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Biologicalisation of manufacturing processes

State of the art, principles and developing trends

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In this paper, a survey of new achievements in the area of biologically-inspired design and manufacturing and fundamental rules of biological transformation in manufacturing – also in relation to mechanical engineering – is provided. Some possible scenarios and several examples of the applications of biological transformation in manufacturing are presented. Some new trends, for instance the pursuit of the so-called Living Manufacturing Systems, which are based on the advanced AI-techniques, are discussed. Finally, some examples of a successful biologicalisation of manufacturing tools, i.e. injection moulds, machine tools, manufacturing processes, and systems are provided. This paper can motivate Polish researchers to undertake this topic in Poland.

KEYWORDS: manufacturing, manufacturing biologicalisation, bio-inspired manufacturing, biological transformation of manufacturing, bio-intelligent manufacturing systems

Introduction

The obviously accepted strategy for a modern manufacturing industry denoted as the Production/Manufacturing 4.0, also termed the 4th industrial revolution, is supported by 9 pillars [1, 2]. They are as follows [1, 2]:

- autonomous robots embedded into production process,
- simulations of manufacturing/production processes,
- vertical and horizontal software integration,
- the industrial Internet of things (IoT),
- cyber security,
- cloud computing,
- additive manufacturing (3D printing),
- augmented reality including software and hardware,
- large datasets and their analysis.

It should be noticed that Industry 4.0 is primarily based on cyber-physical systems (CPS) developments. They are defined as systems of collaborating computational entities, which are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet [6, 16]. In other words, CPS can be generally characterized as "physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core" [6, 16].

The current analysis of further development of this industrial strategy based on numerous reports, e.g. refs. [3, 4, 5], indicates that *Bionics* becomes the 10th important pillar. This interdisciplinary discipline covers studies devoted to living organisms, including plants and animals, in relation to using their structural and functional potentials as technical solutions in both design and manufacturing fields [1]. It should be noted that this analogy to biological phenomena has been

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expanded to include creative processes driven by biological observations. According to ref. [5], bionics is a new scientific discipline dealing with conducting natural studies focussed on the discovery of innovative technical solutions, mainly in machine building, architecture, and civil engineering, as well as in other technical, social, and even health branches. Currently, bionics is defined as the application, imitation or copying of biological functions, structures, and mechanisms in order to design and control technological machines. This fact implies such synonyms as *biomimetic design* or *biologically-inspired design/manufacturing*. Bionics becomes more and more important pillar of the Industry 4.0 strategy because in nature all living organisms are created additively, and, on the other hand, additive manufacturing is one of the leading manufacturing techniques [5, 6].

Bionics has already strongly located itself in technical/engineering sciences, for instance as *biologicalisation/bionisation of design and manufacturing processes*, which results in the transformation to the higher level of *biological transformation of industrial manufacturing* [7, 15]. The general idea and rules of biologicalisation are described in details, for instance, in refs. [10, 11]. Some rules of the application of biological knowledge to the *biologically inspired design* – BID are given in ref. [10]. In this approach, a hierarchical division of *biomimetics* and/or *biomimicry*, as synonyms of bionics, featured in construction, processing and information forms, and each of these subsets can be further subdivided into many applied fields. On the other hand, ref. [11] presents some results of design experiments conducted by collaborative pairs including engineer-biologist and individually in order to improve the biologically-inspired design. The experimental procedure denoted by the acronym *BioId Support (**Bio**-inspired **Id**eation Support)* was basically focussed on the categorization of knowledge transfer to the engineering design as bio-inspired analogies. As a result, a distinct increase in the design quality was observed.

It should be noted that in engineering courses [13] bio-engineering (bionics) is richly collaborative and interdisciplinary and due to this fact creates the link between engineering disciplines (mechanical, materials, chemical, electrical, civil and environmental, and computer science) and biology, physical and life sciences. In this context, the 16 biggest and potentially most rewarding open problems come down to engineering biology, e.g. manufacturing and distribution, and design problems. However, the balance is shifting from "What can we discover?" to "What can we solve?" [14].

The most popular definition of biological transformation of manufacturing proposed by the CIRP Collaborative Working Group "Biologicalisation in Manufacturing (BiM)" founded in 2019 is as follows [6, 7]: "the use and integration of biological and bio-inspired principles, materials, functions, structures and resources for intelligent and sustainable manufacturing technologies and systems with the aim of achieving their full potential".

