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Towards high performance living manufacturing systems - A new convergence between biology and engineering

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ABSTRACT

This paper reports on a highly ambitious international study undertaken in the period 2018–2020 on the topic of convergence between biology and advanced manufacturing systems. The international team (authors of this paper) worked together to analyse the status of this convergence through the assessment of concrete examples, referred to here as demonstrators, within advanced manufacturing systems. Four independent demonstrators from different sections of the manufacturing value chain and involving bio-inspiration, bio-integration and/or bio-intelligence were selected to test the following hypothesis: *“That Future Manufacturing Systems will incorporate Components, Features, Characteristics and Capabilities that enable the convergence towards Living Systems”*. Each of these four demonstrators have succeeded in supporting this hypothesis and in providing clear *evidence* to confirm that *significant performance benefits* may be derived through the “*biologicalisation*” of advanced manufacturing systems. This conclusion is of great significance for the next phases of development of manufacturing science and engineering globally. The evidence reported in this paper provides a robust basis for recommending that a deeper analysis of the implications of biologicalised manufacturing systems be undertaken. As a result of this early stage work, it is concluded that there is a high likelihood that this new convergence will lead to a *major paradigm shift in advanced manufacturing*. Outstanding opportunities exist for high levels of innovation in the next stages of development of advanced manufacturing processes and systems from the biological perspective. The relationship between the human and the physical manufacturing system will also change and the world of advanced manufacturing will be confronted with many new challenges including important ethical questions.

Introduction

The overall underlying hypothesis for the work described in this paper is as follows: *“That Future Manufacturing Systems will incorporate Components, Features, Characteristics and Capabilities that enable the convergence towards Living Systems”*. The hypothesis test has shown that interest and evidence is growing amongst the international community on the topic of Biologicalisation in Manufacturing (BiM). Based on the most recent developments in biology coupled with those in advanced manufacturing it is evident that, following quickly on the heels of digitalisation, convergence between biology and engineering is accelerating. There are very significant implications of this convergence for future engineering systems, with manufacturing systems providing a very good and representative example for this.

This new emerging frontier in the next phase of evolution of manufacturing digitalisation and the 4th industrial revolution (Industry 4.0) has been termed “Biologicalisation in Manufacturing”. This has been defined previously to be: *“The use and integration of biological and bio-inspired principles, materials, functions, structures and resources for intelligent and sustainable*

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manufacturing technologies and systems with the aim of achieving their full potential" [1]. There is a clear need to illustrate and assess the implications of the Biological Transformation in Manufacturing more clearly in the context of this new breaking frontier of Industry 4.0.

Manufacturing processes as defined in DIN 8580 typically incorporate a wide number of variables which are often challenging to precisely control even with advanced process control capabilities. A real time response to changing manufacturing conditions is often highly challenging, particularly as the processes are driven towards the achievement of very high to ultra-high performance levels. Higher level biological systems are characterised by a) the availability of a variety of sensor data coming from partly redundant and failure tolerant sensor systems and b) intelligence that allows for continuous adaption and learning. Furthermore, biological systems can self-maintain their health and can also exchange information with other systems to improve their effectiveness. Hence, the adaption of basic concepts of biological systems to technical systems is of high importance in order to overcome current shortcomings in modern manufacturing processes [2].

The implications for the entire manufacturing hierarchy from the discrete component level to the integrated system, supply chain, and organisational level need to be given detailed consideration.

Historically convergence has been seen to be an integral part of manufacturing development since the 1st industrial revolution. The most recent convergence has been the integration of cyber physical systems and connectivity into the manufacturing systems in the context of Industry 4.0.

The factors and drivers influencing the key elements of the manufacturing value chain from an overall manufacturing technology and systems perspective are summarised in Fig. 1.

These include the resources, the hardware, the software, the human and the manufacturing processes as illustrated on the right hand side of the figure.

The biological transformation has wide ranging implications for key areas in society such as sustainability and manufacturing. One sub-classification of Biologicalisation in Manufacturing (BiM) is illustrated (Fig. 2) as being: Bio-Inspiration, Bio-Integration and Bio-Intelligence. It is essential that these terms be clearly defined. Proposed definitions are provided in Section 4 of this paper.

The main purpose of the work described here was to provide practical demonstrators for the emerging paradigm shift of biologicalisation in discrete, advanced manufacturing. This new paradigm shift is analysed in the context of the impact in terms of achieving higher performance of overall manufacturing systems. Of course it is essential to consider the meaning of *performance* keeping in mind the current situation in industrial manufacturing.

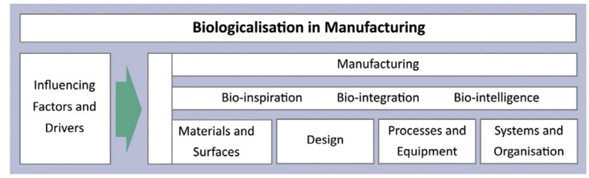

Fig. 2. Classification of BiM under Bio-Inspiration, Bio-Integration and Bio-Intelligence [1].

Clearly performance is to be interpreted in relation to technical efficiencies and capabilities in the context of sustainable manufacturing, whereby sustainability takes on a much more significant role in modern day manufacturing than it has done in the past. The economic performance of manufacturing systems clearly remains fundamentally important.

However, as this paper was in preparation, a new perspective on the interpretation of high performance started to emerge. The first and second stages of the COVID 19 pandemic were sweeping the world and the authors were working from home in isolation and living under strict lockdown conditions. Industrial manufacturing suddenly came under severe and extreme pressure and as a result, new and unanticipated demands are now being placed on manufacturing systems. In some cases, companies have switched from manufacturing their core products to producing artefacts of value to fighting the virus such as respirators and masks. The agility, resilience and robustness of manufacturing systems in crisis situations thus also represent a key indicator in relation to performance. In summary, it is not adequate to only consider the technical/engineering performance of manufacturing systems. It is essential that perspectives of sustainability, economics, society and last but by no means least ethics be incorporated into the key performance indicators for assessing performance improvements.

Early stage evidence of the biological transformation towards the "*Living Manufacturing System*" was to be demonstrated within the work described here through detailed consideration, evaluation and demonstration of a) bio-inspiration, b) bio-integration and, perhaps most significantly of all, c) bio-intelligence. The selected representative areas of production engineering in discrete manufacturing are:

- Design methodologies (Demonstrator 1),
- Materials, equipment, sensors and processes (Demonstrators 2 and 3) and
- Manufacturing systems (Demonstrator 4).

This special edition of the CIRP Journal of Manufacturing and Technology on Biologicalisation in Manufacturing contains five other directly related and strongly referenced papers (cited in

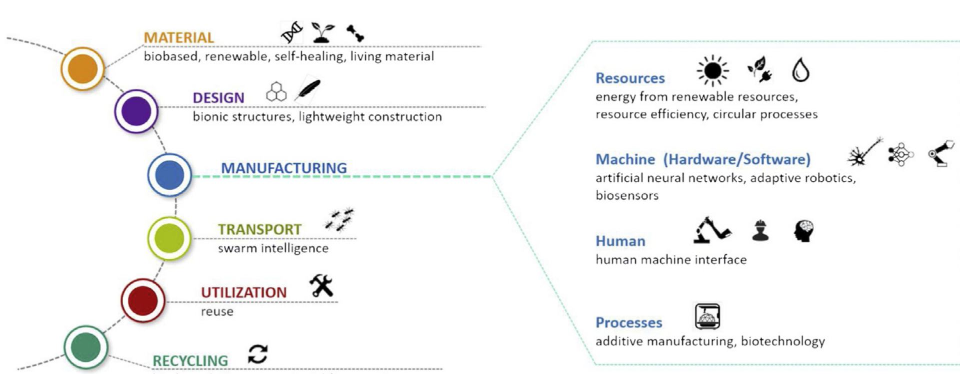

Fig. 1. Biological Transformation and Manufacturing (Source: R. Neugebauer, Fraunhofer Gesellschaft, 2019).

Section 5 below) which focus on the specific details of the work undertaken in these demonstrators. These papers should be read in conjunction with this overarching paper.

An historical perspective on convergences in manufacturing/industrial engineering

It is interesting to consider Fig. 3 in the context of convergence. The three earlier industrial revolutions are presented in the figure and include a brief commentary on some of the key aspects associated with each revolution [3]. In the first industrial revolution, mechanical production equipment was powered by steam and water. This may be interpreted as the first major convergence. Based on mass production achieved by the division of labour concept and the use of electrical energy, the second industrial revolution emerged in the mid to late 1800's – a second major convergence.

The use of electronics and IT to further automate production with numerical control (NC) and later computer numerical control (CNC) found widespread application. This moved to the era of computer integrated manufacturing (CIM) and represented a third major convergence. Finally, in recent times, the developments in computing, digitalisation and telecommunications saw the introduction of cyber physical systems into manufacturing engineering [4]. This can be seen to be a fourth major convergence in industrial and manufacturing engineering.

During the course of industrial development since the early days, materials science and engineering have played a central role in the development of manufacturing systems and processes. For example, the developments in silicon has driven the functional capabilities of chips for the IT sector. Areas and disciplines outside of the physical sciences and engineering have also been fundamental to industrial development, such as the humanities and the social sciences.

