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Towards living manufacturing systems

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Abstract

The impact of the forth industrial revolution on the social and natural environment is considered significant and far-reaching, even though the interactions of the human, natural and manufactured assets are less understood, extremely complex and unpredictable. The paper discusses how present days' – so-called cyber-physical – manufacturing systems operate in the fabrics of society and the natural environment. It is underlined that they show and – to an increasing extent – will show features and capabilities reminiscent of living beings and organizations. This view helps to understand how manufacturing interacts with the ecosystem and suggests resolutions for the dilemma of competitive and sustainable manufacturing.

Keywords: Manufacturing; sustainability; life

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1. Introduction

In the past years growing attention and research activities can be observed towards the question of how the "solutions" present in the nature can be applied for handling the sometimes burning challenges, e.g. raw material shortage, climate change, overpopulation, poverty, the mankind faces. One family of approaches, i.e. *industrial symbiosis* [7] [8] [15] [31], *circular economy* [18][33], and *industrial ecology* [26] puts the sustainability issues in foreground, namely from the aspects of economy, environment and society. The other direction investigates how *biological inspirations* can be used *for developing more efficient and/or robust systems* [14] [42] [43] [44] [45] [46]. Naturally, the two approaches do not represent totally distinct ways.

Translating the above lines into the manufacturing domain, the main challenge is how to develop and realize production systems and networks which can comply with the requirements of *sustainability and competitiveness* at the same time [22] [48] [50].

In the past few years, a new concept has been born, namely the *biological transformation*, shortly *biologicalisation*. It stands for "a process that describes the increasing technological utilization of principles, structures and materials derived from living nature with the goal of establishing sustainable systems of value creation" [10] [29] [35]. The formulation integrates the two directions highlighted above, namely the sustainability and the efficiency / robustness viewpoints.

The concept of *biologicalisation in manufacturing* also indicates this duality: as "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" [3].

We are convinced that by the armory of *cyber-physical production systems* (*CPPSs*) [32], even former concepts and visions, like Ueda's on biological manufacturing systems and biologicalisation can be realized now in the practice [47], which is reflected in the structure of the paper. Section 2 discusses the challenge of reconciling the aspects of

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sustainability and competitiveness. CPPSs are shortly introduced in Section 3, while Section 4 highlights how CPPSs – as an enabling technology – can support sustainability-related subfields of manufacturing. Main aspects of biologicalisation in manufacturing are shortly outlined in Section 5, and the idea of living manufacturing systems is introduced and detailed in Section 6. The paper is closed by the conclusions where further open research issues are also summarized.

2. Sustainability and competitiveness

It has been widely realized three decades or so ago that human activities – and manufacturing in particular – make an impact on the Earth's ecosystem on a global scale and in an ever progressing and unprecedented pace [37]. This anthropogenic pressure on the natural systems has recently been termed as a new geological epoch, the so-called *Anthropocene* [9]. According to this narrative, (the first) industrial revolution marked the onset of sweeping transgressions which resulted in global phenomena like the change of the chemistry of the atmosphere and the oceans, universal carbon pollution (many times mentioned as the main reason of the climate change), and the loss of biodiversity. The role of humankind as a geological agent can though be questioned, and recent negative tendencies can be attributed not only to fossil-fuel technology but also to the very essence of industrial capitalism [27]. Apart from various motivations, analytical explanations, and interpretations, there is a common understanding that our ecosystem is composed of three main kinds of capital – *natural*, *human* and *manufactured* – and their complex interactions [49]. Indeed, most of the links between natural and human capital are mediated via manufactured capital which comprises everything and anything (re-)produced by man: consumer and durable goods, production equipment, transportation, energy, water and waste infrastructure, buildings, but also intangible services related to the provision of all the above.