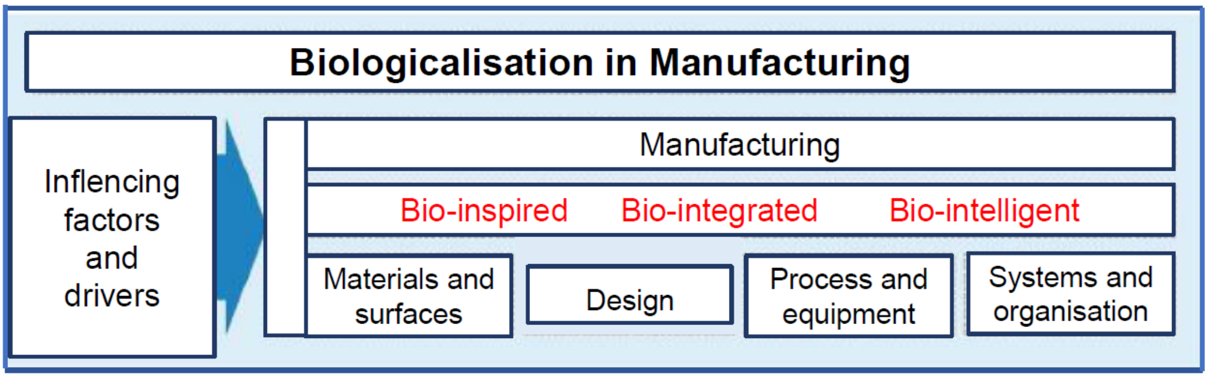

Fig. 1. Subdivision of the manufacturing field into sections [6]

The proposed sub-classification of Biologicalisation in Manufacturing shown in Fig. 1 includes essentially bio-inspiration, bio-integration, and bio-intelligence. Moreover, in order to analyze the factors and drivers relating to and influencing the key elements of the manufacturing value chain from an overall manufacturing technology and systems perspective, the manufacturing field has been subdivided into 4 sections including (Fig. 1): materials and surfaces, design of products and manufacturing systems, manufacturing processes, machine tools, robots and assembly operations, production systems, supply chains and organizations [6].

In particular, such initiatives are introduced in the German manufacturing industry based on the BIOTRAN research program realized by Fraunhofer Society and 15 industrial and research institutions with the main goal to analyse the potential benefits and demands of biological transformation until 2050 year [7]. The four leading aspects are selected within the German manufacturing industry, namely [7]:

- the assessment of key technologies of the biological transformation,
- the assessment of the current status of the manufacturing industry in the context of the biological transformation,
- the forecast of potential scenarios of development of the manufacturing industry in the context of the biological transformation, and
- the deduction of recommendations for future activities.

As important causes of these activities, such reasons as global market challenges, rapid sustainable development and resource shortages (during the last 30 years global resource consumption doubled corresponding to a growth rate of 118% which means that it will be doubled again by 2050) are taken into account. Moreover, resource shortages and its price increase cause that 40% of middle-class companies signalize future economic problems and major risks to production continuity [7]. These challenges also deal with all members of the EC.

Some of the high-level aspects of the new biologicalisation frontier which can create the next phase of developments in digitalization and Industry 4.0 include [6]:

- new developments in chemistry and new construction materials,
- new products fabricated with the increasing share of new biomaterials,
- improvement of classical industrial processes by integration with entirely new bio-inspired industrial processes,
- much higher utilization of the potential for new bio-inspired manufacturing equipment, including robotics, machine tools, and measuring equipment and,
- creating new bio-inspired models for production organisation including manufacturing systems and supply chains.

Principles of biological transformation and possible scenarios

The general concept of biological transformation leading to increasing integration of production, information, and biotechnology is presented as the systematic application of knowledge on biological processes in Fig. 2. In consequence, the process of biological transformation involves three development modes, i.e., *inspiration*, *integration,* and *interaction* which are correspondingly reflected in bio-inspired, bio-integrated and bio-intelligent manufacturing processes.