Within the paradigm of Industry 4.0, it has become possible to connect manufacturing systems directly to the Internet. Machine to machine communication and artificial intelligence allow higher levels of performance and flexibility. Where economy of scale has been the paradigm of the past, flexibility, customisation and sustainability of industrially produced goods is now becoming the standard. Local manufacturing on demand is becoming technically and economically feasible. This however, requires a different view on business models, logistics and impact on the labour market, on the educational system and also on politics [1].

There is still considerable ongoing discussion about the revolutionary or evolutionary character of Industry 4.0. The proliferation of ICT is clearly an evolutionary development. Sensors and actuators, in combination with (big) data analytics, artificial intelligence, digital twins, large scale (real time) simulation, data visualisation by virtual and augmented reality are all elements converging in an integrated way of instructing, monitoring and controlling our manufacturing systems [5,6].

The real additional value-add in moving from Industry 3.0–4.0 has been primarily through the cyber physical systems (CPS) developments. Cyber physical systems are systems of collaborating computational entities, which are connected with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet [4]. In other words, CPS can generally be characterised as "physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core. The interaction between the physical and the cyber elements is of key importance." [4].

Fig. 3 also illustrates the fact that throughout the various industrial revolutions, the complexity of manufacturing systems has been increasing in a non-linear manner. The question of complexity in manufacturing systems is well addressed in the literature. The introduction of the human interface into manufacturing systems brings with it another level of complexity which is given consideration in a CIRP Keynote Paper on modelling of manufacturing complexity. A methodology to systematically determine the product and process complexity for any manufacturing environment was introduced [7,8].

Some of the current and emerging scenarios in relation to digitalisation and Industry 4.0 are:

- The increasing extent of decentralisation of manufacturing,
- Fundamentally new design paradigms e.g. through the rapid developments in additive manufacturing of polymeric, metallic and increasingly bio-materials,
- Emergence of new supply chain architectures and networks and new methods of supply chain/network integration,
- Cyber-security as related to manufacturing,
- Diminishing latency,
- Much higher levels of automation and self-optimisation [9,10],
- New unprecedented levels of connectivity,
- Increasing levels of artificial intelligence (AI) applications and associated machine intelligence,
- More significant focus on the sustainability of machining processes and equipment [11],
- Crisis responsiveness and new levels of robustness and
- Bio-inspiration, bio-integration and bio-intelligence.

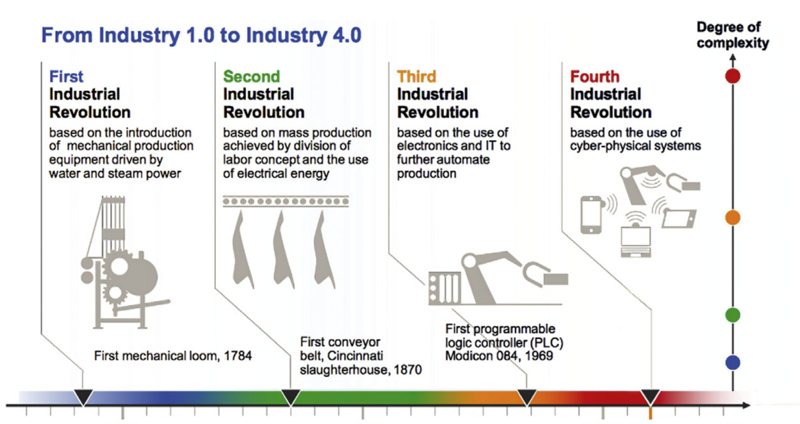

Fig. 3. Biologicalisation in Manufacturing in the Context of Industry 4.0 and Convergences of the past, (original source: Ref. [3]).

The newly emerging convergence of biology and manufacturing engineering exhibits distinctly different characteristics to those of earlier convergences in manufacturing engineering. The earlier convergences e.g. in Industry 1.0–4.0 mainly involved different disciplines of engineering - mechanical to electrical to control to electronic and then to software and to telecommunications. This new convergence is between engineering and science i.e. biology and is therefore considerably more challenging for engineers, as the language, the culture and the systems associated with biology are significantly different to those of engineering. Considerable effort is thus required to overcome the natural barriers which arise.

Manufacturing engineering and biology converging - biologicalisation in manufacturing

In recent years it has become increasingly evident that a new convergence between biology, the physical sciences and engineering is developing. The book published in 2019 entitled "*The Age of Living Machines*" Hockfield [12] highlights the point that the overarching topic of biology will be a driver for the next technology revolution. She refers to growing up in the midst of two major biological revolutions, the first being "*Molecular Biology*" and the second being "*Genomics*". She presents five Demonstrators in the book, and although they are not specific to manufacturing science and engineering, they do provide interesting and important insights. The Case Studies include: "Biology and Batteries", "Biology and Water", "Biology and Cancer fighting Nano-Particles", "Brain" and "Food".

Some of the high-level aspects of the new Biologicalisation Frontier seen to be opening up as a next phase of the digitalisation and Industry 4.0 developments include:

- New developments in chemistry and new materials,
- New products using new bio-materials [13],
- A higher level of understanding of biological materials and processes through the use of modelling and simulation tools,
- Classical industrial processes being influenced, with the potential for entirely new bio-inspired industrial processes to develop,
- Potential for new bio-inspired manufacturing processes and equipment, including robotics, machine tools and measuring equipment [14,15] and
- New bio-inspired models for the production organisation including manufacturing systems and supply chains.

Some of these trends were evident at the 2017 Conference of the International Academy for Production Engineering (CIRP) in Chicago where Mirkin [16] spoke of completely new directions in chemistry and the advent of new materials with capabilities way beyond the present limitations.

The work reported in this paper is aimed at the ambitious target of exploring the effects of Biologicalisation on the entire manufacturing hierarchy: from the discrete component level, all the way to the integrated system, supply chain, and organisational levels. In doing so, comparisons are drawn between the hierarchies existing in manufacturing systems and those existing within biological systems – where the cellular level is equated with the discrete components, organs with machines, entire organisms as equivalent to factories, and ecologies or societies as analogous to complete organisations and supply chains – see Fig. 4.

Each demonstrator explored a different stratum of the manufacturing hierarchy, also illustrated in Fig. 4. However, it was deemed to be very important that the demonstrators do not exist solely in their own strata but that significant cross-collaboration between each of them be explored. The specified intent was to deliver a comprehensive, overall and early stage representation of elements of the Biologicalisation Transformation in Manufacturing.

As well as covering the broad spectrum of the manufacturing hierarchy, the demonstrators had the objective of exploring the transformation from the old, lifeless, non-connected manufacturing systems to *"The Living Manufacturing System"*. It is hypothesised that future manufacturing systems will develop in this direction in the contexts of *a) bio-inspiration, b) bio-integration and c) bio-intelligence*.

Fig. 5 presents a general block diagram showing a systematic bi-directional approach – "Manufacturing-Driven" (blue) and "Biology-Driven" (green), to analyse and identify the potential and impact of biologicalisation in manufacturing. These two main directions are presented in 5 stages, either starting from the industrial/technical/manufacturing stage or from the biological/nature/scientific point of view, both aiming to improve manufacturing processes and product quality.

When starting from the manufacturing side, the first stage is to define the problem, including setting targets and goals for material, surfaces, design, processes, control, system, organisation, functions, etc. In Stage 2, checking biological options requires searching for and identification of analogical solutions, relevant options, and similar concepts or to look for available solutions. Stage 3 starts with the selection of a relevant solution or a concept, including analysis and abstraction in order to explain and make it understandable for the engineering community. The ever-growing database, including that for biology, is an excellent background facility from which to search for relevant algorithms and to retrieve updated information. In Stage 4, parallel to an iteration process, the potential benefit to and impact on manufacturing is evaluated

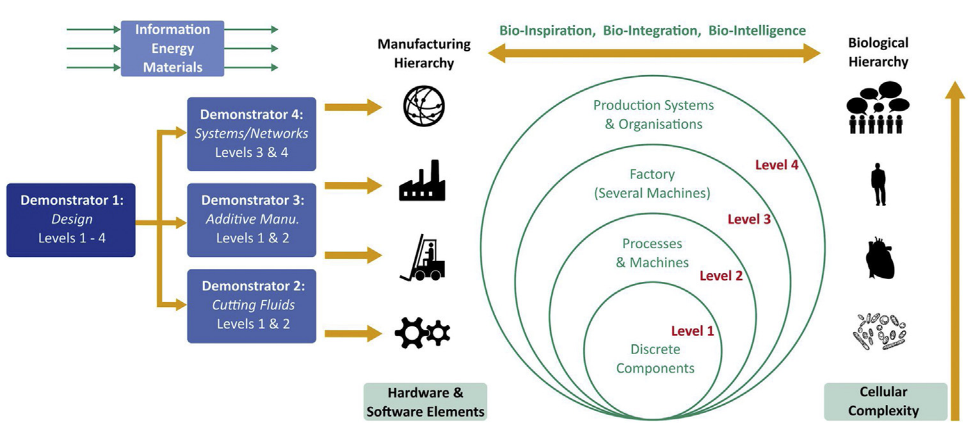

Fig. 4. The relationship between manufacturing and biological hierarchies, and the individual demonstrator strata (Source: early version from inspire AG).

