# Challenges and Properties for Bio-inspiration in Manufacturing

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**Abstract.** The increasing market fluctuations and customized products demand have dramatically changed the focus of industry towards organizational sustainability and supply chain agility. Such critical changes inevitably have a direct impact on the shop-floor operational requirements. In this sense, a number of innovative production paradigms emerged, providing the necessary theoretical background to such systems. Due to similarities between innovative modular production floors and natural complex systems, modern paradigms theoretically rely on bio-inspired concepts to attain the characteristics of biological systems. Nevertheless, during the implementation phase, bio-inspired principles tend to be left behind in favor of more traditional approaches, resulting in simple distributed systems with considerable limitations regarding scalability, reconfigurable ability and distributed problem resolution.

This paper analyzes and presents a brief critical review on how bio-inspired concepts are currently being explored in the manufacturing environment, in an attempt to formulate a number of challenges and properties that need to be considered in order to implement manufacturing systems that closely follow the biological principles and consequently present overall characteristics of complex natural systems.

**Keywords:** Bio-inspiration, Self-Organization, Manufacturing Systems.

## 1 Introduction

Nowadays, manufacturing companies are facing a very challenging reality. Not only society is demanding more customized high quality products than ever, but also markets are becoming increasingly characterized by an erratic behavior. Hence, sustainability and responsiveness at the shop-floor level are fundamental factors to survive and thrive in such harsh and challenging conditions. The short life-cycle of products and the need to promptly respond to product demand fluctuations and short-term business opportunities is compelling companies to shift from traditional shop-floor approaches, towards more modular and reusable systems.

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Mainly in the last two decades, academia has been developing a number of innovative production philosophies that provide the theoretical background necessary for the implementation of such distributed and decoupled systems. As result of this effort a number of manufacturing paradigms focused on agility emerged, supported by the advances in ICT (Information and Communication Technology) and based on AI (Artificial Intelligence) and complexity science concepts. Some examples are Bionic Manufacturing Systems (BMS) [1], Holonic Manufacturing Systems (HMS) [2], [3], Reconfigurable Manufacturing System (RMS) [4], [5] and Evolvable Production Systems (EPS) [6], [7], etc. Despite some conceptual differences, most modern manufacturing paradigms theoretically rely on bio-inspired principles to attain the necessary adaptation and responsiveness to unpredictable scenarios. Nevertheless their application, so far, has been limited to specific manufacturing problems, such as: scheduling, planning, layout formation, modeling, fault detection, etc [8]. Consequently the resulting systems are typically distributed, but not necessarily highly scalable, reconfigurable and able to tackle problems in a distributed manner. The network-like architecture and modular functional complexity of modern shop-floors supported by the innovative production paradigms closely follow the structural patterns presented by complex natural systems. In this context, the following question is raised: **what are the main challenges and required properties necessary to foster the development of real production systems that closely mimic biological systems behavior and consequently present overall characteristics of complex natural systems?**

To some extent, this paper attempts to answer this question by presenting a critical analysis on how bio-inspired concepts are currently being explored and used under the scope of modern production systems. For this purpose, a brief review of some applications of bio-inspired approaches in manufacturing is presented, in order to highlight the advantages of bio-inspiration, leading to the formulation of a set of challenges that need to be tackled and to the identification of a number of required properties necessary to enact a production system as bio-inspired.

## 2 Relationship to Collective Awareness Systems

The origins of Life can be traced back to more than 3500 Million years ago. Since then, primitive organisms were subjected to an evolutionary process in which the occurrence of changes in the environment conditions fostered the reproduction of individuals that better matched their characteristics against the environment functional requirements. Hence, generation after generation individuals developed more adequate characteristics to handle the challenges posed by their natural habitat.

Today's natural diversity is the reflection of such evolutionary process. Biological systems are typically distributed and usually composed by numerous individuals that exhibit simple behaviors. However, through the exchange of meaningful local information the individual entities are able to foster the emergence of a collective action that drives the system towards common goals. The collective behavior itself is greater and considerably more complex than the sum of the behaviors of its parts [9].

Swarms of insects, such as ants, bees, termites, fireflies, among others, are recurrent examples of biological collective systems present in the literature.

Nonetheless, collective systems can be encountered in all sizes, forms and scales. Critical to the emergence of the collective behavior is however the self-awareness of the individual entities. Each entity, despite its simplicity and limited cognitive ability, needs to be able to assess the local surroundings and its internal state in order to make adequate decisions and consequently establish meaningful interactions in response to internal or environmental changes. In this context, collective awareness should not be perceived as an intrinsic characteristic of collective systems per se, but instead as a property that emerges in result of the awareness and social abilities of the individual entities. Even though optimal decisions can only be enacted with a global perspective, the local nature of the interactions and the efficiency of the communication mechanisms endow biological collective systems with the necessary edge to quickly respond as a whole to environmental perturbations. Collective biological systems can therefore be perceived as a unique entity that is aware of the environment and consequently act according to it.