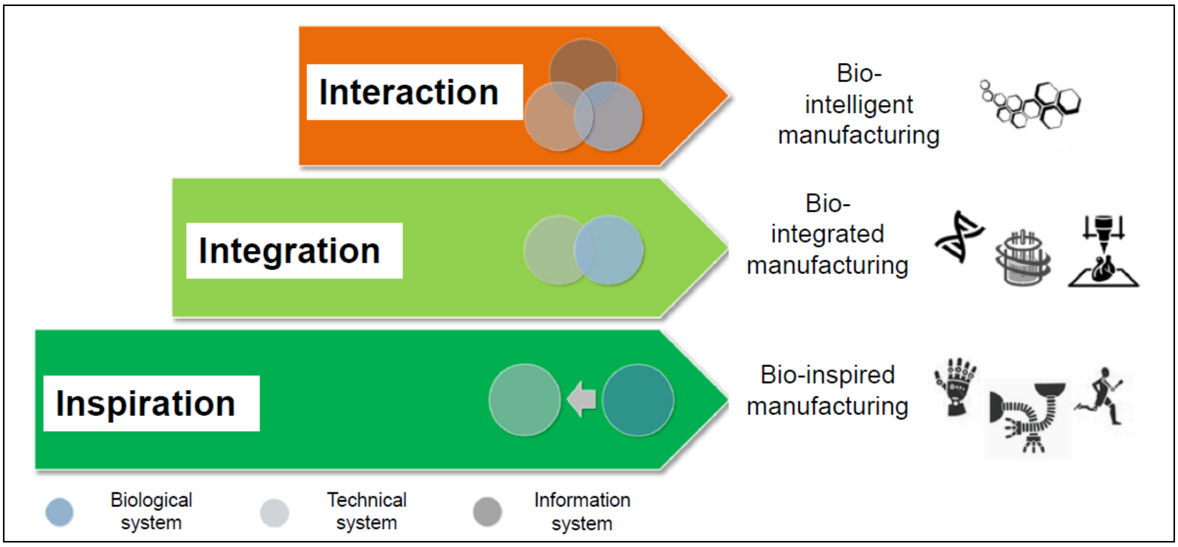

Fig. 2. Development modes of the biological transformation according to Miehe [7]

In the first mode, the *inspiration* supports the translation of evolutionary biological phenomena into the systems creating solely technical features, e.g. lightweight construction, functionalities, e.g. biomechanics, organizational intelligent solutions, e.g. swarm intelligence, artificial neural networks. In the second mode, the biological knowledge is applied in a real form in the *integration* of biological systems into production systems, e.g. replacing chemical systems with biological systems using enzymes, cells and other biological microorganisms. Some practical examples of these activities concern the recovery of rare earths from magnets, the functionalization of polymers and the recovery of bioplastics from CO_2 waste streams. In the third mode, the comprehensive *interaction* of technical, information, and biological systems leads to the creation of completely new, self-sufficient and self-optimizing production technologies and structures, so-called *bio-intelligent manufacturing systems*. This implies that the concept of biological transformation is developed in three stages with visibly increased complexity and interdisciplinarity. The structure of biological transformation is presented visually in Fig. 3.

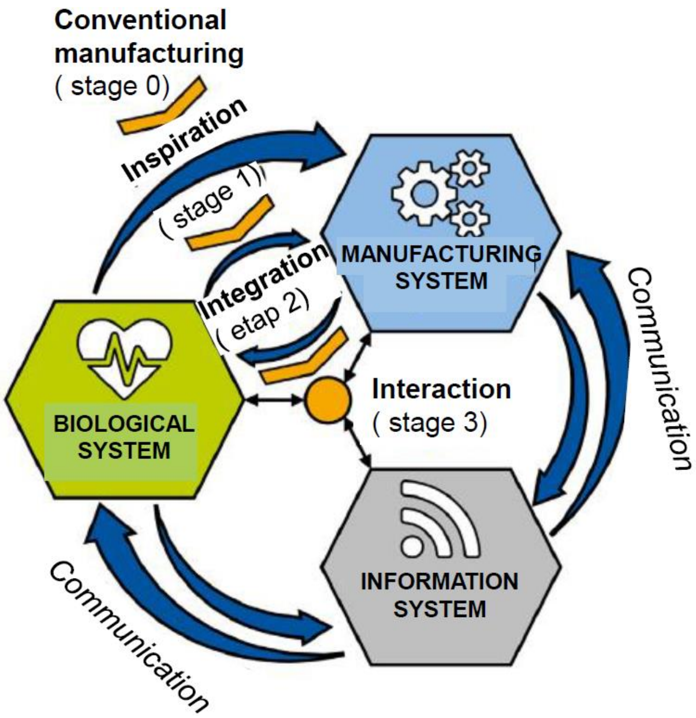

Fig. 3. Framework of biologicalisation in manufacturing [8]