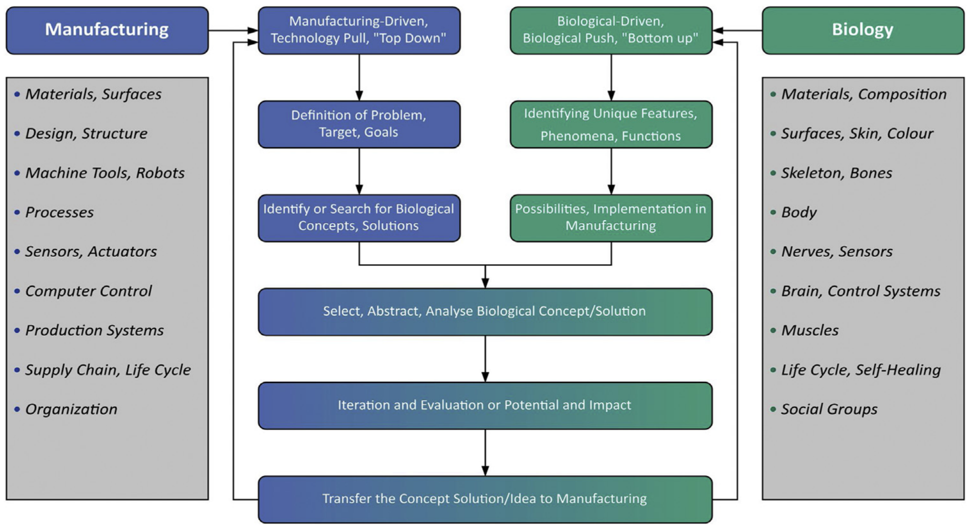

Fig. 5. The bi-directional systematic approach to identify potential and impact of biologicalisation in manufacturing [1].

before transferring the “biological solution” to the relevant manufacturing topic(s).

The block diagram also includes the second approach, the biology-driven or “Bottom Up” from biology to manufacturing. Starting from a biological system with unique characteristics then followed by identification of these features, phenomena and functions in Stage 1 can be identified and in the next stage by evaluation of possible implementation capability. The next 3 stages, starting from selection, abstraction and analysing, iteration and evaluation, followed by transferring the selected one to manufacturing are then identical to the top down approach.

To examine the potential applications of biologicalisation in manufacturing (BiM) systems, work was divided into four demonstrators. These were chosen to demonstrate the principles of bio-inspiration, bio-integration and bio-intelligence when applied to key elements of manufacturing. These demonstrators represent an initial attempt to give early stage confirmation of progress towards Biologicalisation in Manufacturing as well as early stage insight into the outstanding challenges and future direction of the field. The specific details of the chosen demonstrators are included in Section 4 below.

Performance improvement in biologicalised advanced manufacturing systems

The main objective of the study reported here was to illustrate the role of the Biological Transformation in Manufacturing as a new frontier of Digitalisation and Industry 4.0, leading to a

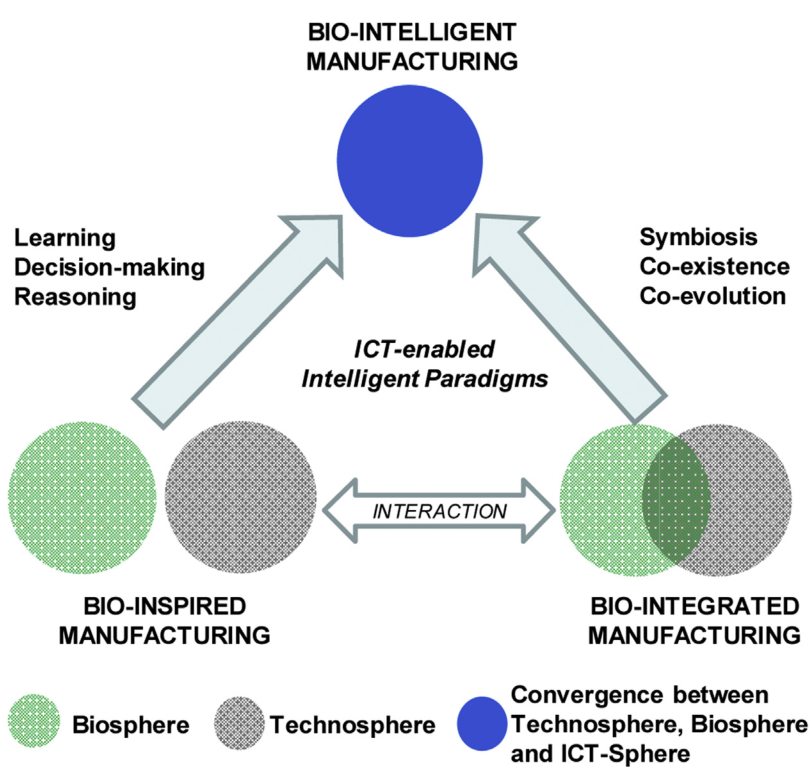

Fig. 6. Relationship between bio-inspiration, bio-integration and bio-intelligence.

paradigm shift in advanced manufacturing. A further objective was to evaluate and assess a potentially new emerging concept of the "*Living Manufacturing System*". For that purpose, four demonstrators, each representing significant areas of discrete manufacturing, were selected. These demonstrators form the basis for which various scenarios and technical aspects of Industry 4.0 from this new Biologicalisation in Manufacturing perspective were analysed and tested.

Building on the previous work of the authors [1] and on the work of other researchers e.g. [17–20], it was assumed that future biologicalised manufacturing systems will continue to develop along the three directions of: *a) bio-inspiration, b) bio-integration and c) bio-intelligence*.

The work undertaken involved assessment of the chosen areas from the perspective of performance enhancement through the incorporation of each of the three elements. Fig. 6 illustrates the relationship between bio-inspiration, bio-integration and bio-intelligence. The figure reports on a scheme which indicates that both bio-inspiration and bio-integration solutions can develop towards bio-intelligent solutions with the merging/convergence of ICT enabled intelligent paradigms. The six aspects: learning, decision making, reasoning, symbiosis, co-existence and co-evolution all relate to the attainment of bio-intelligence.

Proposed definition of Bio-Inspired Manufacturing:

Bio-inspired manufacturing is realised by transferring concepts concerning principles, functions, structures and/or solutions from the biosphere to the manufacturing technosphere.

In regard to bio-inspiration, the lower part of Fig. 6 shows two circles to illustrate the separate areas of the biosphere and the technosphere, whereby inspiration is drawn from the biosphere into the technosphere. The grey circle represents the technosphere and the green circle represents the biosphere.

Proposed definition of Bio-Integrated Manufacturing:

Bio-integrated manufacturing is realised by integrating elements from both the biosphere and the technosphere within the manufacturing environment.

In Fig. 6 (lower part, right hand side) bio-integration is illustrated by showing an overlap of the biosphere and the technosphere circles to highlight the fact that elements of both spheres are integrated within the technical manufacturing solution/system.

Proposed definition of Bio-Intelligent Manufacturing:

Bio-intelligent manufacturing is realised 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 systems.

Finally, in Fig. 6 it is shown that in order to reach the stage of bio-intelligence in technical manufacturing solutions/systems (illustrated by the blue circle at the top of the diagram), ICT enabled intelligent paradigms, such as Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Evolutionary Computation (EC) etc., are required. Additionally, it is shown that there is also a requirement for merging with either bio-inspiration or bio-integration or with both.

The horizontal double arrow in Fig. 6 refers to the possibility of interaction between bio-inspiration and bio-integration in manufacturing solutions that can also be developed through convergence. In relation to the two slanted arrows towards bio-intelligence (blue circle), in addition to the interaction illustrated, the inclusion of ICT enabled intelligent paradigms is a requirement.

It is noted that the above definitions are proposed by the authors and that they require further consideration before being recommended for adoption by the community involved in manufacturing research. In this regard, a joint activity was established between the Collaborative Working Group (CWG) on *Biologicalisation in Manufacturing* of the International Academy for Production Engineering (CIRP) and the CIRP Committee on Terminology. The aim of the joint activity is to provide proposals and solutions to address terminology issues concerning the Biological Transformation in Manufacturing.

Manufacturing system performance improvement is considered in the light of broader perspectives and has sustainability as a core focus. Besides the technical process efficiency aspects (such as higher degrees of automation, increased output, part quality, knowledge in the company and retained skills within the manufacturing system) also ethical questions, economic issues and in particular sustainability issues are all highly relevant [21].

Four demonstrators were developed to gather evidence showing a performance improvement from the Biologicalisation in Manufacturing (BiM) perspective. The areas of the demonstrators selected and the associated primary focus of each were as follows:

- Demonstrator 1: Bio-based Design Methodologies for Products, Machine Tools and Processes (primary focus: bio-inspiration),
- Demonstrator 2: Microbial-based Cutting Fluids in Machining (primary focus: bio-integration),
- Demonstrator 3: Bio-Inspired, Self-Learning Additive Manufacturing Systems, Machines and Processes (primary focus: bio-inspiration and bio-intelligence) and

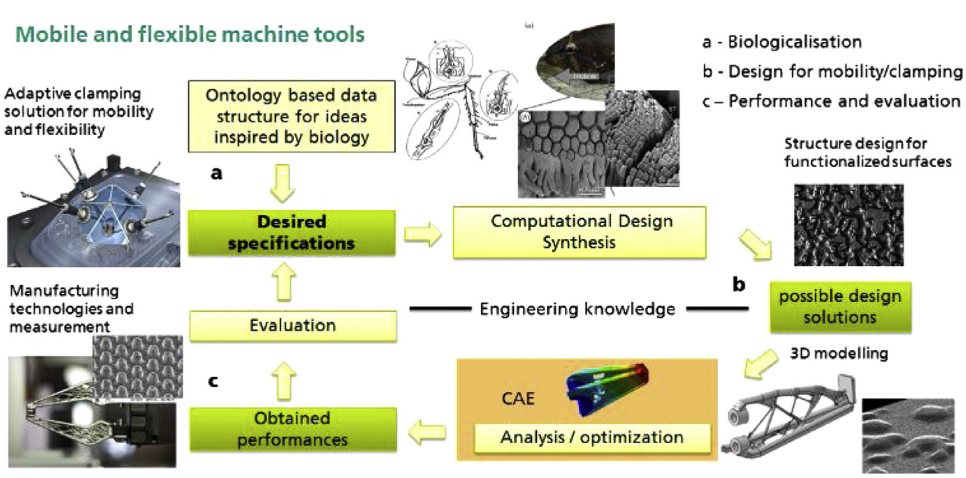

Fig. 7. Demonstrator 1: Mobile and flexible machine tool.