The challenge of *sustainability* is how to use all these capital in a parsimonious way so as to serve the well-being of society. Due to its direct relation to manufactured capital, *production engineering* has a special role and responsibility. While mobilizing and transforming energy, material and human resources to this end in as efficient ways as possible, the limits of human condition – present and future – should not be violated. Hence, there is an ever changing but apparently prevalent dilemma for production: how to align requirements of industrial efficiency and competitiveness with those of sustainability. The resolution of this dilemma calls for new approaches and mindsets – one of which can be developed by taking the analogy of life and living beings. This view helps not only in transferring useful ideas to the field manufacturing but also in defining and analyzing its role in the "web of life" [5] which are compulsory though, certainly, not sufficient steps towards sustainability.

3. In the age of the 4th industrial revolution – cyber-physical production systems

Converging and mutually interacting research of manufacturing science and technology, computer science including artificial intelligence, as well as information and communication technologies resulted in what is termed now CPPs [32]. They consist of autonomous and cooperative elements and sub-systems that are connected based on the context within and across all levels of production, from processes through machines up to production and logistics networks. CPPSs is the main technological driver of the 4th Industrial Revolution, frequently noted as Industrie 4.0 [1] [23].

The main traits of CPPSs, which at the same time support the statements formulated in the Introduction, i.e., that they are predestinated to support biologicalisation are: (1) *intelligence and smartness* of elements, (2) *connectedness* that enables harnessing the data/knowledge and services available via a network (including the internet), as well as (3) *responsiveness*, a continuously ongoing interplay and mapping between the status of physical system components and their virtual counterparts.

The importance of *digital twins* within CPPSs is hard to underestimate. Digital twins provide the passages between the real and virtual worlds of manufacturing. There is now generally accepted definition for digital twins. According to [40] "a digital twin is the digital representation of a unique asset (product, machine, service, product-service system or other intangible asset) that compromises its properties, condition and behaviour by means of models, information and data". Some authors distinguish digital twins and *digital shadows*. The latter incorporated data and information gained during the usage / operation phases of the individual product or production system [40].

The application of the digital twins and shadows, together with *predictive engineering* [25] can lead to anticipatory rather than reactive enterprise. High-fidelity models (digital representations) of the phenomena of interest can be constructed, by which future spaces can be explored and by this way more appropriate decisions can be made.

However, when setting up, designing, planning and managing the operation of a CPPS one has to find some acceptable resolutions between a series of conflicting issues: reliance on background knowledge (incorporated in models) vs. (big) data; optimality vs. adaptiveness; complexity vs. time-criticality; openness and sharing of data vs. security and privacy; local autonomy vs. globally acceptable behaviour; emergence vs. purposeful design; robotics and automation vs. human work; cooperation and the pursuit of common goods vs. competition and self-interest, and after all, sustainability vs. efficiency and competitiveness [48].

4. Sustainability in the era of CPPSs

4.1. Life cycle engineering

Life cycle engineering (LCE) puts directly environmental sustainability into the focus of production engineering [20]. Earlier, a number of tools have been developed to take also this aspect into consideration starting from product development, via manufacturing (including the extraction of materials) up to sales and after-sales services. Supporting maintenance was a key point, and of course, end-of-life activities like reuse, re- and de-manufacturing, recycling and disposal were explicitly handled [41]. The proliferation of CPPS techniques—large scale sensing, monitoring, data collection and broad-band communication in particular—contributed much to these developments. Now, the integration of these LCE tools is targeted into a consistent framework, forming a so-called LCE toolbox [20] which focuses not only on the technological issues and solutions but also on the overall impact of a suggested solution to (environmental) sustainability. This is a step towards absolute sustainability (see Sect. 4.3).

4.2. Industrial and circular economy, industrial symbiosis

Industrial ecology embeds systems of technology and production into that of the society and environment. The motivation of this holistic approach is to have a better understanding of the complex interactions which are modelled in terms of flows of information, energy and material. Here again, a life cycle approach of materials, products and services are taken, but in an abstract model resembling *metabolism* [49]. The recently emerging paradigm of *circular economy* attempts to decouple resource consumption from economic growth by including restorative and regenerative loops into the life cycle of products by design and planning. Hence, re- and de-manufacturing [41] as well as recycling loops are implemented, possibly also across several sectors.