Generally, approaches for biologicalisation of manufacturing can be created based on various scenarios with clustering into different development stages but they differentiate between technical, information and biological systems. Moreover, a typical framework describes their levels of interaction (communication) between the three systems. The framework presented in Fig. 3 is referred to three development stages leading to the materialization of biologicalisation of manufacturing systems.

Applications of the potential and impact of biologicalisation in manufacturing

Some examples of the assessment of the potential of biological organisms and the impact of the application of biological transformation in manufacturing are specified in Fig. 4. They are related to 4 sections subdivided in Fig.1. It should be noted [6] that biological transformation seems to be the most promising in Section "Design of products and manufacturing system" and in Section "Manufacturing processes, machine tools, robots and assembly operations".

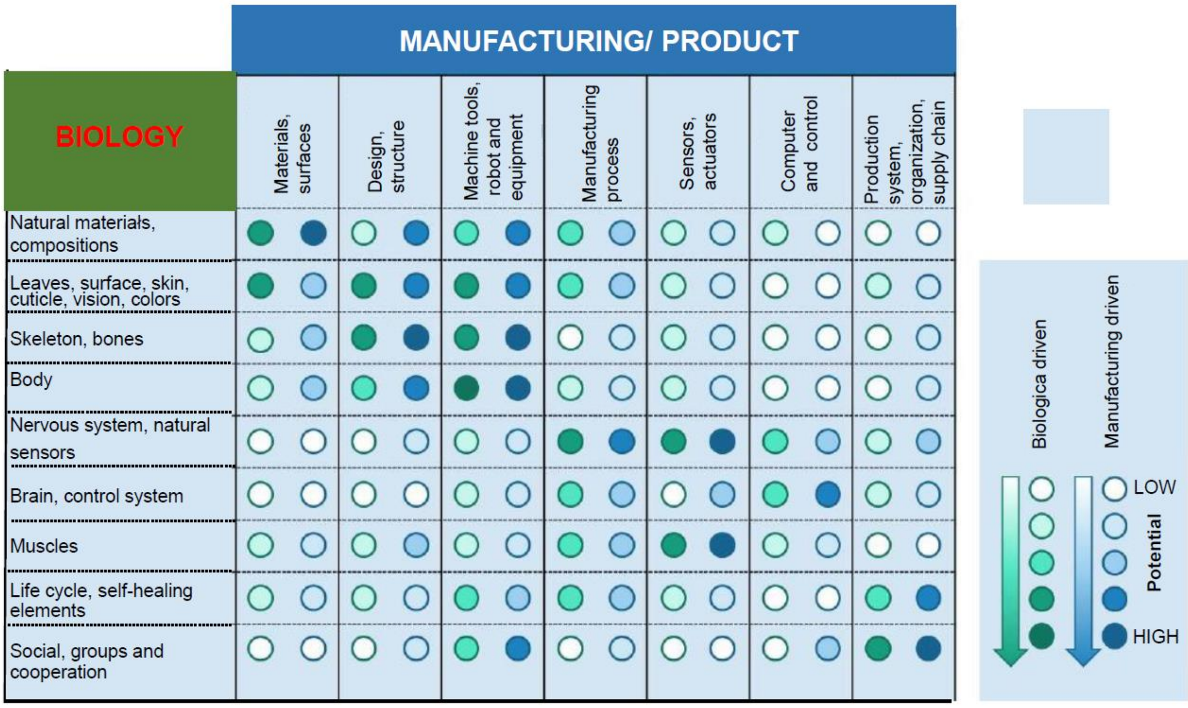

Fig. 4. Examples of assessment of the potential and impact of applying biological transformation in manufacturing [6]

