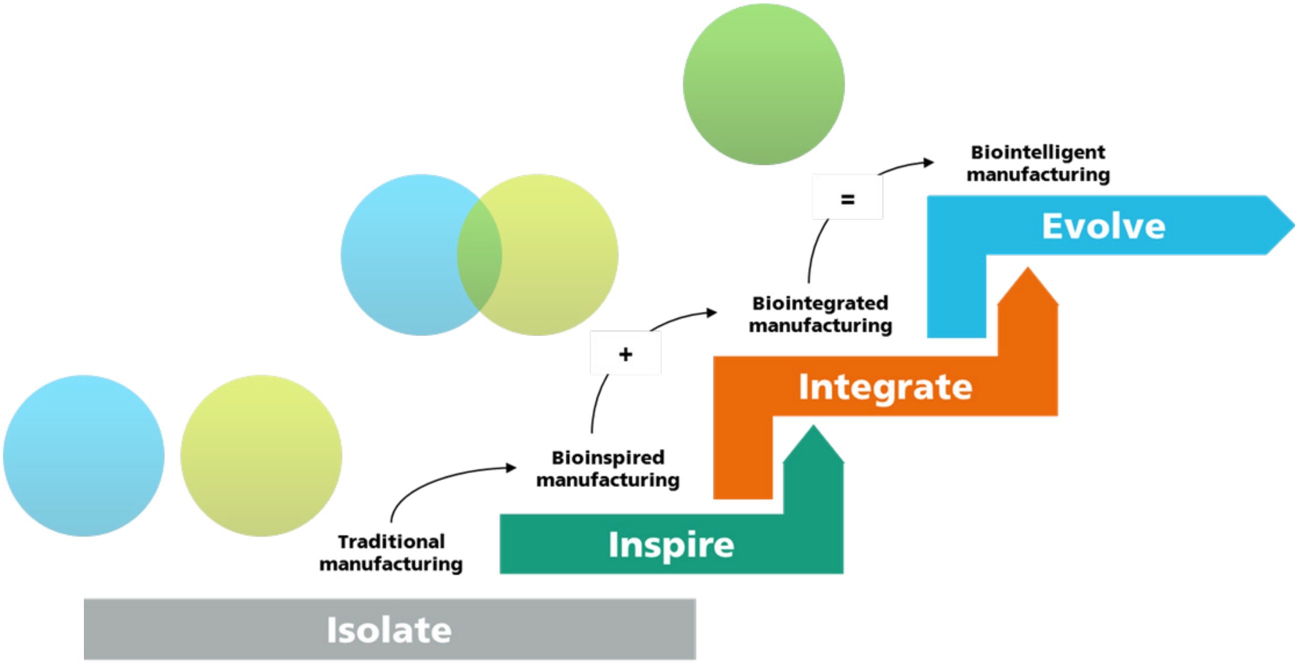

Figure 2 Process and modes of development of a biological transformation of the manufacturing industry

Its approach is based on the idea of technically duplicating concepts/characteristics of nature (e.g. fluid dynamics, lightweight construction, biomechanics), the process of evolution (e.g. bioanalogue optimization techniques), and principles of nature (e.g. modularity, resilience, self-organization, self-healing) in order to fulfill a certain purpose. Results of the inspiration mode are solely technical solutions. Examples are manifold, Table 1 summarizes a selection.

Table 1 Examples of technologies inspired by natural processes

Natural system	Technical system
resource efficient bark construction	additive manufacturing
insect exoskeleton	exoskeleton
lotus effect	functionalization and coatings
bone structure	lightweight construction
flock of birds	swarm intelligence for the management of organizations
plant photosynthesis	artificial photosynthesis

Integration

Another mode of development of the biological transformation is the integration of technical and biological processes to combine bio- and traditional manufacturing technology initially referred to as biologicalisation by Kremoser [25] and Patermann [26]. Therefore, the main enablers are white, blue, red, gray and green biotechnology. Examples of the systematic use of synergy potentials of industrial value creation and nature include the use of micro-organisms to recover rare earths from magnets, the function-nalization of polymers, the recovery of bioplastics from CO_2 waste streams, the extraction of methane from industrial wastewater, and the implementation of natural Filter mecha-nisms for closing value creation cycles. The cooperation mode creates bio-technical systems.