Industrial symbiosis (IS) is a special form of industrial economy focusing on the utilization of the waste streams of primary production processes [8]. Typically, firms operating in different sectors are linked by streams of energy, water, materials and product residuals. The formation of IS networks depends on key factors like the types of waste streams, transport modalities and costs, as well as the market value of secondary products [7] [11]. That means, if the processing of the waste stream(s) is economically feasible and competitive, then the overall system as a whole may stiffen due to the vested business interests of the partners. Hence, industrial symbiosis may easily be proven controversial as a barrier to changes facilitating production with less waste.

4.3. Absolute sustainability

Absolute sustainability defines the sustainability performance of production against so-called absolute environmental boundaries: it assumes that departing from Earth's carrying capacity, there can be defined an operating space for production. The main challenge is to arrange production within these boundaries. Introduced by production engineering already almost a decade ago [2], the idea gets impetus now, also in other sectors like agriculture and chemistry [6] [13]. Absolute sustainability directly implies a *shared use of common* material, energy and human resources. This requires *cooperation*, the patterns of which can emerge if autonomous stakeholders of production have trust in each other as well as reputation in a community, which includes also their customers [48]. Prerequisites of trust and reputation in any community are easy-to-measure, understand and communicate performance measures (like carbon footprint). The practice of standard corporate reporting is also based on this principle [24]. However, it is still open how global environmental boundaries can be defined when many resources are geographically located. It is also unclear what an incentive scheme may facilitate the cooperative use of these resources in an essentially competitive economic setting.

4.4. Service-oriented production, ecosystem services

As a way to resolve the oxymoron of sustainable and competitive manufacturing, one can look at these issues through the lens of *services* [47]. Service essentially entails a cooperative attitude being its basic question "How can I help you?" Departing from real-life case studies it can be shown that it is possible to construct such rules and protocols for buyer-supplier relationships where autonomous stakeholders have an incentive to align their disparate interests and information asymmetry while operating efficiently in terms of total production and logistics costs. Here, supply is a service in face of uncertain demand that provides not only goods with guaranteed service level but also flexibility to the other partner [48]. In a broader context, one can take *social-ecological systems* as providers of fundamental services for human activities including manufacturing. In these so-called *ecosystem services* (ES) the natural capital directly contributes to sustaining the human capital, and – in a large extent – to exploiting and creating the manufactured capital. Thanks to interdisciplinary efforts, ESs are not perceived as free and almost limitless services any more. Monitoring and measurement schemes have recently been elaborated, the impact of the use of various ESs on nature's regenerative ability has been assessed and a number of policies and institutions have been designed and implemented to better aligning short-term business with long-term societal goals. In all these initiatives, using the apparatus of CPS has been instrumental [19]. However, no informatics solution can resolve the key dilemma, namely how to handle the intrinsic asymmetry between short-term rewards of market and long-term stewardship of the natural capital (which is not acknowledged by the market).

4.5. Summary

All the above approaches are in common that they build on common sense, everyday concepts of how we see life and the circulation of energy and material in and around living beings. "Life" and the life cycle view is ubiquitous, just like the notions of flow, circulation and metabolism, however, without going into deeper implications of these analogies.

Both absolute sustainability and the ESs view expose a global resource allocation problem, burdened by uncertainties (actual boundaries, their future evolution, valuation of resources and services) and by local, distributed and unbalanced knowledge, interests, power and autonomy (c.f. geographical distribution of limited resources, information asymmetry, disparate interests). Who will set the limits and resolve the conflicts? How can the "challenge of common pool resources" [36] be handled?

In any case, without some form(s) of cooperation, we see the resolution of the dilemma of (absolutely) sustainable and competitive manufacturing next to impossible. What economic, social, legal, technical institutions need to be formed–in fact, designed–so as to find and maintain a resolution of the ever changing but apparently prevalent conflict? Can contemporary information and communication technologies employed in cyber-physical production systems be technological enablers of this resolution? Can the 4th industrial revolution correct the path of the planet what went wrong with the 1st industrial revolution?