- Demonstrator 4: Robust, Cooperative Manufacturing Systems (primary focus: bio-intelligence)

The work undertaken in each demonstrator is described in detail below.

Demonstrator 1: bio-based design methodologies for products, machine tools, processes and systems

The emphasis within this demonstrator was on the development of design methodologies for complex products and production systems [22]. Such a concept has also been proposed by Zhang et al., whereby innovative design methodologies have been implemented in the optimisation of advanced manufacturing systems for the case of additive manufacturing [23]. In order to allow biological principles to be implemented into the bio-inspired design of technical components, approaches have been developed to determine the best sets of solutions. The demonstrator uses a scientifically based method for the systematic collection and storage/retrieval of bio-inspired design principles (bio-design base) as an input for set-based design. A computational design synthesis algorithm then evaluates the design principles and develops possible design solutions for technical components/ systems.

The computational design synthesis methods developed were applied to the design of the kinematic layout and adaptive clamping devices of flexible and mobile machine tools. Furthermore, the design methodology could be demonstrated on light weight clamping jaws and surface structures with biological integrated layers to protect mechanical components of the machine tool. The overall workflow involved in this design demonstrator is illustrated in detail in Fig. 7. Depending on the goals of a design solution, functional surfaces, lightweight components and integrated sensors can systematically implement different biological principles as input data by inspiration and/or integration for effective results. The inspiring biological phenomenon and principles related to the flexible machine tool, discussed in the paper are leg and body structures, sensors, movement of animals and insects, as well as leg adhering mechanism to smooth surfaces. From the biological investigations, it could be concluded that legged locomotion (bio-inspired) is the most advantageous means of locomotion. Six-legged locomotion excels especially on uneven, unexpected terrain and surfaces.

The primary focus of this design demonstrator relates to the potential of biological systems as sources of inspiration in the design of manufacturing systems. In nature, an abundance of versatile solutions exists for design problems that may be encountered in a contemporary engineering environment. By carefully observing, collecting, sorting, cataloguing, examining and thus understanding the solutions to these problems that have evolved in the natural world, it is possible to solve the analogous engineering problems in efficient and effective ways. Another method for being inspired by nature consists of emulating the method by which nature has arrived at these solutions: *evolution*.

By making use of iterative design methodologies and selection criteria, a modern computational simulation can algorithmically optimise a design to generate a new solution to the problem encountered. As a demonstration of this bio-inspired design methodology, the work reported here sought to design a mobile machine tool using bio-inspired methods, attempting to improve existing designs from the perspective of a number of key metrics. The overall workflow involved in this design demonstrator is illustrated in detail in Fig. 7.

Demonstrator 2: microbial-based cutting fluids in machining

This demonstrator refers to physical classical machining processes (turning and milling) operating with novel, sustainable microbial-based cutting fluids and endowed with smart sensor monitoring. It provides a tangible example of bio-integration in advanced manufacturing. It is easy to visualise the integration aspect as living organisms are supplied directly into the manufacturing system. This demonstrator had the objective of early stage testing to evaluate whether the mineral oil in conventional cutting fluids can be substituted with suitable microorganisms for the lubrication function without negatively affecting performance and manufacturing process efficiency, thereby eliminating the former's negative environmental and societal impact. The work to validate this hypothesis element focused on systematic metal cutting tests using cutting fluids based on a microalgae strain and two strains of yeast, respectively.

The fundamental feasibility of using cutting fluids based on microalgae and yeast for different machining operations (turning of carbon steel and milling of titanium Ti6Al4V alloy) was demonstrated. Three microbial-based cutting fluids were successfully produced with a microalgae strain (Spirulina arthrospira maxima) and two strains of yeast (Saccharomyces cerevisiae and Metschnikowia pulcherrima).

Micrographs of the spirulina platensis cells following machining at different cutting speeds are shown in Fig. 8. Images (a) and (b) in the figure refer to samples recovered after turning with lower cutting speed (v_c = 130 m/min) and (c) and (d) images refer to

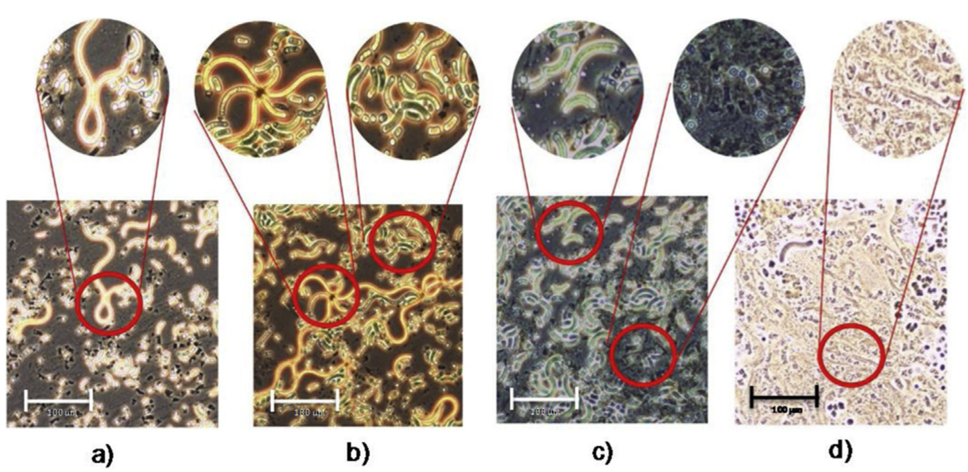

Fig. 8. Microscopic view of microalgae-based cutting fluid (note that the bar length shown represents 100 μm).

samples recovered after turning with higher cutting speed (v_c = 230 m/min). [(a) Red circle: undamaged cells. (b) Red circles: undamaged cells (left) and fragmented cells (right). (c) Red circles: cell fragments (left) and cell lysates (right). (d) Red circle: cell lysates (cell membrane destruction)].

Demonstrator 3: bio-inspired, self-learning additive manufacturing systems, machines and processes

The new paradigm associated with this demonstrator is to employ and implement more functionalities of biological, living systems in new technical systems, i.e. a biologicalisation of technology. The basic hypothesis is that for manufacturing machines, using the example of selective laser melting (SLM) machines, there is a significant benefit through the adoption of artificial intelligence, whereby artificial intelligence is understood to be a deeply integrated combination of a large number of related technologies. Manufacturing processes require skilled operators and these are a scarce resource. The basic concept of the demonstrator thus revolves around the integration of the operator's skills to the greatest possible extent into the machine. This at the same time means an increase in the capabilities of process observation combined with on-line closed loop control strategies for the repair of imperfections induced during manufacturing, along with self-learning cycles. An integrated expert system stores data on operator experience and gives the reasoning for the provision of useful information for new manufacturing tasks. Furthermore, besides state monitoring, channels for machine communication need to be designed to suit the source of information, other machines, operators, manufacturing tasks and/or manufacturing execution systems (MES). An overview on the concept is provided in Fig. 9. Two critical aspects of the concept are elaborated on in more detail:

a.) Utilisation of a camera as broad band sensory for the in- situ recognition of faults developing on individual layers, as a prerequisite for repair strategies and
b.) Feature segmentation of products to be built and synthesis of feature programs to the product program as a prerequisite for self-learning of manufacturing strategies and process parametrisation.

A machine learning approach (pre-trained deep convolutional Neural Network-based image processing) was tuned for the identification of deviations in a SLM layer. This was implemented for on-line fault recognition based on automatic image processing during selective laser melting of metallic powders. The concept allows the identification of the onset of defects due to process nonconformities and to subsequently counteract or correct such faults in the next layer. This can lead to improved part quality and a reduction of scrap.

Various Artificial Intelligence (AI) tools were investigated for different tasks within the SLM process chain, namely image recognition for correction of faults and irregularities, nesting optimisation, support structure optimisation, build strategy evolution and process parameter generation for new alloys and powder specifications. Communication, learning from skilled persons and information provision to unskilled operators represent basic elements of a bio-intelligent system of this nature. Fault detection with fully integrated sensor systems and the question of how to deal with the outer learning cycle (namely feature segmentation, layer-wise correction to enhance part quality) formed a major part of the work of this demonstrator. A general layout of the bio-intelligent manufacturing system with all required functionalities was investigated. Fig. 9 illustrates the overall concept associated with this demonstrator.

Demonstrator 4: robust, cooperative manufacturing systems

This demonstrator relates to "StemCellDiscovery", an automated stem cell production platform developed at the Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University and at the Fraunhofer Institute for Production Technology (IPT), Aachen (illustrated in Fig. 10).