The principle of symbiosis is an evolutionary key principle of nature, which is likely to gain relevance in the context of a sustainable industrial value creation. Figure 3 exemplifies a cooperative application in form of a functional diagram showing the symbiosis between a traditional value-added environment and a microalgae photo-bioreactor.

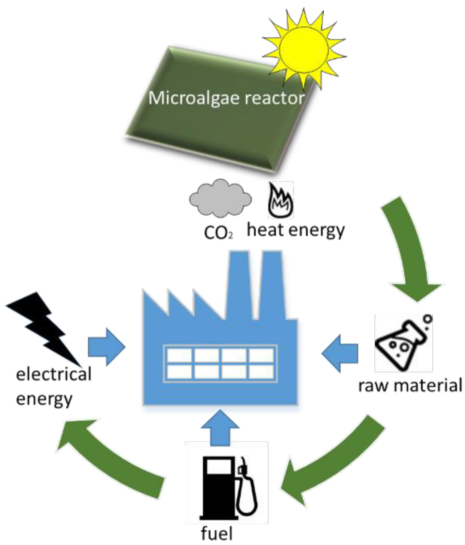

Figure 3 Exemplary cooperative use of nature in the form of an algae reactor in a traditional value creation environment

The algae growing within the photo-bioreactor use CO_2, heat and sunlight for photosynthesis and self-replication. The CO_2 can come from factory emissions and contribute to algae growth together with process waste heat from factory production. The cultivated algae, in turn, can be used in many ways for value-creation processes of the factories. From the microalgae biomass, e.g. energy and material can be recovered. The biomass can be converted into biogas and applied in combined heat and power plants, whereby the chemical energy of the biomass in the form of heat and electrical energy for factory production can be made available again. The produc-tion of raw material such as bio-plastic from microalgae oil or the use of algal biomass in dried and ground form as a heavy metal filter is possible.

Evolvement

The final and most likely to be a gamechanging approach to future manufacturing science is the complete mergence of bio- and technosphere in form of a thorough cross-linking of bio, manufacturing, and information technology referred to as *evolvement*. The result of this mode is a biointelligent manufacturing system that is designed according to the characteristics of living beings. According to Goertz and Bruemmer, characteristics of living are [24] cellular organization, metabolism, homeostasis, complexity, stimulation and communication, reproduction, heredity and development, movement and evolvability. Decisive in the realization of a biointelligent system is not the single characteristic, but the sum of properties. The transfer to a system represents a hitherto barely implemented, highly complex interaction of information, biotechnology and conventional production technology, with the goal of implementing an autonomous and ad hoc adaptation of the system architecture to the optimal solution of a value creation task. Here, a system is no longer to be understood as a delimited unit but as a regional value adding cell. Biointelligent value adding cells are decentralized, apply regionnal resources in symbiosis with their surrounding natural environment, and engage in a variety of exchange relationships with their surrounding, inferior, and superior systems. Figure 4 illustrates the above described understanding of biointelligent value adding cell interaction.

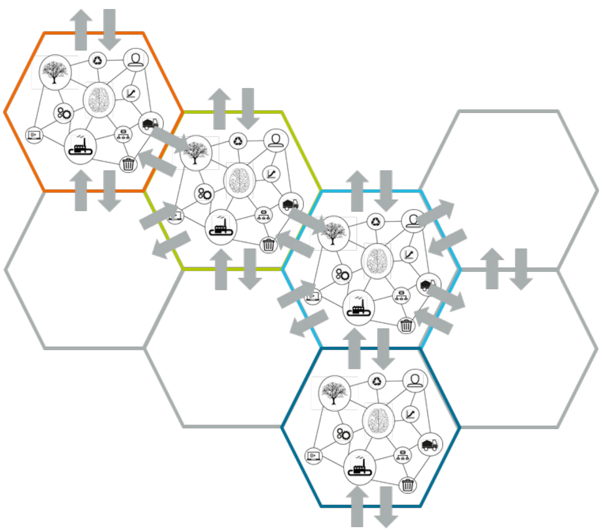

Figure 4 Bio-intelligent value adding cell interaction

4. Fields of further action

In order to transform traditional towards biointelligent manufacturing, various actions in terms of future research, industrial investment, policy initiatives, and societal involvement are required. Based on an extensive literature review of over 270 potential technological solutions as well as a survey with 43 outstanding experts of various fields (manufacturing, information and biotechnology, social and political science) we have identified 10 major fields of action for industries. Figure 5 illustrates their relation in three levers: intra-organizational challenges (green), inter-organizational challenges and social/ political challenges (grey) according to the framework recently presented by Yang et al. [25] in the field of biohybrid robotics.

