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A Conceptual Framework for Biointelligent Production—Calling for Systemic Life Cycle Thinking in Cellular Units

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Abstract: A sustainable design of production systems is essential for the future viability of the economy. In this context, biointelligent production systems (BIS) are currently considered one of the most innovative paths for a comprehensive reorientation of existing industrial patterns. BIS are intended to enable a highly localized on-demand production of personalized goods via stand-alone non-expert systems. Recent studies in this field have primarily adopted a technical perspective; this paper addresses the larger picture by discussing the essential issues of integrated production system design. Following a normative logic, we introduce the basic principle of systemic life cycle thinking in cellular units as the foundation of a management framework for BIS. Thereupon, we develop a coherent theoretical model of a future decentralized production system and derive perspectives for future research and development in key areas of management.

Keywords: biointelligence; biointelligent production system; systemic life cycle thinking

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1. Introduction

Sustainability has become an increasingly relevant societal [1], political [2] and corporate topic [3,4]. Despite immense technological progress in the past years, current methods of industrial production are not sufficient to establish a sustainable economic system [5]. Several planetary boundaries are already beyond the safe operating space, e.g., climate change, nitrogen and phosphorus cycles and the loss of biodiversity [6,7] (Figure 1). In response to increasing pressure, e.g., from the Fridays/Scientists for Future movements [1], the European Commission has recognized climate change as one of today's major challenges and provides a framework for the development of a new economic model. The so-called European Green Deal urges EU member states to significantly reduce their level of emissions and envisages Europe to become the first climate-neutral continent by 2050 [8]. In addition to extensive changes in the transport, construction and energy sectors, this requires large-scale restructuring of existing production structures [9]. Future production systems must be substantially more integrated in terms of flexibility, efficiency and autonomy (following nature's example), i.e., engineered as interface systems between different fields of human demand (health, nutrition, living, energy, consumption, etc.) [10]. In this context, a number of recent studies view biointelligent production systems (BIS) as a promising approach [11–17].

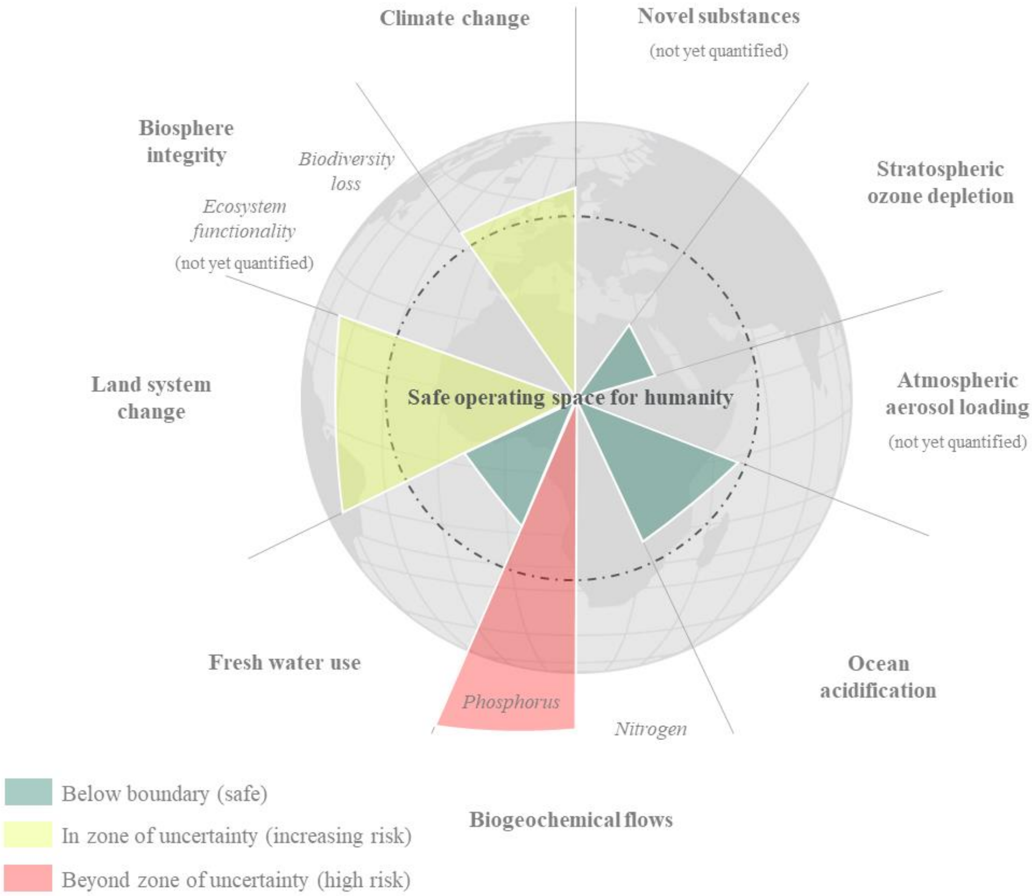

Figure 1. Concept of planetary boundaries according to Rockström et al. [18].