Here, the product is not a passive element of the production process but rather a living organism. This fact induces challenges such as: 1) there is inherent diversity of the products (stem cells), 2) there is varying growing speeds and process times, 3) there is a

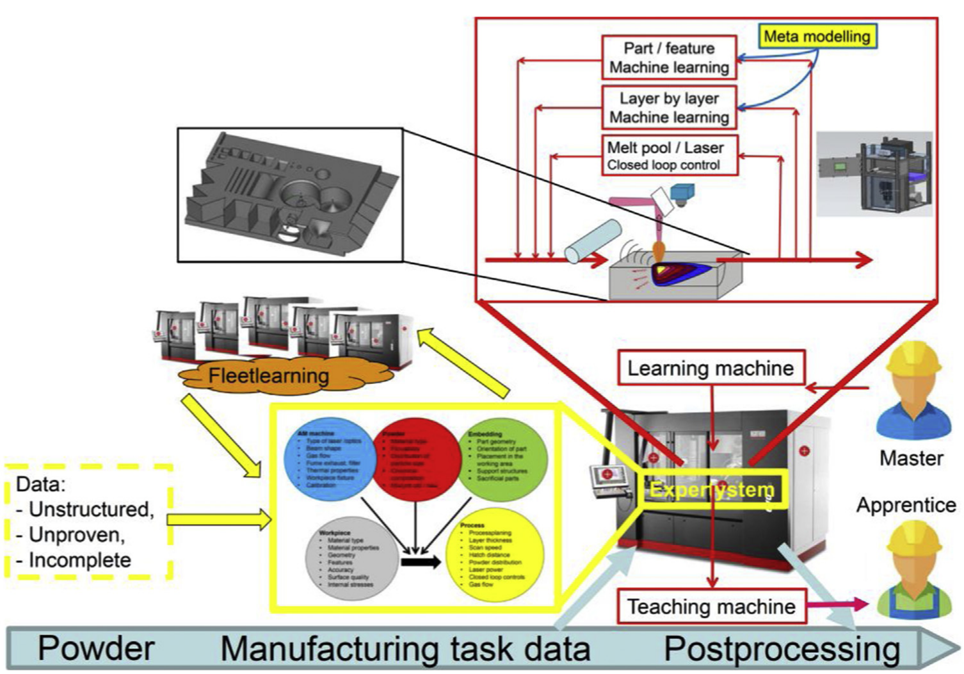

Fig. 9. Concept of a bio-intelligent AM system.

Fig. 10. The StemCellDiscovery platform in Aachen (WZL/IPT).

need for their regular observation and process adaptation, and, therefore, 4) a need for mixed-initiative production control.

A distinctive feature of the domain is the symbiotic co-existence and co-evolution of the technical, ICT and biological elements in production structures. According to the understanding of the participants involved with this demonstrator, this represents another level of biologicalisation in manufacturing, referred to by some as bio-intelligence (see definition above).

The novel solution developed in this demonstrator, proposed by the Institute of Computer Science and Control. Budapest, involves the use of reinforcement learning (RL) technics, a biologically inspired machine learning approach, i.e. learning from interactions for controlling manufacturing cells producing biological material [24]. For this purpose, a simulation model of the automated stem cell production platform StemCellDiscovery developed in Aachen was progressed. The simulation system was used, on the one hand, for testing different scenarios of the present cell type, and on the other hand, for improving the platform performance by reinforcement learning based algorithms.

Impact analysis of biologicalisation – Convergence towards the *Living Manufacturing System*

The research hypothesis associated with the work outlined here was *"that Future Manufacturing Systems will incorporate components, features, characteristics and capabilities that enable the convergence towards living systems"*. The demonstrators described in high level summary form in Section 4 above assessed this hypothesis, proactively sought concrete evidence to show as clearly as possible that a convergence of biology with the engineering and physical sciences is taking place and that this convergence will have a significant impact on the performance of advanced manufacturing systems and in turn on industrial development beyond Industry 4.0.

A biological system can be defined as a complex network of biologically relevant entities, such as genes, proteins, metabolites etc. interacting in a non-linear fashion and acting as a network to perform different tasks/functions. The new paradigm being tested in the study reported here is the employment of more functionalities of biological, living systems and implementing them in new technical systems. Such new systems will be differentiated from current systems by their *life-like* nature, hence the emergence of the new concept of the "*Living Manufacturing System*" in relation to discrete component manufacture. The expectation therefore is that adopting biological functionalities for machines and manufacturing systems increases their sustainability and optimises their behaviour within their operational and environmental conditions.

Primary Focus - Bio-Inspiration:

Demonstrator 1 – Bio-based Design Methodologies for Products, Machine Tools and Processes

Fig. 11 highlights the fact that the primary focus of this demonstrator was on bio-inspired manufacturing (grey and green circles separated, the solid red lined box in the figure represents the primary focus of the demonstrator and the dotted lined boxes the secondary focus). It also indicates that further development can take place towards bio-integration (grey and green circles overlapping). Further development can also take place towards

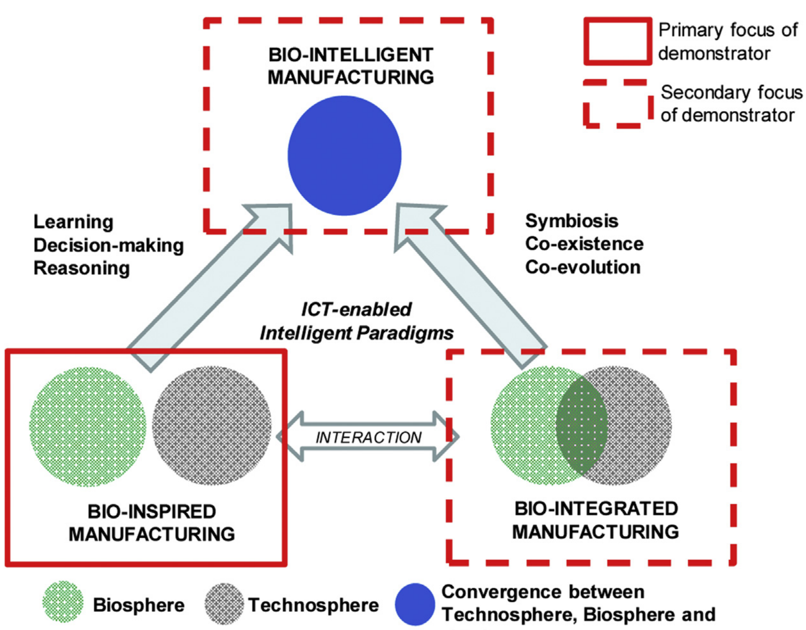

Fig. 11. Relationship between bio-inspiration, bio-integration and bio-intelligence in regard to Demonstrator 1.

Table 1
Bio-inspiration and the impact of Demonstrator 1.

Impact of Demonstrator 1: Bio-based Design Methodologies for Products, Machine Tools and Processes
Impact on design methodology: • Shows the value of a methodical approach of biology-inspired design and manufacturing technologies • Shows the value of systematic computational analysis of literature from the biology domain • Demonstrates the applicability of biology-inspired design methodologies • Confirms computational design synthesis as a tool to support "Manufacturing for Design" • Presents innovative ways to deal with changing design constraints • Dynamic data structures for design processes based on ontologies • Constrained set-based design
Impact on manufacturing systems and biological transformation: • Shows the viability of the combination of biology-inspired geometry, material and surface properties, sensors and control strategies • Explores the relationship between bio-inspiration, bio-integration and bio-intelligence • Capturing of biological knowledge • Incorporating new manufacturing methods and tailored materials (including additive manufacturing)
Impact on sustainability: • Weight reduction of products and systems leading to diminished energy utilisation • Higher level of adaptability, leading to shorter design cycles and fewer wasted resources

bio-intelligent manufacturing (blue circle) through incorporating ICT-enabled intelligent paradigms such as smart sensors and intelligent process optimisation in the bio-integrated manufacturing solution.

It was shown in this work that the benefits of bio-inspiration in manufacturing can be substantially strengthened by applying systematic mapping of scientific publications of both domains (biology and manufacturing engineering). It was concluded that the biological principle of "*Effectiveness*" in achieving goals by means of redundancy can be mimicked by applying methods of Computational Design Synthesis (CDS) enabled by (massive) digitalisation. The combination of bio-inspired, shape optimised additive manufacturing enables lighter and functionally optimised/integrated parts. In one example it was shown that topology optimisation of a bio-inspired gripper led to weight reduction from 312 g to 50 g. Configuration design improved mobile machine tools - towards autonomous mobility. It was concluded that new innovative ways to deal with changing design constraints emerge when a proactive focus is placed on bio-inspiration. The results of the work on this demonstrator are summarised in Table 1.

This result can have significant implications for the performance of manufacturing processes, machines, systems and networks. Ensuing methods of computational design synthesis can be applied at all levels within the manufacturing systems and networks. Each of the other demonstrators reported in this study embodies very specific characteristics and challenges related to this design-focused demonstrator including:

- Developing design support systems that systematically make use of principles inspired by biology,
- Delivering integrated interdisciplinary support for complex system design,
- Creating awareness among designers that (classical) optimisation strategies may no longer be fully effective,
- Realising a paradigm shift from today's split of manufacturing into intelligent preparatory work and execution work towards an integrated system embodying both and
- Deployment of coordination and cooperation strategies that lead to adaptive, flexible and coherent collective behaviour in manufacturing systems and supply chains.