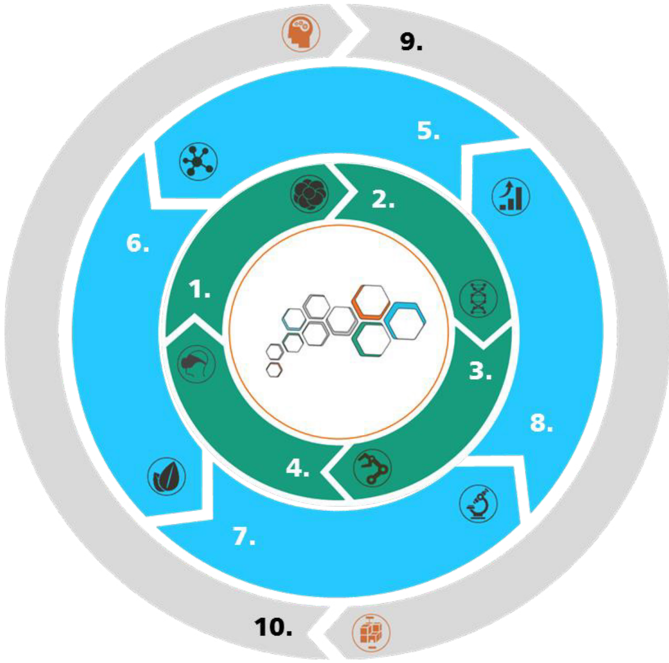

Figure 5 Fields of action in the context of biointelligent manufacturing in accordance to Yang et al. [25].

The four *intra-organizational challenges* consist of: 1. The development and fabrication of biobased, functional, self-x-capable (i.e. biointelligent materials), 2. the proper configuration of bio-tech-interfaces (molecule-/cell-/organism-tech-connection) in order to realize communication via appropriate sensors, actuators etc., 3. biohybrid and bioinspired (i.e. biointelligent) manufacturing technology and organizations (robotics, processes, logistics etc.) and 4. the arrangement of human-centred work-places in a biointelligent manufacturing environment (bio-hybrid work stations, man-machine-relation etc.).

The four *intra-organizational challenges* consist of: 5. data processing in order to enable real time data exchange between technological an biological systems (using machine/deep leaning algorithms, etc.), 6. the decentralization and transfer to biobased/renewable energy generation, 7. the expansion of the methodological basis of technology impact assessment as well as its standardization and 8. the creation and financial support of new business models in terms of innovative approaches and access to venture capital.

The two most pressing *social and politcal challenges* of a biological transformation of the manufacturing industry are: 1. to establish an increased social dialogue in order to explain chances and risks of this development to the general public as well as to enable participation of each individual within the process of value adding (from consumption to presumption) and 2. to create an effective knowledge transfer between manufacturing and bio engineers, biologists, managers and humanists. The challenges outlined above, without any claim to completeness, require intensive interdisciplinary collaborations and a transfer of knowledge between disciplines as well as an early sensitization of young academics.

5. Summary and outlook

A sustainable transformation of traditional industrial value creation is essential for both societies and economies. While solutions (e.g. circular and/or bio-economy) and enabler (e.g. digitization) are well-established, principles of a sustainable transition are not. We identified the convergence of manufacturing towards biological processes – the biological transformation - as a future trend in research and industries with a potential of drastically changing the face of traditional value creation. This novel field of research comprise the systematic application of the knowledge of nature and/or natural processes to optimize a manufacturing system with regard to its societal and business challenges. Thereby, we differ three modes of development (inspire, integrate, evolve) eventually leading to the vision of a biointelligent value creation. Based on the characteristics of living beings future manufacturing systems among others will be self-organized in cells, exhibit a distinct metabolism, are evolvable and in constant self-controlled interaction and communication with its local surroundings, inferior, and superior systems.

Thereupon, we discussed its impact on traditional patterns of thought outlining 10 crucial fields of further action in terms of future research, industrial investment, policy initiatives, and societal involvement that when targeted appropriately, will lead to a major paradigm shift in traditional manufacturing science and practice.

As bio-intelligent manufacturing represents a comparatively new field of research, decision makers at political, business and scientific levels will have to act courageously and rapidly in order to appropriately target the sustainability challenge by realizing the full potential of the biological transformation.

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