A pivotal enabler for the realization of BIS is the increasing convergence of engineering, life, and information sciences. In the technical (explicit) sense, BIS represent a further development of the concept of cyber-physical systems (CPS) by adding a biological element. Despite the fact that Digitization, Digital Twins, Blockchain, and Industry 4.0 represent promising approaches for more effective process designs in various industries [19], a sufficient reorientation of production technology using only these approaches seems impossible. The integral reciprocity between the technical, information and biological system opens up new possibilities in approaching concepts for innovative and sustainable production [10,11]. In this understanding, BIS contain a biological and a technical component and/or an active principle that autonomously interact in a way such that the behavior of the system corresponds to the understanding of narrow intelligence, i.e., the analytical and responsive ability for self-optimization [5]. From a technical standpoint, BIS thus enable a virtually endless range of innovative technologies and products in almost all sectors of the manufacturing industry.

An example of such an innovative technological concept is smart biomanufacturing devices (SBMDs), i.e., small-scale, intelligent biomanufacturing systems that enable on-demand, on-site production from locally available resources. Such approaches are already increasingly applied in the context of advanced therapy medicinal products (ATMPs), e.g., CAR-T-cell therapies [20], or food production, e.g., 3D food printing [21]. However, potential applications of SBMDs go far beyond these industries and potentially enable fundamental transformations of established production economic patterns, e.g., the shift from centralized to decentralized production, increasing self-supply of consumers, and the elimination of the strict separation of material and energy flows (sector coupling 2.0). As such, SBMDs exhibit significant potential for a sustainable design of production systems, e.g., by reducing the need for complex, global supply chains, providing on-demand production, largely avoiding packaging waste, reducing transportation efforts and consequently reducing the environmental footprint of industrial production. A crucial aspect of these production cells is an extensive circularity of material supply, leading to an independence from goods originating from countries or suppliers assessed with high supply risks (e.g., specific materials for future technologies like electrolysers) [22].

However, the ability of a technology to truly contribute to a sustainable future cannot be ensured solely by its well-intentioned vision. Miehe et al. thus introduce an extended understanding of biointelligence [5,23]. This implicit, holistic understanding equally applies to each technology alongside the above-sketched explicit one and represents the basis for an iterative optimization towards a sustainable optimum [5,23]. In this understanding, biointelligence has to be considered an applied science that aims to achieve an equilibrium of economic, ecological and social benefits in order to contribute towards solving the sustainability problem [11]. Consequently, a system is biointelligent if it handles natural resources responsibly and if it strives towards a state of balance with its natural environment as well as its surrounding systems. While the explicit concept is restricted to the micro level (individual systems, e.g., machines), the implicit concept of biointelligence is mainly directed at the macro level. Only systems that evidentially adhere to the criteria of both concepts can be considered fully biointelligent. Figure 2 illustrates this understanding.

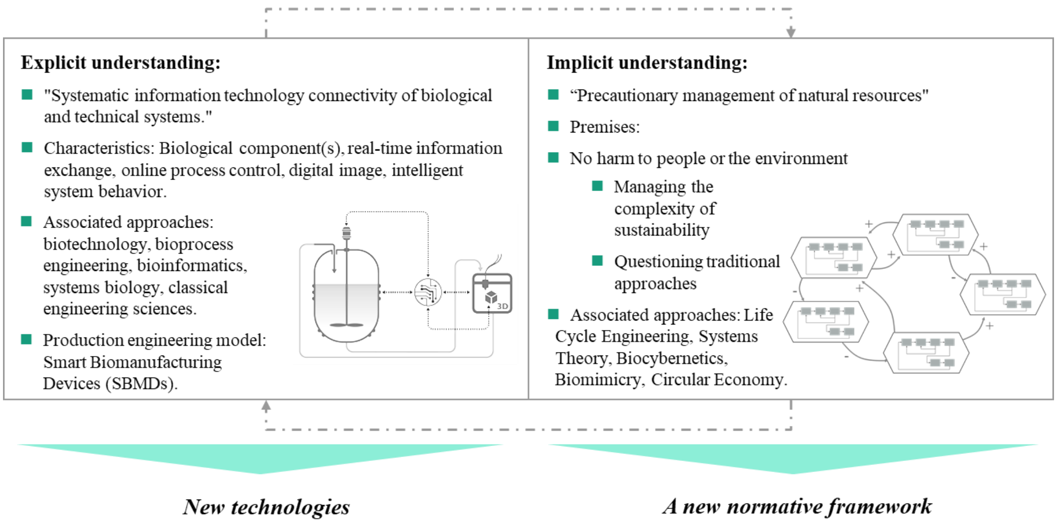

Figure 2. Distinction between explicit and implicit interpretation according to Miehe et al. [5,23].

While BIS and their potential applications according to the explicit understanding have been introduced to the scientific community in various publications, e.g., as a conceptual vision for a biointelligent manufacturing cell for Selective Laser Melting, nature-based digital manufacturing technologies or bio-based technologies used for manufacturing of multifunctional metal-based parts [11–17,24,25], it remains unclear how to ensure that such systems meet the criteria of biointelligence in the implicit sense.