Modern manufacturing systems, as they are idealized by modern manufacturing paradigms also consist on many 'intelligent' autonomous modular entities with social capabilities, that dynamically establish interactions with each other, in order to achieve common objectives. However, the development and implementation of innovative industrial applications which rely on bio-inspired principles tend to stumble in some important gaps between the conceptual academic models and their technological realization, as pointed out in [10]. Hence, one as to master the intricacies of biological complex systems in order to effectively translate their regulatory principles into modern modular manufacturing structures. Only in this way it is possible to truly profit from their dynamics, and achieve a collective level of awareness that allows the system to successfully face environmental changes and uncertainties.

## 3 On the Application of Bio-inspired Concepts in Manufacturing

Considering the before mentioned paradigms, the increasing structural modularity and autonomy of manufacturing systems means that production floors are becoming evermore complex, rendering traditional control approaches insufficient. On the other hand, ICT-based decentralized control solutions that support advanced AI, are naturally designed to efficiently support the current requirements imposed by modern manufacturing systems. However these solutions are naturally of complex nature. Bio-inspired mechanisms are currently recognized as a powerful and viable solution to tackle complex engineering problems, particularly in situations where there is a lack of available information or in cases where the search space is so large that brute-force optimization algorithms are out of the question [11]. In this context, it is the purpose of this section to discuss and analyze how bio-inspired techniques are currently being applied and explored within the manufacturing context.

Evolutionary concepts have been widely used in schedule optimization, such as flexible manufacturing scheduling problem [12] and flow shop scheduling [13]. Furthermore many evolutionary applications have also been reported in planning

[14], [15], [16], manufacturing cell formation problems [17], [18] and modeling manufacturing processes [19], [ 20], among others.

Biological collective systems behaviors, commonly colonies of insects, have also been applied to a number of manufacturing problems. An application based on stigmergy to regulate the self-organizing behavior is presented in [21]. Ants' behaviors are also an option to tackle layout problems [22] and vehicle routing problems [23]. Bee's food foraging behavior has also been the source of inspiration to solve job scheduling problems [24], and the printed circuit board (PCB) assembly planning problem [25]. In addition, bacterial foraging behavior provides adequate principles to tackle assembly line balancing [26]. The flashing lights of fireflies were also explored in the development of scheduling mechanisms [27], cell formation problems [28] and solving machining models [29]. Mechanisms based on the neural behavior have been widely applied in recognition problems [30, 31] and fault detection [32], among others.

Finally, the dynamics of the biological immune systems have also been a source of inspiration in manufacturing applications. Similarly to other biological sources, immune behavior has been explored to handle scheduling [33], layout problems [34] and fault diagnosis [35] and detection [36].

Bio-inspired methods, as the previous short literature review also illustrates, are generally focused on the parallel resolution of problems, not necessarily computationally distributed. Moreover, these methods are typically explored as optimization techniques. Hence, it is only natural that the majority of the applications of these techniques within the industrial context are also applied in an optimization perspective. In this sense, and according to the searching approaches generally followed by metaheuristic methods, the algorithms iterate over several possible solutions until a specific stopping criteria is satisfied. Once the stopping criterion is satisfied, the solution is assumed by the system. It is however, in the variety of solutions, distributiveness of information, type of interactions and operators used to explore and select the solutions that the biological inspiration lays. Nevertheless, bio-inspired approaches are generally not envisaged to consider the manufacturing problem from a distributed problem resolution and holistic perspective, but instead to simply tackle narrow and specific manufacturing problems. For a more extensive review on bio-inspired methods and applications please refer to [8].

## 4 The Relevance of Evolution and Adaptation

As previously stated, modern manufacturing paradigms clearly support the introduction of bio-inspired concepts in the so traditional field of industrial production. Some of the more desirable from a manufacturing point of view are: adaptation, evolution, self-organization and emergence. These are the key fundamental concepts behind the success of biological systems. Evolution in the natural world is a long term optimization/adaptation process. Evolutionary adaptation is a pervasive feature of biological organisms and it is the outcome of natural selection, mutation and genetic drift. The conjugation of these properties leads to an optimization process which is only constrained by the genetic code itself. In such evolutionary process, the individuals with features that better match the environmental requirements, have higher probability to survive and therefore reproduce. Consequently, those features that foster the survivability of particular individuals are passed to the next generations increasing their adequacy towards the environment. The existence of biological diversity implies however that populations do not reach adaptive peaks and that evolutionary adaptation is an open-ended optimization process that is always reacting to the environmental changing conditions, in order to provide the best functional solutions to the current state of the environment. Since manufacturing systems cannot physically adopt a similar genetic evolutionary process, evolution in this case implies the development and integration/removal of new equipment/modules in the system, to explore alternatives in the system reconfiguration, leading to new evolutionary states through which the system should be able to meet the new manufacturing requirements.