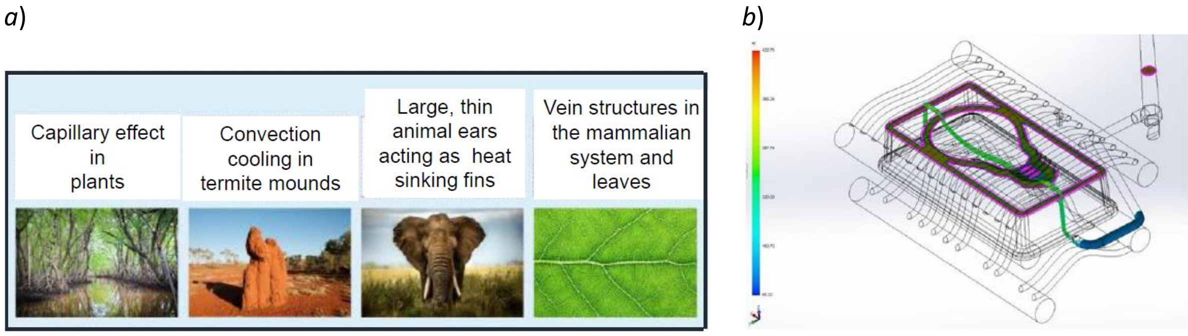

Fig. 5. Evaluation of biological systems (*a*) selected for optimization of conformal cooling channels in injection mould (*b*) [6]

Fig. 5 presents an example of biologicalisation concept using several biological solutions applied in the design, optimization and fabrication of an injection mould die with conformal twisted cooling channels, which guarantee the highest quality of a plastic product in terms of minimizing surface defects, which predominantly result from non-effective and non-uniform cooling. In the research project named HARBEC [6] the top-down concept was used and the start point was based on the search and evaluation of biological solutions as the biomimicry influencing new manufacturing technologies.

As shown in Fig. 5*a*, a number of biological and botanic structures were selected and analyzed including capillary action in plants, natural convection cooling in termite mounds, large thin animal ears and vein structures in mammalian vascular systems and dicotyl leaves [6]. It is predominantly important that all these biological and botanic systems act effectively as heat sinks. The mould presented in Fig. 5*b* was made of an aluminum alloy and fabricated using both DMLS (Direct Metal Laser Sintering) and SLM (Selected Laser Melting) techniques. As a result, the combination of biological transformation along with additive manufacturing allows to produce of a final product of a higher quality and reduces the production cycle as well as energy consumption [6].

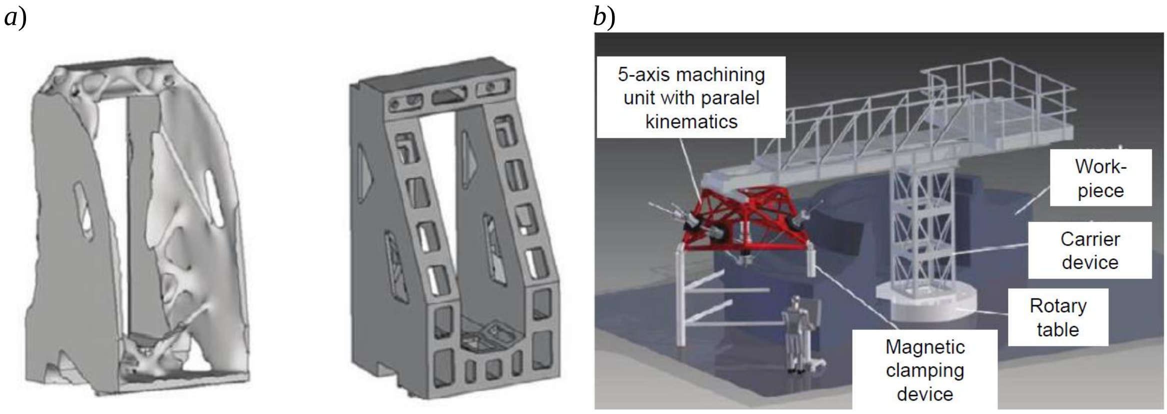

Fig. 6. Examples of application of biologicalisation in machine tool design: (*a*) topological optimization of a machine stand (left) and its technical representation (right), (*b*) modular mobile 5-axis parallel kinematic machine tool [6]

In the case of machine tools, the application of biologicalisation can significantly change the concept of their construction and structure. The three main directions which result in more efficient machines are improved mobility, reduced motion redundancy and lightweight housing [6]. A new concept of a mobile machine tool for large and heavy workpieces (Fig. 6*b*) in which the workpiece stays stationary and the machine is mobile was proposed based on the observation of woodpecker's work. It is obviously accepted that such a machine tool needs a lightweight structure in order to minimize the energy consumption. Both bone and plant structures can be analogical biological solutions and the result of bio-inspired topological optimization of the housing of a 5-axis machining center is shown in Fig. 6*a*.