The conclusion is that systematic and structured approaches can be adopted which can more effectively search for the highest potential of bio-inspiration. The approach of computational design synthesis will permit the development of new methodologies for enhancing the performance levels of bio-inspired manufacturing systems. New and exciting opportunities will emerge for the industries involved in advanced manufacturing as the computational design synthesis approach matures [22].

Primary Focus - Bio-Integration:

Demonstrator 2 – Microbial-based Cutting Fluids in Machining

Demonstrator 2 had the objective of testing whether the mineral oil in conventional cutting fluids can be substituted with suitable microorganisms without negatively affecting performance and manufacturing process efficiency, thereby eliminating the former's negative environmental and social impact. Fig. 12 highlights the fact that the primary focus of this demonstrator is on bio-integrated manufacturing (grey and green circles overlapping, the solid red lined box represents the primary focus of the demonstrator and the dotted lined box the secondary focus). It also indicates that further development can take place towards bio-intelligent manufacturing (blue circle) through incorporation of ICT enabled intelligent paradigms such as smart sensors and intelligent process optimisation in the bio-integrated manufacturing solution

Two sub-demonstrators (one in Italy, R. Teti and one in South Africa, O. Damm) were successfully developed which show the benefits of bio-based cutting fluids for the turning and milling processes. For each of the microbial-based cutting fluids, the cutting forces, tool wear and workpiece surface finishes were found to be *comparable to or better than* for conventional cutting fluid in turning (microalgae-based cutting fluid) and in high-speed milling (yeast-based cutting fluids). The microbial cells in the cutting fluid were severely damaged during the turning and milling tests, with only 5–10% of cells surviving. The extent of damage was found to increase with increasing cutting speeds.

The impact of the results of this demonstrator on manufacturing systems in the context of biologicalisation is summarised in Table 2.

It is concluded that although these are very early stage demonstrators and that high levels of complexity arise in such investigations, the potential exists to significantly reduce the considerable volumes of mineral oil required for the machining of metallic materials. Indeed, the elimination of the use of mineral oils in cutting processes may be possible at some time in the future - achieved through the integration of biological materials into the cutting fluid. The implications of this become ever more significant as the critical question of sustainability of manufacturing systems moves centre stage in relation to the achievement of the UN Sustainability Goals.

It is very clear however, that these demonstrators require further research and analyses. Besides the open technological questions, there are also open issues regarding the introduction of microorganism cultures into the manufacturing environment. In this regard, it is to be noted however, that there are examples from other sectors e.g. the food sector, where living cells/cultures have been in an industrial, scaled-up manufacturing environment for many decades. The overall economics of the use of microbial-based fluids clearly needs detailed investigation.

This demonstrator provides a very good and relatively easy to understand example of bio-integration in advanced manufacturing systems [25,26].

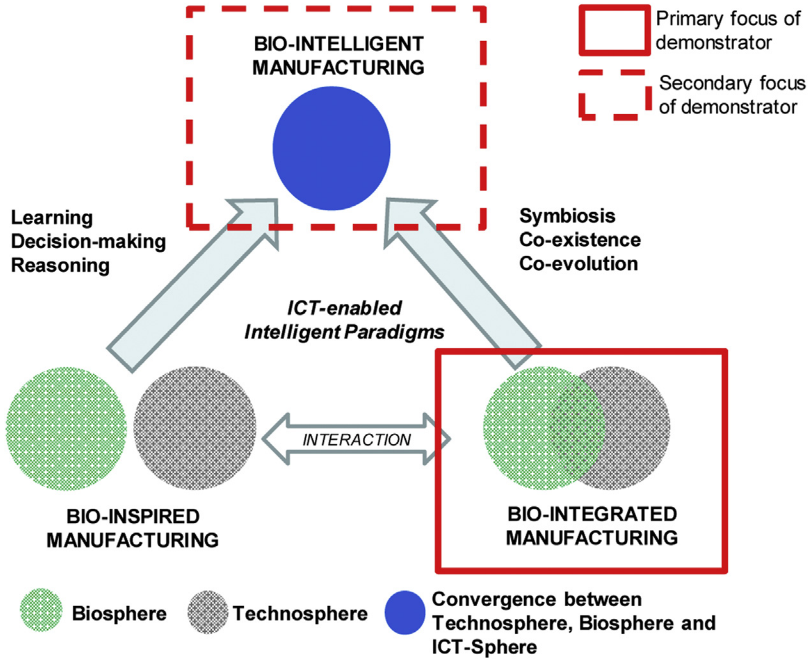

Fig. 12. Relationship between bio-inspiration, bio-integration and bio-intelligence in regard to Demonstrator 2.

Table 2
Bio-integration and the impact of Demonstrator 2 – technical/engineering perspective.

Impact of Demonstrator 2: Microbial-based Cutting in Fluids in Machining
Impact on machining process:
Cleaner, healthier working environment
Cost reduction of machining process
Impact on manufacturing systems and the biological transformation:
Cost reduction of machining process can alter or lead to process substitution in manufacturing systems
Bridge building between manufacturing/technology and natural/biological sciences, leading to new solutions
Demonstrator shows applicable approach for bio-integration
Simplified supply chains through decentralised, local production
Impact on sustainability:
Use of renewable materials and simpler end-of-life disposal
Improved health and safety – benign materials compatible with humans
Reduction of environmental footprint (no toxic waste, highly reduced CO_2 footprint)

Primary Focus: Bio-Inspiration and Bio-Intelligence:

Demonstrator 3 - Bio-Inspired, Self-Learning Additive Manufacturing Systems, Machines and Processes

The basic hypothesis associated with this demonstrator is that for manufacturing machines using the specific example of selective laser melting (SLM) machines, there is a significant benefit through the adoption of bio-intelligence as further elaboration of AI. An attempt was made to use a control system that integrates the tasks and decision making of the operator/expert. He/she is capable of observing the process and interaction based on his/her experience, which he/she in turn gained from operating the machine and theoretical knowledge of the physics of the process. The functionality of the operator as a biological system was integrated into the manufacturing system to increase the autonomy. Besides this, an artificial operator might acquire some additional capabilities, as for instance observing the process by its infrared emissions. In the demonstrator, the necessity of a bio-intelligent approach was shown. This is in accordance with the definition above which is understood in this context as a deeply integrated combination of a larger number of different technologies, sensors and information channels with a learning ontology based expert system. The work on this demonstrator has highlighted the need for very careful assessment when comparing natural and technical solutions in order to successfully adopt bio-inspired principles and integrate them into manufacturing systems.

The demonstrator presents the highly challenging ambition of benchmarking against the human brain and the associated intelligence level. The human brain can significantly outperform technical solutions for enhanced quality, efficiency, robustness and sustainability of additive manufacturing and other manufacturing processes. The demonstrator successfully showed that incorporating high level (towards human level) intelligence for technical systems can improve the quality, robustness and efficiency of additive manufacturing and other manufacturing processes. Adopting biological functionalities for machines increases their sustainability and optimises their behaviour within their own operating and environmental conditions.

Fig. 13 shows that the primary focus of this demonstrator is both on bio-inspired manufacturing (grey and green circles separated, boxes with solid red lines) and bio-intelligent (blue circle) manufacturing.

The work undertaken has shown that manufacturing machines (e.g. additive manufacturing machines) equipped with AI will be capable of permanently acquiring new knowledge and continually seeking self-optimisation.

Careful estimation of technological consequences of the investigation undertaken raises the expectation of:

a) fault reduction and increase in the dynamic strength of components to the level of that of forged parts,
b) fault correction to reduce the scrap due to prematurely aborted build jobs by a factor of 10 due to early in-situ counteraction after detection of deviations,
c) Reduction of average setup times in today's production mix in SLM by a factor of 2–4 due to the input of operator experience and newly generated knowledge.

It is concluded that a useful and highly autonomous manufacturing machine (example SLM) can be designed with

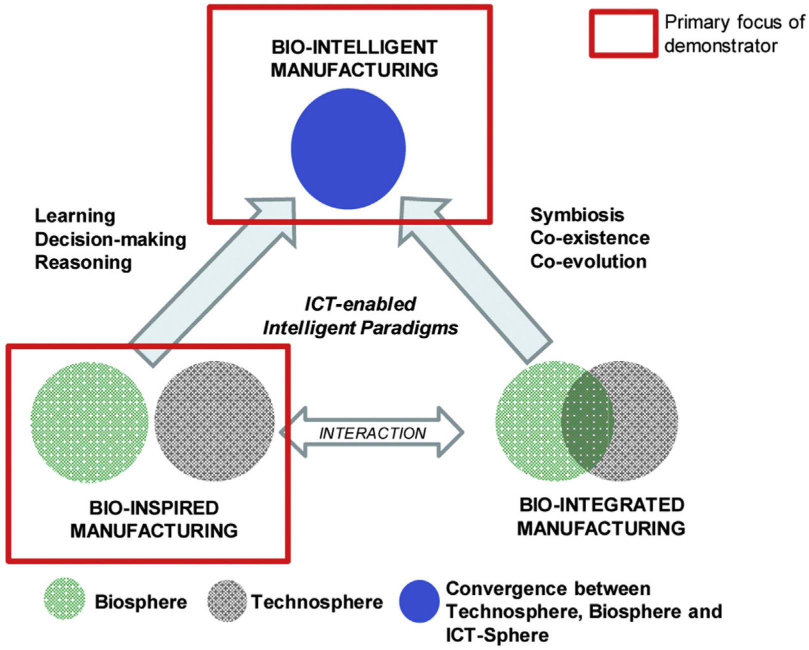

Fig. 13. Relationship between bio-inspiration, bio-integration and bio-intelligence in regard to Demonstrator 3.

methods available today including AI technologies and computational power. It is also recognised that simply using Artificial Neural Networks (NN) for individual tasks alone does not allow the full exploitation of the potential of AI. It is the combination of different AI technologies and their integration into the information streams gathered from bio-inspired sensory human-like communication channels with people, machines, manufacturing execution systems and the internet that has the major impact. To a certain extent this means the integration of the capabilities of the skilled operator into the machine.