5. Biological transformation of manufacturing

A new emerging frontier in the evolution of the digitalisation and the 4th industrial revolution is considered to be that of "Biologicalisation in Manufacturing" [3] [10] [35]. Its underlying concept is not new. What is novel, however, is the acceleration of the realisation of the concept, which builds on the capabilities available today and in the future through digitalisation and Industrie 4.0 developments. Although not called by this name, the principles of biologically inspired manufacturing systems have a long history [32].

Miehe et al. distinguish three levels of biological transformation in manufacturing (1) *bioinspired manufacturing*, i.e. translation of biological phenomena into solely technical value creation systems; (2) *biointegrated manufacturing*, i.e. integration of biological materials or systems into production systems; and (3) *biointelligent manufacturing*, i.e. comprehensive interaction of technical, informational and biological systems [28] [29].

Egri et al. in their work on bio-inspired control of automated stem cell production (where not only the production control is bio-inspired, but also the product is a biological material) characterize the third (highest) level of biologicalisation as "the symbiotic co-existence and co-evolution of the technical, ICT and biological ingredients in production structures" [12]. Naturally, a key point is how to integrate the above three worlds [17] [30].

In the long term perspective, transition is expected "from the old, lifeless manufacturing systems to the manufacturing systems being alive: self-learning, cognitive, communicative, self-healing, self-assembling: in short, towards a "*Living Manufacturing System*". The overall hypothesis of the internal Fraunhofer project BioMANU II on Biologicalisation in Manufacturing is as follows: "Future manufacturing systems will incorporate components, features, and capabilities that enable the convergence towards living systems" [4].

6. Systems of life and of manufacturing

In the previous sections–without any specific intentions–the notion of "life" cropped up time and again in relation to manufacturing, in different contexts and combinations, such as life cycle, end of life, life cycle engineering, let alone related biological concepts such as ecosystem, metabolism, symbiosis, circulation to name the most frequent ones. It seems that–perhaps unconsciously–production engineers have credited the products, manufacturing processes and systems with some forms of life long before. Certainly, there is a potential in this attitude when finding, defining and making operational the role of manufacturing in the broader context of sustainable development.

Before we consider whether the analogy of life and living systems is useful or even instrumental to manufacturing, we have to sum up the main defining features of life. What is the *essence of life*, how can it be characterized and defined beyond common sense notions?

The properties that characterize living systems and are absent in non-living systems can be deemed "the absolute principles of life" [16] [39]. (1) Life in any form can exist in an *environment* which includes abiotic, non-living entities and typically also other living entities. However, living beings delimit and distinguish themselves from their environment as *individual units*. (2) Living systems are in a continuous *interaction* with their environment: sense its changes in some way, respond to the stimuli, exchange materials so as to breakdown nutrients to obtain energy and to dispose of waste. Shortly, they perform *metabolism* which warrant them a sort of biochemical *autonomy*. (3) Processes in living systems are *controlled* by multiple regulatory mechanisms to coordinate internal functions, respond to stimuli, control metabolism, and cope with environmental changes. (4) Despite changes of the environment, living systems are inherently in a stable, steady state thanks to their ability to maintain constant internal conditions. This so-called *homeostasis* is characteristic even to non-functioning (albeit not dead) living beings. (5) Every living system possesses an *information carrying subsystem* representing in some form the information necessary for its origin, development and proper functioning. (6) Furthermore, there are some potential criteria which stand for most (but not necessarily all) living beings. These are capabilities to *growth* and *reproduction*, according to the encoded information (see above). (7) Finally, living beings as a member of a population can partake in an *evolutionary* process creating increasingly complex and differentiated forms of life. Note that while all the above principles can be made operational by non-living mechanisms, one by one, the implementation of *all* principles must be combined to form a living system.

Even though there is still no common understanding of how an organism could be defined (or should it be defined at all), the *organization* of living beings can be differentiated and discussed in five levels (see the left column of Table 1).