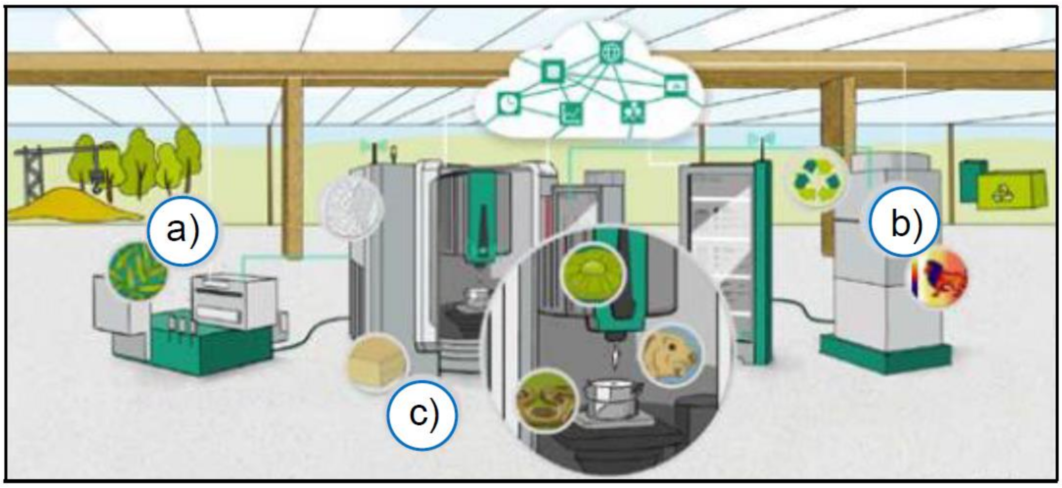

Fig. 7. Concept of a fully biologically transformed machine tool [9]

Although the proposed solutions are valuable from the scientific perspective their sustainable transfer to the industry is not yet possible now. As an example of such a project which can address the industry's needs, one can indicate the project named *BioManuIII* [9] aimed at building a completely biologically transferred milling machine, shown in Fig. 7, by Fraunhofer researchers together with the world-leading manufacturer of machine tools DMG Mori. For instance, cooling-lubricating emulsion will be completely replaced by emulsion containing vegetable oils (detail *a*), and CO_2 footprint and environmental pollution will be reduced in comparison to conventional cooling using cutting fluids based on mineral oils. In addition, it is proposed such innovative strategies as a completely self-sufficient cooling system when bio-integrated, e.g. fluids integrated by bacteria, algae and yeast, can be supplied, as well as sustainable energy supply, biologically functionalized contact surfaces, waste recycling and high-quality raw materials. Further research studies will be focussed on the thermal and heat control in order to design a so-called *homoiothermal* machine tool by analogy to animals that are able to keep the same temperature. As a result, a higher thermal stability can be achieved by targeted regulation and consideration of local temperature gradients (detail *b*). Moreover, higher ecological sustainability will be achieved by the application of biodegradable thermal and acoustic materials (detail *c*) instead of highly-ecologically harmful polystyrene as an insulation cover. As mentioned above, bio-based materials will be coated and functionally adapted to the harsh machining conditions.