The impact of the Demonstrator 3 in the context of biologicalisation in manufacturing is summarised in the Table 3 below.

The underlying principles can be applied to other machine types in advanced manufacturing systems. The demonstrator clearly moves the thinking forward into the realm of autonomous, bio-intelligent systems. Developments are taking place at such a rapid rate that deeper levels of bio-intelligent manufacturing systems will be realisable, albeit in an incremental manner, in the near future [2].

Primary Focus: Bio-Intelligence:

Demonstrator 4 - Robust, Cooperative Manufacturing Systems

This demonstrator relates to the “StemCellDiscovery” automated stem cell production platform developed at the Fraunhofer Institute for Production Technologies (IPT), Aachen (Fig. 10). The primary focus of this demonstrator was on the bio-intelligence aspect of biologicalisation in manufacturing and the development of bio-inspired algorithms such as reinforcement learning for control. The results achieved in this demonstrator were: optimised process parameters, better resource usage, higher throughput, increased and more uniform quality, cost reduction and higher robustness/resilience.

Fig. 14 highlights the fact that the primary focus of this demonstrator is on bio-intelligent manufacturing (blue circle, solid red lined box). It also indicates that bio-inspired (grey and green circles separated) and bio-integrated (grey and green circles overlapping) are also incorporated (illustrated by the dotted red lined boxes).

The two scenarios which included the confluence threshold resulted in approx. 15–20% increase in cell production and up to 30% in the largest system. A new biologically inspired control algorithm can now be demonstrated by using this simulation. A new concept of co-existence, co-evolution and mixed initiative control was considered.

Bridge building was demonstrated between discrete part manufacturing science and technology, on the one hand, and biological/medical sciences, on the other. Such bridge building is a critically important component of the convergence of biology/medical science with the engineering physical sciences. It was concluded that the automated production of biological materials (such as stem cells) represents perhaps the highest level of biological transformation in manufacturing, where a symbiotic co-existence and co-evolution of the technical, ICT and biological sub-systems are manifested.

Table 4 summarises the impact of this demonstrator in the context of biologicalisation.

This demonstrator provides early stage evidence of the significance of the “biologicalisation in manufacturing” strategic approach to the development of future manufacturing systems. The early results clearly underline the significant benefits which can be derived. The physical stem cell demonstrator element is available on the system in the Fraunhofer Institute for Production Technologies (IPT), Aachen, Germany. The simulation of the functioning of the present StemCellDiscovery platform can be demonstrated by the software developed at the Institute of Computer Science and Control, Budapest, Hungary. The biologically inspired control algorithm can also be demonstrated by using this simulation. This result is highly significant in the context of productivity improvements and the biologicalised manufacturing system [27].

Table 5 provides an overall summary of some of the key evidence which was collated from the each of the demonstrators described above for which a focused biologicalisation approach was adopted. It was shown that for each demonstrator, significant benefits in the performance of the relevant element of the manufacturing system could be demonstrated.

Table 3
Bio-Inspiration and Bio-Intelligence – impact in the context of biologicalisation in manufacturing – Demonstrator 3.

Impact of Demonstrator 3: Bio-Inspired, Self-Learning Additive Manufacturing Systems, Machines and Processes
Impact on additive manufacturing processes:
High requirements of industrial processes can only be met by additive manufacturing processes through the integration of AI
Generation of new knowledge in SLM
Enhanced quality and productivity of AM processes
Impact on manufacturing systems and the biological transformation:
Enhanced quality and productivity of AM, thus leading to cost reduction and therefore a wider adaptation of AM in manufacturing supply chains
Demonstration of benefit of Bio-Intelligence in AM with relatively easy adaption to other manufacturing processes
Demonstrator paves the way to a bio-inspired intelligent manufacturing system
Demonstrator makes implicit knowledge explicit e.g. making the knowledge of skilled operators available to the company
Impact on sustainability:
Reduction of environmental footprint (reduced scrap, reduced set-up and process times, increased throughput)

Table 4
Impact of Demonstrator 4.

Impact of Demonstrator 4: Robust, Cooperative Manufacturing Systems and Production Networks
Impact on manufacturing process:
Minimisation of human errors, enhancement of reproducibility
Enhanced quality and productivity through higher throughput of the system, leading to cost reduction
Improved robustness (resilience, flexibility, changeability, agility, responsiveness, adaptability etc.)
Enhanced predictability and increased planning ability
Impact on manufacturing systems and the biological transformation:
Demonstration of benefit of Bio-Intelligence
Bridge building between discrete part manufacturing science and technology on the one hand and biological/medical sciences on the other hand
Co-existence and co-evolution, as well as mixed-initiative control
Improved robustness (resilience, flexibility, changeability, agility, responsiveness, adaptability etc.)
Impact on sustainability:
Balancing between robustness, complexity and efficiency

It is concluded for all four demonstrators, that due to the significant performance benefits that can be achieved through the incorporation of bio-inspired, bio-integrated and/or bio-intelligent aspects, that future manufacturing systems *will* converge towards living systems. This conclusion has implications which are of enormous consequence as it has the potential to reshape the design, functioning and performance levels of future manufacturing systems and to have a highly positive impact on global sustainability goals. Based on the depth of analysis undertaken in each demonstrator, it is concluded that an early stage body of scientifically based evidence has now become available through this work which provides initial validation of the appropriateness to give further and more detailed consideration to the concept of the *"Living Manufacturing System"* (LMS). This evidence encompasses for example; higher performance and decreased weight of components through bio-inspired design methodologies, mineral oil reduction in manufacturing processes, optimised process parameters and increased process quality, stability and robustness through the use of differing levels of Artificial Intelligence and Machine Learning along with the application of biologically inspired control algorithms etc.

When considering manufacturing system performance, it is important that the engineering and technical performance aspects not be considered in isolation. We must incorporate areas such as ethics, sustainability, economics, system robustness etc. In regard to ethics where particular attention is required, it is clear that it is very early days in the new convergence of biology and engineering and only very limited research work has been undertaken on this topic as related to the field of the biological transformation. The biologicalisation of manufacturing provokes several specific ethical challenges including those pertaining to unintended consequences e.g. moral hazard, responsibility etc. [28]. Incorporation of detailed consideration of ethical questions into engineering/technology research is particularly important in order to achieve increased awareness, openness, and course-correction, as well as a clearer vision for future developments.

The implications of biologicalisation in manufacturing are wide-ranging and there is a high likelihood that a *major paradigm*

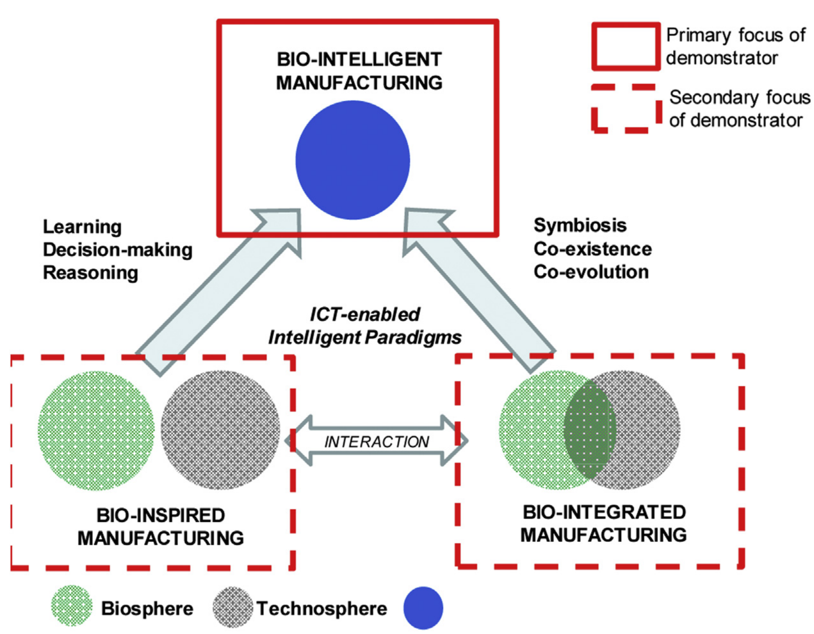

Fig. 14. Relationship between bio-inspiration, bio-integration and bio-intelligence in regard to Demonstrator 4.

Table 5
Collated Demonstrator evidence showing significant performance enhancements.