This paper thus further specifies the basics of implicit biointelligence and presents a conceptual framework for the management of BIS in order to derive topics for future research and to enable a holistic impact assessment of respective utilizations.

2. Materials and Methods

The research process of this work follows the standard approach of real sciences according to Ulrich and Hill [26]. The aim of this work is thus to execute subjectively perceived sections of reality by describing and defining concepts, to abstract on the basis of individual cases and to develop alternative courses of action for the realisation of future realities. By identifying essential issues of integrated production system design in the context of biointelligence, a search string for a literature review according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was developed. The results of the literature review were reviewed in relation to previous studies. Thereupon, a coherent theoretical model of a future decentralized production system was developed and perspectives for future research and development in key areas of management were derived. Similar approaches are well documented in the literature [27]. Figure 3 illustrates the research process.

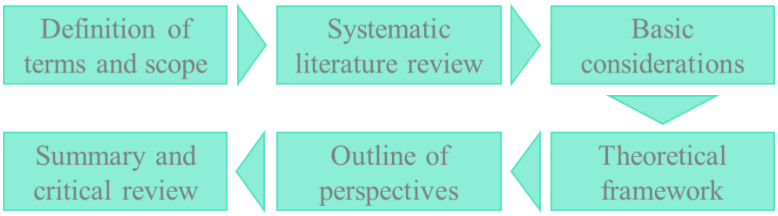

Figure 3. Research process of this paper.

3. Basic Considerations on Implicit Biointelligence

The concept of implicit biointelligence is closely related to the basic concept of sustainability [28]. Although various visions for overall economic renewal, such as bioeconomy [29] or circular economy [30], are increasingly regarded as baseline visions for a sustainable economic practice, biointelligence needs to be regarded as a separate concept. This is due to two reasons, which arise from the explicit and implicit understandings of biointelligence.

First, the explicit comprehension represents a clear technological strategy that can contribute to different interpretations of bioeconomy or circular economy. Its desired state is a technology-oriented demand economy in which products are produced on demand in decentralized, small-scale units largely based on biological resources, with all materials being managed in scalable recycling systems within local communities.

Second, the implicit concept provides a unique normative framework. Its underlying holistic benefit criterion exceeds the conventional economic benefit by contributing to the preservation of human existence as well as the environment on a micro and macro level [31]. In this regard, production represents a recurring phase in a constant recirculation of matter that occurs between the provision of input factors (by end of life treatment) and the sales of products. Biointelligent production thus has to be understood not only as a single economic act but a self-contained organism whose natural basis (the planetary boundaries) must not be exceeded [23]. Accordingly, technologies shall not be valued solely on the basis of economic feasibility but must always be assessed in the context of potential consequences on its environment and every stakeholder.

Biointelligence represents an interface between social and natural sciences, as it combines both disciplines to derive applications, which results in a balance of economic, ecological and social benefits. While it relies on other disciplines, such as bioinformatics and systems biology, it creates new knowledge through the interdisciplinary focus on application and the holistic benefit criterion. Corresponding to the explicit concept of biointelligence, which envisages the convergence of technological, biological and information systems towards a biointelligent value creation [10], the implicit concept envisages the convergence of sciences and a systematic interdisciplinary cooperation to create a sustainable technological basis for industrial value creation. It is mainly the iterative relationship between explicit and implicit understanding that establishes biointelligence as a distinct scientific discipline.

In the context of production theory, implicit biointelligence is characterized by an inherent mindset of system-oriented life cycle thinking in cellular units, which represents a specific combination of three different approaches to the perception of reality.

First, system thinking relies on the system dynamics (SD) approach of Forrester [32–34] and the biocybernetics approach of Vester [35,36], according to which the behavior of complex systems corresponds to a continuous circular process. The description of complex problems requires an approach that acknowledges that actions influence future conditions and are themselves based on current conditions, while changes in conditions become the basis for future actions. These actions further have an impact on superordinate systems [35,36]. To avoid damaging the overall system, the approach thus aims to establish a balance with surrounding systems.

Second, the term life cycle thinking refers to the insight that each entity influences its environment throughout its life. Therefore, the life cycle from cradle to grave needs to be assessed to evaluate an entity (e.g., a product) [37,38]. Considering the life cycle of individual units alone, however, does not adequately address the complexity of managing biological resources. Instead, it is imperative to ensure that the interactions of all subsystems of the entire 'organic' production system operate together within planetary boundaries in the long term. Consequently, a single assessment should never serve as a stand-alone model but should be embedded in a larger SD model.