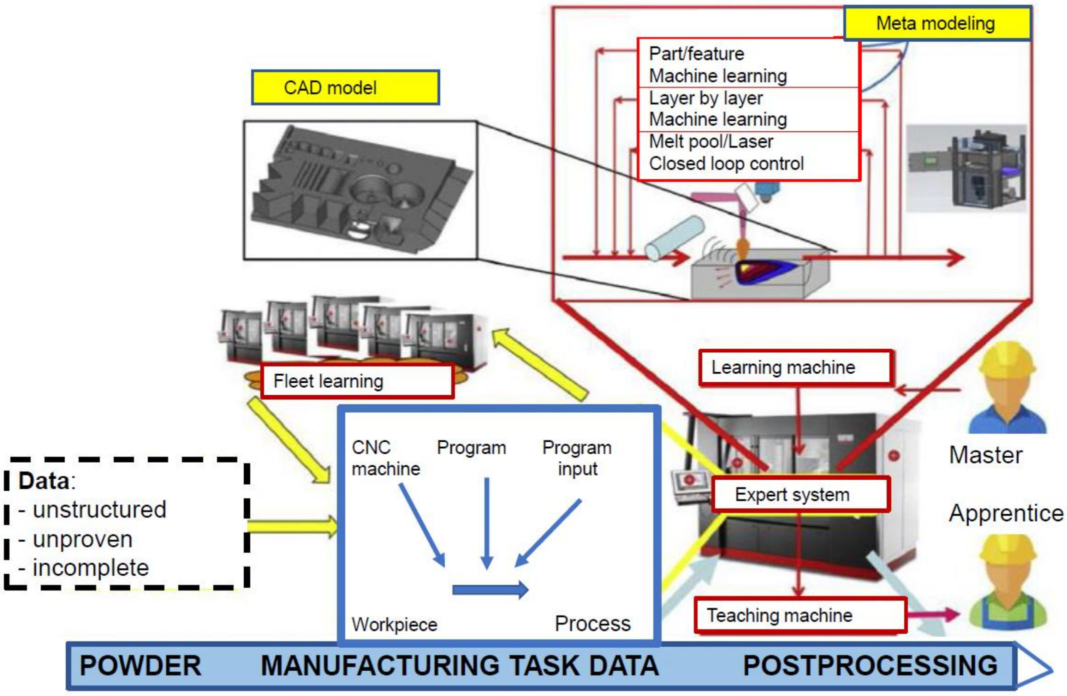

Fig. 8. Concept of a bio-intelligent AM system [16]

The next level of the demonstrators for biological transformation in manufacturing are *bio-inspired, self-learning additive* (3D printing) machines, systems and processes [16]. A general layout of a bio-intelligent additive manufacturing system with implemented various functionalities of biological, living systems, especially with adopted artificial intelligence (AI), is shown in Fig. 8. Due to a large number of related technologies the integration of skills gathered by different operators seems to be a very important task. An integrated expert system stores the data based on operator experiences and provides the reasoning for the provision of useful information on subsequent manufacturing tasks. In the case shown in Fig. 8, the recognition of defects appearing in the SLM layers is based on the image processing method but also machine learning approach was tuned to support this process. As a consequence, the recognized faults are automatically corrected when depositing the next layer which results in the scrap reduction. The basic components of the presented bio-intelligent manufacturing system include a communication system, learning from skilled operators, and information provision for unskilled operators (apprentices).

Some conceptual studies on the bio-inspired future factory [9] in which the idea of a factory inspired by a biological cell is planned to be materialized are successfully continued. In this proposal, schematically highlighted in Fig. 9, stationary production resources such as casting and forming machines represent cell nucleus (*1*) and other parts of production equipment (*2*) are distributed around these nuclei. While the stationary production units remain unchanged, a large number of highly-flexible units (*3*) like roboticized cells being positioned around the nucleus can be quickly transformed for varying production tasks. This situation clearly shows the obvious analogy of the production system to the *biological cell* which is very flexible by nature.

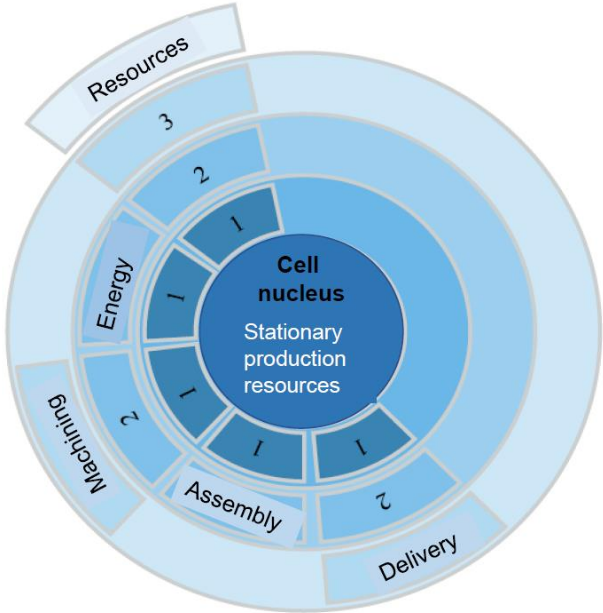

Fig. 9. Vision of a cell-inspired factory of the future [9]