Demons-trator	Topic Area	Summary of Evidence to Demonstrate the Benefits of a Biologicalisation Approach from the Perspective of the Performance of Manufacturing Systems
1	Design	Bio-Inspired Design of Mobile Machine Tools: Bio-Inspiration Evidence: The biological principle of “Effectiveness” in achieving goals by means of redundancy can be mimicked by applying methods of Computational Design Synthesis enabled by (massive) digitalisation. Configuration design improved mobile machine tools towards autonomous mobility, flexibility and adaptive clamping. The design is based on insect leg structures for movement, flexibility, stability and adherence or clamping features, enabling also innovative structures related to miniaturization, stiffness and lightweight. Bio integration is also implemented during the design by using biological layers to protect the mechanical components of mobile machine tool. The combination of bio-inspired shape optimisation and additive manufacturing enables lighter, functionally optimised/integrated parts. Topology optimisation of a bio-inspired gripper led to a weight reduction from 312 g to 50 g. New innovative ways have emerged to deal with changing design constraints.
2	Cutting Fluids	Microbial-Based Cutting Fluids and Intelligent Process Monitoring Systems: Bio-Integration Evidence: As the global cutting fluid consumption amounts to over two million tons/year, the development of more sustainable cutting fluids is highly desired in industry. In the work described above, the replacement of mineral oil in cutting fluids with suitable microorganisms providing the lubrication function is studied with the aim of markedly reducing the negative impacts of traditional cutting fluids. Comparisons were made with conventional mineral oil-based cutting fluids for a microalgae-based cutting fluid in a steel turning process and two yeast-based cutting fluids in high-speed milling of titanium Ti6V4Al alloy. For all three microbial-based cutting fluids, the cutting forces, tool wear and workpiece surface finish were *comparable to or better than* for conventional cutting fluid. Initial evidence of the potential for the elimination of mineral oils in cutting processes has been shown.
3	Additive Manufac-turing	Bio-Inspired and Bio-Intelligent Additive Manufacturing: Bio-Inspiration and Bio-Intelligence Evidence: Adopting biological functionalities for machines has been shown to increase their sustainability and can lead to optimisation of their behaviour within the prevailing operational and environmental conditions. Careful estimation of technological consequences raises the expectation of advancement in relation to: a) fault reduction and increase in the dynamic strength to the level of forged parts (from AM parts), where today 20% reduced dynamic strength has to be taken into account, b) fault correction to reduce the scrap due to prematurely aborted build jobs by a factor of 10 due to early in situ counteraction after the detection of deviations, where today 5–40% of all build jobs suffer from fatal errors, c) reduction of average setup times in the today’s production mix in SLM by a factor of 2–4 due to the experienced and newly generated knowledge. This advantage plays a particularly significant role for individualized production, which is typical for additive manufacturing.
4	Control	Adaptive Stem Cell Processing on Automated Production Platforms: Bio-Intelligence Evidence: Bridge building was demonstrated between discrete part manufacturing science and technology, on the one hand and biological / medical sciences, on the other. It was shown that biologically inspired algorithms, e.g. reinforcement learning for designing, planning and controlling such structures can bring significant benefits. The results are optimised process parameters, better resource usage, higher throughput, increased and more consistent quality, cost reduction and higher robustness / resilience. For example, up to 30% increase in throughput was experienced compared to the values achieved by the original controller parameters (based only on expert knowledge, without having any additional optimisation.)

shift in advanced manufacturing lies ahead. As a result, there will be a need to undertake the following:

- Initiate programmes to develop collaboration between biology and engineering (including manufacturing),
- build national and international initiatives and collaborations,
- analyse the potential market opportunities for Biologicalisation in Manufacturing (BiM),
- extend standards and regulations and incorporate a greater focus on Biologicalisation in Manufacturing and
- stimulate educational training programmes as well as stakeholder and societal dialogue.

New research programmes are likely to emerge around the world in the coming years and new industries will form as a result of this new convergence. Some valuable results within the demonstrators described above show that the sustainability impact of manufacturing in terms of ecological and social sustainability can be improved through the biologicalisation of manufacturing processes. For example, Demonstrator 2 showed

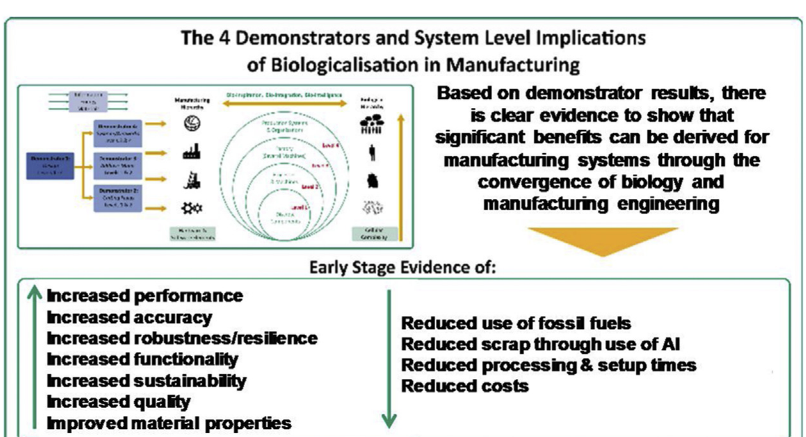

Fig. 15. Early stage system level performance enhancement based on evidence from demonstrators.

that the use of microbial-based cutting fluids can produce comparable machining results to those using conventional fluids in both turning and milling operations, which in turn could lead to the elimination of the use of mineral oils from cutting processes. The implications of the reduction in mineral oil usage in manufacturing engineering are very significant.

Fig. 15 summarises the overall implications at the manufacturing system level of Biologicalisation in Manufacturing.

Conclusions

Each of the four demonstrators described in this paper have succeeded in providing clear *evidence* to confirm that *significant performance benefits* may be derived through the biologicalisation of advanced manufacturing systems. All four demonstrators showed the capability of improved performance of the tested methods/systems and processes through analysis and experimentation from the perspectives of the underlying principles of bio-inspiration, bio-integration and bio-intelligence. Each of these three terms have been defined by the authors in this paper.

The evidence is now available from this work to provide a robust basis for recommending a deeper analysis of the implications of biologicalised manufacturing systems. It is concluded that there appears to be a high likelihood that a *major paradigm shift in advanced manufacturing* will take place as a result of the convergence between biology and engineering in general and in manufacturing engineering in particular. New research programmes are likely to emerge around the world in the coming years in this important area.

Existing industries will change and new businesses and industries will form as a result of this new convergence. The utilisation of manufacturing systems will be different and the divisions of knowledge between different systems like manufacturing execution systems (MES), computer aided manufacturing (CAM), machine control or even more significantly the “machine brain” will change. Outstanding opportunities therefore exist for high levels of innovation in the next stages of development of advanced manufacturing processes and systems. With this new paradigm shift, the relationship between the human and the physical manufacturing system will also change. This requires serious consideration of the ethical questions arising from this convergence.

One key development on the international front was the establishment in 2019 of a new *Collaborative Working Group* (CWG) of the International Academy for Production Engineering (CIRP) on the topic of Biologicalisation in Manufacturing. There is already a strong indication that the forthcoming EU Horizon Europe Programme will support research work in this field across the different technology readiness levels. As a result, the new convergence will develop and will lead to an upwards shifting of the technology readiness level (TRL). This development will lead to increasing levels of interest in this field by industry as convergence progresses.

In conclusion, the research hypothesis “*That Future Manufacturing Systems will incorporate Components, Features, Characteristics and Capabilities that enable the convergence towards Living Systems*” has been tested and can be supported. It can be inferred from the evidence from each of the four demonstrators that, in addition to the improvement in “traditional” performance indicators of manufacturing systems, there are other measures which will be positively and significantly impacted as the transition is made from the old, lifeless manufacturing systems to manufacturing systems with capabilities such as: self-learning, cognitive, communicative, self-healing, self-assembling, self-optimising etc.: in short - toward “*Living Manufacturing Systems*”.

This conclusion has enormous significance for the next phases of development of manufacturing science and engineering globally whilst also bringing with it challenges in a number of associated topic areas such as ethics, regulation and sustainability. Planning for the future education of engineers and biologists and the teaching-learning methodologies is a fundamental requirement.

Future directions

The following list identifies some key points for consideration:

1 A strengthening of the cooperation between biologists, engineers and ICT specialists needs to be systematically supported. This may involve some changes in the structure of third-level education programmes, as a convergence of these disciplines increasingly requires cross-disciplinary knowledge and skills.
2 A structured approach to addressing the benefits of Biologicalisation in Manufacturing (BiM) from the sustainability perspective should be adopted, with particular focus on the UN Sustainability Development Goals (SDGs) from a manufacturing perspective.
3 Further research is required on how BiM can contribute to the resolution of the dilemma of achieving competitive and sustainable manufacturing at all the levels of the manufacturing hierarchy from the processes, through the manufacturing systems up to the level of production organisations.
4 The use of biological materials and biological principles in manufacturing requires mapping onto current regulations/standards in order to identify gaps where further regulation/standards are necessary.
5 BiM opens up new ethical questions due, for example, to the changing working relationship between humans and manufacturing systems, and these must be addressed in parallel.
6 Living systems are in a continuous interaction with their environment and sense its changes. Further exploration and incorporation of sensor technology – including bio-sensing – for state monitoring of machines and processes for high levels of autonomy and cooperation is required. Modelling and simulation work in relation to the convergence between biology and engineering requires intensification.
7 A deeper analysis of the understanding and definition and meaning of bio-intelligence is required.
8 A demonstrator with industrial participation moving up the TRL scale should be developed and used for purposes of communication of the latest developments in the biologicalisation in manufacturing (BiM) systems.

Conflict of interest

No conflict of interest exists

Funding

No funding was received for this work.

Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

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