Third, the perception of reality as cellular units constitutes another unique concept that needs to be regarded in correlation with the above-sketched approaches. Although the model of cellular production may not be new in the context of manufacturing science, the approach advocated here represents a significant change from the traditional interpretation. Whereas, for example, the fractal factory model presumes a cellular production within the defined structures of a given plant, this system boundary is now obsolete. The concept of biointelligent production, as outlined above, envisages a much more decentralized production of goods by non-expert systems. As a result, more actors perform roles in the production system, actors that are not part of it today (e.g., individuals, households, non-specialized producers). Ideally, all steps in the production, use and utilization of a good should take place on site, based on local resources. For this, the division of reality into cellular units is indispensable. In the context of biointelligence, a single segment of reality is represented by a cell. Following the system thinking approach, a cell forms various interrelations and interacts with numerous surrounding cells as well as the overall system. Different levels can be defined as cells, such as molecules, organisms, products or ecosystems, which can form complete networks due to various interrelations. Cells are sufficiently described by six factors: (1) type of matter (biotic, abiotic, other), (2) internal processes (hierarchy, segments, metabolism, etc.), (3) interactions with surrounding cells and the system as a whole (physical, nominal, informational), (4) intended purpose (production, decomposition, cohesion, etc.), (5) functional principle in relation to the intended purpose (mechanical, chemical, optical, biological, economical, etc.), (6) conditions to fulfil the purpose (connectivity, viability, etc.). Cells are characterized by their ability to spontaneously assemble, establish multiple connections among each other and instantaneously detach themselves.

4. Conceptual Framework of Biointelligent Production

Prior to developing a model for effectively managing BIS in the implicit sense, it is necessary to identify the specifics of a biointelligent production system. Table 1 summarizes the difference between traditional and biointelligent production.

It becomes clear that biointelligent production fundamentally alters the framework conditions and constellations while requiring a different handling of knowledge, skills, technology, infrastructure and governance. From a contemporary perspective, the draft of a large-scale biointelligent production system is purely a thought experiment. Figure 4 thus illustrates a thought model that differentiates an unstructured basic system, a structured production system and a semi-structured consumption system.

In this thought model, the basic system includes all input factors required for a production task, such as materials, knowledge providers/experts, technology, etc. An impulse that triggers the production task might result from customer pull or technology push. The necessary input factors are provided by a corresponding mechanism, e.g., a platform. The spontaneously emerging production network fulfills the respective task and provides the output (i.e., the product). After doing so, it dissolves back into cellular units and structures. The consumption system is considered semi-structured, as not all paths of a product's utilization and abrasion can be monitored, and a use according to the original purpose cannot be ensured. Following the use of a product, another production task is triggered for reproduction.

Table 1. Comparison of traditional and biointelligent understanding of production.

	Traditional Understanding of Production	Biointelligent Understanding of Production
Definition	Production as a planned combination of input factors enabling satisfaction of individual customer needs	Production as a spontaneous or planned combination and recombination of cellular units to create or dismantle a cellular structure capable of intelligent behavior, enabling satisfaction of individual, social and environmental needs
Scope	Production (enterprises) as individual units for the purpose of economic benefit to the shareholders	Entirety of production as an organism aligned with planetary boundaries, individuals, communities and enterprises as subsystem production units
Scale	Mostly medium sized or large enterprises	Networks of cellular units in the form of small enterprises, communities, individuals and households
Volume	Mostly centralized production units operating in series and mass production processes; partly small series production; individual production only in few cases	On-site production of single products in individual spontaneous production networks as standard model
Decision Context	Free, i.e., fully independent decision making	Normative, i.e., regulated decision making directed to planetary boundaries/budgets
Decision Parameter	Mostly efficiency and costs	Increasingly effectivity and sufficiency-driven
Scientific Basis	Engineering and information science	Engineering, information and life sciences

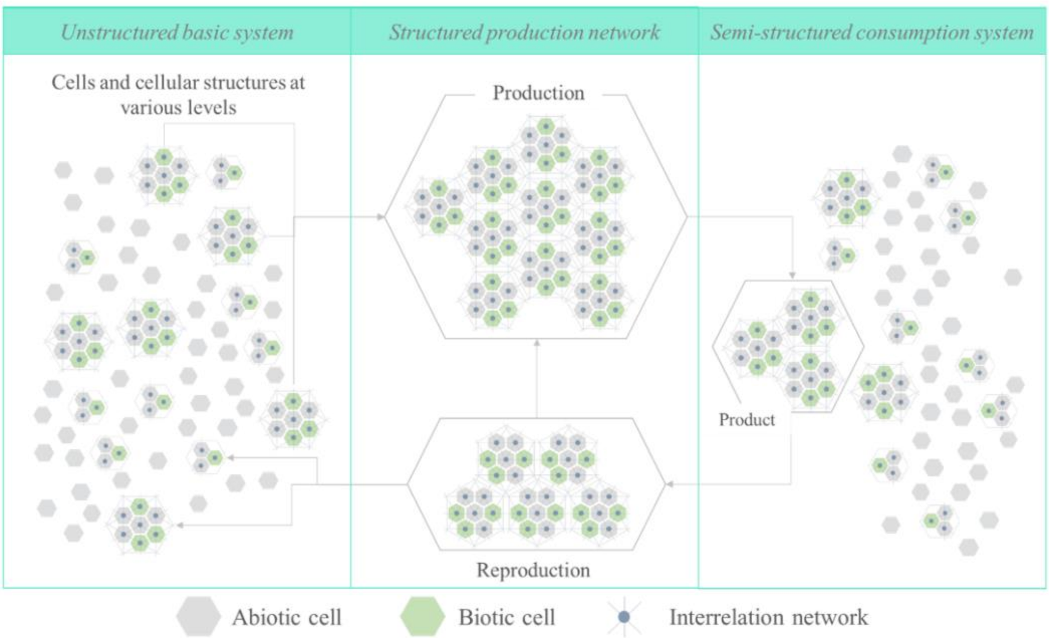

Figure 4. Thought model for the description of biointelligent Business Models (BMs).