Table 1. Organization levels of living and manufacturing systems.

Living systems	Manufacturing systems
Population (species living in a specific area); community (combination of populations in a particular area); ecosystem (all the living beings in an area together with the abiotic, non-living parts of that environment); biosphere (the collection of all ecosystems)	*Circle of production companies*, production networks: complexes functioning within a specific area (region, country, continent, world-wide) as part of the related ecosystem
Organisms (individual and autonomous living entities), including also microorganism	*Production companies and organizations*, complexes with growth and development capabilities, functioning in close correlation with their living and non-living surroundings, by using and influencing them
Tissues (groups of similar cells carrying out similar or related functions); organs (collections of tissues grouped together performing a common function); organ system (functionally related organs)	*Integrated systems*, manufacturing cells, production lines, manufacturing systems, entities which consist of lower level ones grouped together in a fixed od flexible, changeable way, in order to fulfill specific tasks in a controlled way
Smallest individual living unit: cell (BTW: viruses are not considered living: they are not made of cells); prokaryotes (single-celled or colonial organisms) and eukaryotes	*Elements with embedded control*, CNC-controlled machine tools, robots, automated guided vehicles (AGVs), entities which have a given structure (order) to fulfill their purposes, can sense and react on external circumstances, possess some self-regulatory abilities, use energy and information
The building blocks: atoms, molecules, macromolecules (polymerization), organelles	*Building elements*, like cutting tools, machine tools' spindle, axles, touch probes, fixtures, etc.

The right column of Table 1 summarizes the corresponding organization levels of manufacturing systems. On both sides, the classification schemes mirror the complexity, scale and granularity of systems at various levels, whereas the fit between the two sides is strikingly apparent. The principal question for production engineering is whether these parallels can be exploited in some way for resolving its key issues inherent in sustainable and competitive production. In search for answers, we suggest the following closing considerations:

1. In the organizational hierarchy, the highest level ecosystem view is a must if production engineering is seeking answers to the challenge of sustainability. This is not really new, many approaches presented in Sect. 4. are common in this view.
2. However, it is an open issue if one can tackle the highest level of organizational complexity by skipping any (or all) of the lower levels. One can hypothesize that analogies with living systems can be appropriate—and indeed, necessary—also on the levels of organism, tissues and cells when looking for operational solutions on the grand scale of populations, ecosystems and the entire biosphere.
3. Manufacturing borrowed time and again some properly selected principles of living systems with considerable success for solving particular technological and organizational problems (see biointelligent manufacturing). However, we are not aware of any solution which combined *all* the absolute principles of life.

7. Conclusions

In the paper the seemingly irreconcilable contradiction between the sustainability and competitiveness aspects of today's manufacturing was addressed. In awareness of the danger our natural surroundings face through the human activities, and in the firm belief that we can learn from nature, concepts from the side of the environmental consciousness, e.g. industrial symbiosis, circular economy, and industrial ecology were introduced in short.

It is to be admitted that we have a long way to reach the final goal of truly sustainable and competitive production, which will go through different trade-offs between the two, at the moment distant goals. The constraints between which the balancing solutions have to be found will always depend on the actual maturity level of the society and the available technologies and resources. The overwhelming profit-centric thinking is to be exceeded and incentives have to be introduced which drive the stakeholders towards sustainability. The society should not be anymore only an accessory of the economic system [38].

In the paper, it was underlined that new, more powerful tools are offered by the CPS armory to realize novel and former, until now not materialized concepts related to sustainable and efficient production. Biologicalisation, i.e. the biological transformation of manufacturing can be undoubtedly considered as such a concept.

Comparing the systems of life and of manufacturing in respects of their organization levels and features, we came to the conclusion that the research and development activities which intend to resolve the conflicts between sustainability and competitiveness should be directed towards *living manufacturing systems*.

This conclusion is fully in line with the statement formulated in [21], namely, „the convergence of biology with engineering and the physical sciences, offers a new model for invention, for collaboration, and for shared ambition to solve some of the most pressing problems of this century".

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