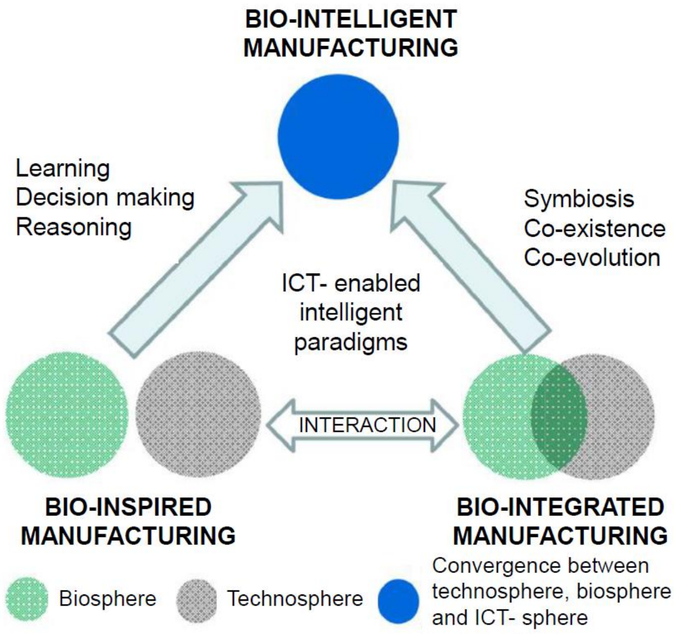

Fig. 10. Relationships between bio-inspired, bio-integrated and bio-intelligent manufacturing [16]

The relationships between bio-inspiration, bio-inspiration and bio-intelligence are illustrated in Fig. 10. The attainment of bio-intelligence is related to the development of both bioinspiration and bio-integration via the convergence of ICT (Information and Communications Technology) enabled intelligent paradigms including six aspects [16]: learning, decision making, symbiosis, co-existence and co-evolution. That means that in order to reach the level of bio-intelligence the requirement is to include such ICT-enabled paradigms as Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Evolutionary Computation (EC), and others [16]. Correspondingly, the following definitions of bio-inspired, bio-integrated and bio-intelligent manufacturing can be formulated based on the mentioned-above ICT enabled paradigms [16]:

- ***Bio-inspired manufacturing*** *is realized by transferring concepts concerning principles, functions, structures and/or solutions from the biosphere to the manufacturing technosphere.*
- ***Bio-integrated manufacturing*** *is realized by integrating elements from both the biosphere and the technosphere within the manufacturing environment.*

- ***Bio-intelligent manufacturing*** *is realized through merging ICT-enabled intelligent paradigms with bio-inspired and /or bio-integrated manufacturing solutions, incorporating information channels, sensor and actuator systems. A special form of bio-intelligent manufacturing is when co-existence, mutual interactions and co-evolution of technical, informational and biological elements (or sub-systems) take place, with the potential of converging towards Living Manufacturing Systems.*

The relationships between the three mentioned systems are schematically presented in Fig. 10. In ref. [16] a hypothesis was formulated that the current achievements in the biological transformation of manufacturing systems inspire to make the statement that future manufacturing systems will include components, features, characteristics and skills which allow their convergence with *Living Manufacturing Systems*. Functional principles of these systems are overviewed in details in refs. [15, 16].

Summary

At present, the rapid development of research studies on biological transformation in both design and manufacturing fields is mentioned. It is accepted that such research activities are necessary for the further development of production digitalization and Industry 4.0 strategy. A general concept includes three development stages, i.e. bio-inspiration, bio-integration and bio-intelligence. The future solution is the so-called living manufacturing system which uses, in a systematic way, large resources of natural solutions existing in nature. Currently, several but rather conceptual research projects are realized.

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