How does production management work in a system like this? To answer this question, a management framework is required. In contrast to existing management frameworks, which primarily assume a single company (e.g., the St. Gallen Management Model and the Stuttgart Enterprise Model [39,40]), a management framework for BIS must address the fact that value creation takes place in a production network consisting of decentralized production units, which include novel types of producers such as households and individuals outside of the traditional factory system. Additionally, such a framework must be normative and align production with the capacity of the ecosystem. The scope of management concern should thus include the essential basic elements of conducting business by addressing the basic technologies, markets, customers, Business Models (BMs), strategies and innovations for BIS. It should include how biointelligent products can be developed, how the organization and management of a cellular production network can be designed and how it can be ensured that producer and consumer responsibilities are fulfilled. In addition, it should specifically combine elements of all three sustainability strategies (efficiency, effectiveness, sufficiency) in order not to exceed planetary boundaries and ensure that the basis for the prosperity of societies (material standard of living) is maintained and equally distributed (i.e., scope of environmental concern). Thus, system oriented life cycle thinking must be the underlying management and monitoring approach. Figure 5 illustrates the management framework for biointelligent production according, in part, to Hauschild [41,42].

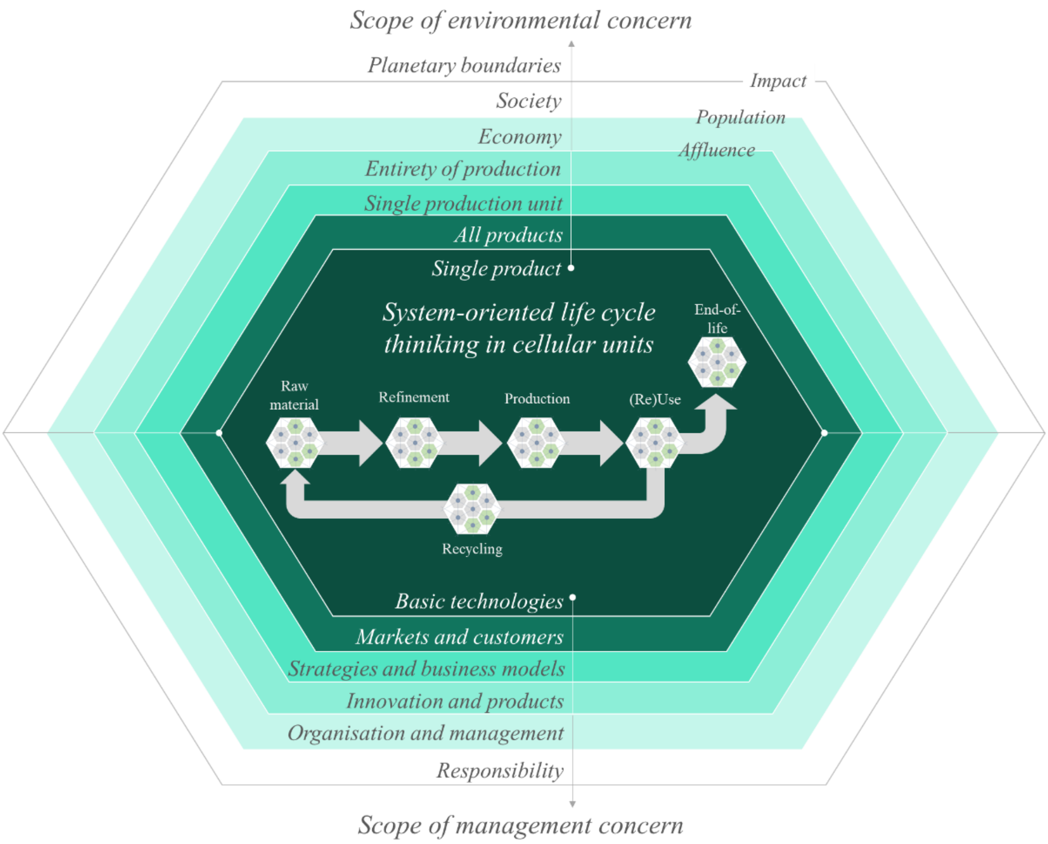

Figure 5. Framework for the management BIS (own illustration based on Stead and Stead [43] and Hauschild et al. [41,42]).

According to the presented conceptual structure, the production system requires biotic and abiotic cellular systems, which are constantly interrelating with surrounding cells. Their configuration is determined by system-oriented life cycle engineering. Within the responsibility of the system-oriented life-cycle-management lies the leadership, organization, planning and control of production units (e.g., households, companies). The application of technologies relies on existing basic technologies, their convergence, which is directed by research and development, and their appropriate placing in markets. In this production system, consumers increasingly become producers of goods (e.g., via horticulture). Producers and consumers merge into prosumers. A strategy and BM are necessary to channel entrepreneurial activities, while innovation product development as well as the organization and management of production must ensure the efficiency and sustainability of operations within the cellular network. Finally, all participants involved in the biointelligent value creation must be held accountable for their actions.

5. Perspectives for the Management of Biointelligent Systems

Each subfield of the framework includes numerous existing approaches that have been present, in part, in management science for decades. For a biointelligent production as outlined above, a variety of opportunities for future research and development arise. The following subsections discuss excerpts of these.

5.1. Markets and Customers

While customers and markets for biointelligent products cannot be determined conclusively (application areas cover virtually every sector of the economy), the concept of biointelligence envisions that the focus of value creation shifts towards the customer and that the environment and society are established as equal customer groups. This requires an extension of the concept of prosumers by regarding individuals as worthy producers [44,45]. Potential fields of action have further been discussed by Miehe et al. [10], who envision a shift to personalized therapies in medicine, on-demand production for nutrition, circular patterns of consumption and self-sustaining life styles.

5.2. Strategies and Business Models

Due to the above-outlined perceptions of production, strategies and business models (functional nature of a company and its way of generating profits [46–48]), BIS can be expected to differ significantly from traditional systems. Product and production represent the key differentiating features for potential strategies. As a result, four approaches emerge for the actors:

1. Production of conventional products with conventional production technologies
2. Production of biointelligent products with conventional production technologies
3. Production of conventional products with biointelligent production technologies
4. Production of biointelligent products with biointelligent production technologies

For the strategic management of BIS, two perspectives need to be differentiated: individual (corporate) strategies, which represent the vision, mission and targets of a production unit, and production network strategies, which represent the collaborative vision, mission and targets of spontaneously merged production units. The former are the central concern of conventional strategic management (be it via a market or resource-based view) [49–54]. In contrast, the network-based view [55,56] for biointelligent production must provide a more granular understanding of production strategy development, evolvement and merging within networks. Similar basic considerations are required for BMs. Table 2 summarizes a number of design options for BMs in a biointelligent production system.

A possible approach to the further development of biointelligent BMs could be based on the work of Weiblen [57], who presents fundamental considerations on the topic of collaborative BMs.

5.3. Innovation and Product Development

The normative approach of biointelligence prioritizes sustainability as a major goal of innovation. Each product or production task must contribute to the viability of the natural overall system. Innovations in the context of biointelligence are thus characterized in the sense of Schumpeter's principle of creative destruction of existing structures [58,59], under the condition that adverse effects on other subsystems of the overall system are avoided. For innovators, cellular thinking and additional actors in the production system (individuals, households, non-specialized producers, etc.) in particular require a more expansive innovation horizon. After innovation management occurred for years within a closed framework (i.e., the company), recent developments have increasingly seen open innovation approaches [60,61]. This trend is now being reinforced by biointelligent production. The goal is not just to expand the scope of thinking, but rather to come up with innovative, sustainable solutions in a network of highly diverse players. Thus, further empirical research, e.g., to develop a biointelligent innovation framework (Figure 6) is required [62].

Table 2. Design approaches for potential BMs in biointelligent value creation system.

Business Model	Value Proposition	Provider	Buyer	Earnings Model
Know-how as a service	Providing know-how, design plans and skills	All market participants	All market participants	Common advisory and consultancy models, pay-per-unit
Labour as a service	Providing necessary staffing	Individuals	All other market participants	Pay-per-hour, common employment models
Equipment as a service	Providing equipment and infrastructure for production task	All market participants	All market participants	Common contracting models
Capital as a service	Providing required capital for production task and/or spontaneous emergence of production networks	Individuals, companies	All market participants	Common investment and financing models
Platform as a service	Providing platforms, either technological or as mechanism for input factor allocation	All market participants	All market participants	Participant fee, pay-per-use
Product as a service	Providing products that have to be returned after use	All market participants	All market participants	Common leasing models

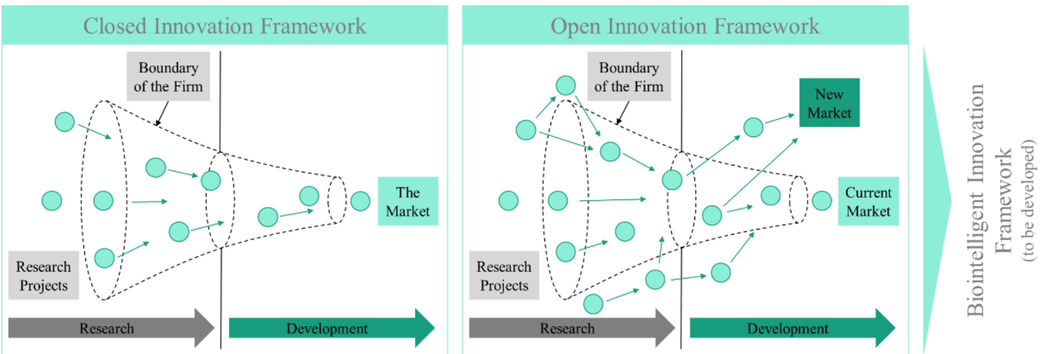

Figure 6. Difference between closed and open innovation frameworks according to Simic [62].

A rethinking is also needed for product development. While traditionally, products have been developed in manufacturing companies, non-experts (individuals or small groups) will increasingly develop and produce biointelligent products. Apart from the inherent verification of established models (e.g., V-model of product development [63,64]) by the 'additional' biological component, the scope of product development has to be extended to include factors such as services and the satisfaction of communities and societies as well as by considering the environmental performance of the production system/product. Simultaneously, the methodological basis must continuously be supplemented to reproduce the holistic benefit criterion. Figure 7 indicates the potential scope of yet-to-be-developed 'design-for-biointelligence' strategies in the current life cycle design framework, according to Ceschin and Gaziulusoy [65].

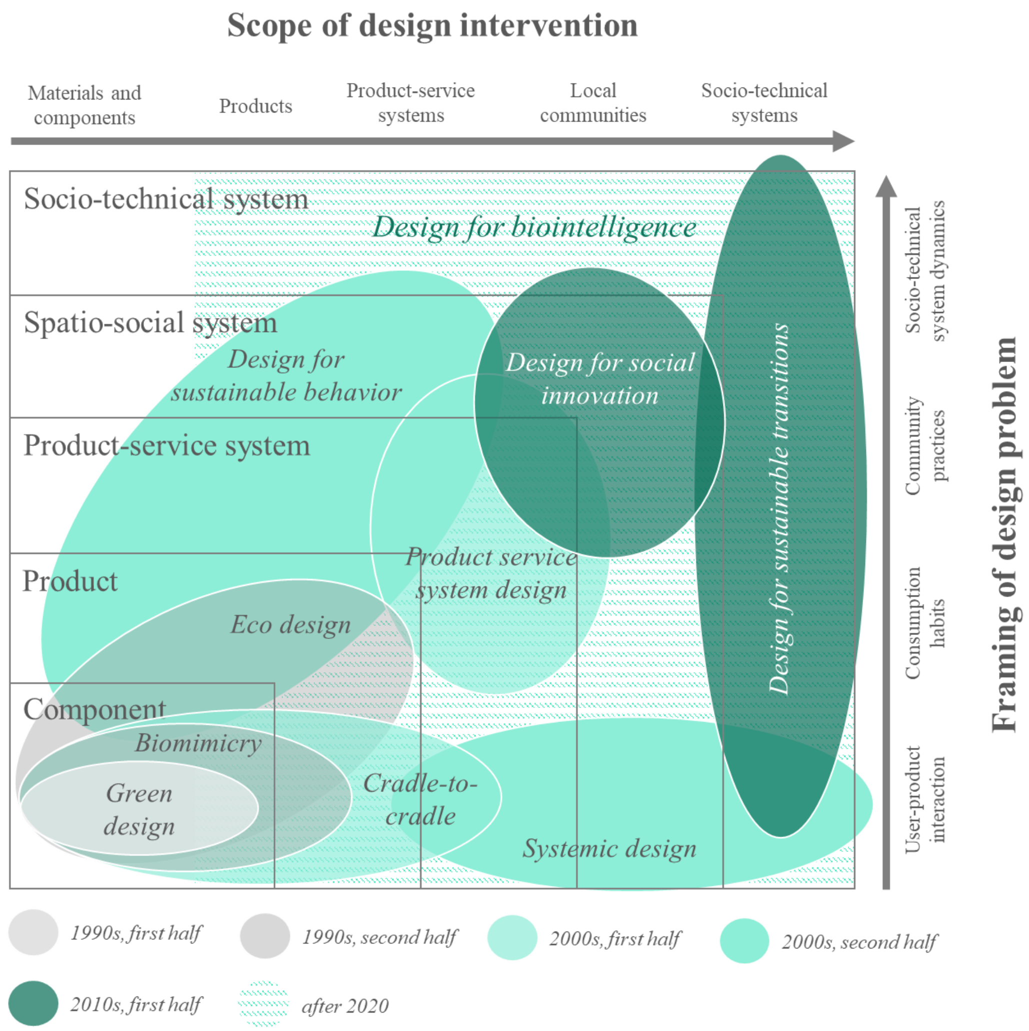

Figure 7. Evolution of sustainable design approaches according to Ceschin and Gaziulusoy [65] and scope of 'design-for-biointelligence'.

5.4. Organization and Management

The organization of a biointelligent production network represents a fundamental change compared to existing approaches of the classical, neoclassical and digital area (Figure 8). In a biointelligent production system, all necessary steps (energy and raw material extraction, storage, and refinement as well as (re-)production) ideally occur in a closed loop structure at a single location. This requires small-scale on-site production systems, e.g., based on additive manufacturing, which are coupled with self-learning algorithms to refine regionally available biobased materials (e.g., bioreactors, biorefineries), process them and adapt them to specific requirements (e.g., use, end of life). The technological and biological systems are enabled to communicate and learn from each other. Mini-cell factories, following the principles of tissue engineering, are finding their way into households. In this way, the production of foods will be made possible at the push of a button. Household waste is recycled directly with the help of bioelectrochemical production cells, and waste is incorporated into new products in the form of energy and/or raw materials (sector coupling 2.0). It is clear that this type of approach to production organization requires the development of a new methodological basis.

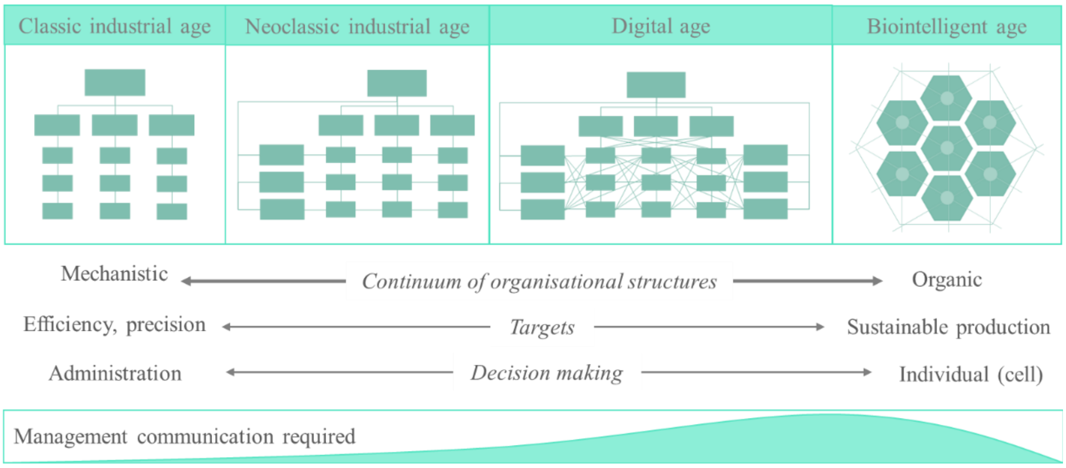

Figure 8. Biointelligent organizational structure in comparison to existing industrial structures (own illustration based on [39]).

While approaches for concepts of organization and management that consider production as an organism have been introduced to the scientific community, they have rarely been transferred into practice (e.g., Beers viable system model (VSM) [66–68]). The management of BIS requires methodological support for the mapping of interrelationships within the system as well as the integration of social and environmental aspects into all levels of decision making. Primarily, the concept of cellular thinking and the extension of the production system beyond factories to novel groups of producers (e.g., individuals and households) distinguishes the concept of biointelligent production from previous concepts such as the fractal factory described by Warnecke [69]. VSM in particular can be considered as a fundamental approach towards the organization and management of biointelligent production systems, although the concept of cellular thinking has not been integrated into VSM to date.

5.5. Responsibility

BIS require a highly responsible management. Individual voluntary action or governmental regulation can be used to ensure that all actors fulfil their responsibilities within the context of biointelligent production. Consequently, the basis must be the systemic life cycle monitoring of all activities and the compliance with all applicable regulations over an entity´s entire life cycle. In this context, Hauschild et al. present an LCE framework based on the IPAT equation [41,42]. According to the formula developed by Ehrlich and Holden [70], $I = P * A * T$, the impact (I) of human activities is the product of the factors population (P), affluence (A) and technology (T). Manufacturing companies may align their activities with its inverse eco-efficiency (EE) [41,42]. Although this equally applies to biointelligent production systems, the convergence of several technologies that are regarded as critical in parts of society (biotechnology, AI) requires a particularly cautious approach. For this purpose, new models must be developed, e.g., in the context of life cycle impact assessment, in order to provide relevant ex ante information for handling genetically modified cells [10].

6. Conclusions

BIS are currently considered one of the most innovative paths for sustainable production by enabling the highly localized, on-demand production of personalized goods via stand-alone non-expert systems. Recent studies primarily adopted a technical perspective; thus, this paper addressed the larger picture by the discussing essential issues of integrated production system design. In addition to the explicit technical understanding of biointelligence, we introduce an implicit holistic understanding (the responsible handling of biological resources), which we subsequently use as the foundation of our elaborations.

We conclusively argue that a system can only be regarded as fully biointelligent if it evidentially adheres to the explicit *and* implicit definition. Its application in theory and practice requires a unique perception of reality as an inherent mindset, which can be classified as system-oriented life cycle thinking in cellular units. Hereby, a single segment of reality is regarded as a cell, which forms various interrelations and interacts with numerous surrounding cells as well as the overall system. Each entity influences its environment throughout its entire life (from cradle to grave). From this basic mindset, we derived a thought model of a biointelligent production system, which in turn forms the nucleus of a management framework. We then identified key fields of action for which we outlined perspectives for future R&D, including the analysis of relevant strategies and business models, the development of "design-for-biointelligence" approaches, the evaluation of cellular management concepts, the development of holistic evaluation schemes, etc. It should be clear that many of the considerations outlined here are purely theoretical. Although we can observe strong trends toward biointelligent production in individual areas (health, nutrition, housing, energy production, etc.), it is impossible to predict the extent to which the conceptual model on which this paper is based might be applied comprehensively. Hence, this publication is to be understood as a starting point for the further development and application of the concept of biointelligent production.

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