On the other hand, short term adaptation (behavioral adaptation) is the concept behind the responsiveness and agility of biological systems. It is therefore, the critical property that endows the system the ability to handle changes and uncertainties of dynamic environments. From a manufacturing perspective, adaptation is similarly a short-term process that concerns the system aptitude to revise its logical parameters and reorganize or redesign its set of processes. The extension of the adaptation process should be as big as necessary to overcome requirements or disturbances, within the constraints of the actual physical system.

Collective living systems are characteristically composed by numerous simple 'homogeneous' (possess a common interface or means to seamlessly interact with other components of the system) constructs. Typically, these systems rely on simple principles and local information, without requiring any centralization of the control and information flow. In this sense, behavioral adaptation is mainly attained by self-organization mechanisms. Interaction patterns which are locally and asynchronously established, according to the individuals internal and surrounding status, support the main regulatory principles that lead to the emergence of the necessary individuals functional adaptation and coherent global system behavior. It is however curious that the biggest advantage of these collective systems, is also their greatest weakness. As stressed before, an optimal decision can only be taken when there is a general overview of all the system information. Even though, it is possible to compose a consistent global view by the exchange of local information, it is impractical and inefficient with the increasing number of entities [10]. Nevertheless, the distribution of both the knowledge and decision nodes ensures the system responsiveness and robustness to malfunctions, reducing the effect of deviations or catastrophic failures of the individuals. In other words, the system is not dependent on specific individuals. In a certain extent, every individual unit is relatively negligible to the proper functioning of the system. Yet, every entity contributes to the whole, and the whole supports the individual entities.

This represents one of the major gaps of most modern manufacturing paradigms. The centralization of the knowledge and regulatory control on certain hierarchical structures, simply results in a computationally distributed system in which the control mechanisms are still dependent on key higher hierarchical entities to manage the execution of critical processes. Although the effects of any malfunctioning or removal in lower level entities are easily suppressed by relocating the process, if there is sufficient redundancy or simply by replacing the component. The failure or removal of a key hierarchical node however is critical to the correct functioning of the system.

Similarly to the biological systems, central to manufacturing systems' evolution and behavioral adaptation are the concepts of self-organization and emergence that need to be properly supported by the control architectures, in order to endow the system with the ability to autonomously handle both logical and physical changes.

## 5 Towards Bio-inspired Complex Manufacturing Systems

The currently growing interest and development of modular mechatronic production systems provides the opportunity to explore highly reconfigurable and scalable architectures with simultaneous and distributed resolution of various manufacturing problems. In this context, the integration of regulating bio-inspired principles, particularly bio-inspired self-organization, may be the way to unravel the potential of modern manufacturing paradigms. Even though these techniques have been fairly used in modern approaches [8], [10], when down to the implementation, bio-inspired methods tend to be replaced by negotiation-based procedures which tend to be efficiently poor. Consequently, current modern manufacturing systems architectures performance and scalability is typically constrained by the architecture's artificially devised self-organizing approaches and control structures. In this sense and in order to attain biological-like agility bio-inspired mechanism should be considered from a considerably more holistic perspective. This necessarily introduces a number of challenges that need to be tackled:

- Despite the technological and distributed support provided by modular mechatronic systems, the bio-inspired structural characteristics and concepts need to be properly abstracted by a robust technical architecture.
- Production requirements, typically centralized on single entities, should be distributed over the manufacturing system components in order to reduce the necessary specification and simultaneously foster the optimization and distributed execution of production workflows.
- The reconfigurable ability, scalability and distributed coherent execution of production plans must be the outcome of efficient and semantic interaction patterns that support the implementation of regulatory bio-inspired self-organizing principles. Although the feasibility of the state transitions is not so relevant for the normal execution of the bio-inspired algorithms itself (providing that the viability of the solutions is ensured), it is critical for systems that holistically follow the same principles. Every transition may have a direct impact in the physical shop-floor consequently the devised regulatory principles need to ensure the transition feasibility. In this way the system should be able to closely mimic the robustness and adaptation of biological systems.
- As opposed to natural systems, production systems evolutionary cycles have to be proportional to the very demanding production time frames [10].

Recent developments in distributed manufacturing architectures have attempted to attain agility and sustainability through the implementation of complexity abstraction layers, based on dynamic self-organizing logical hierarchical structures. Nevertheless, these efforts have only been partially successful. In this sense, through the literature review and analysis of the most common biological inspiration sources, a set of properties required by distributed systems to support biological-like structures and dynamics were identified:

1. **Use of genetic operators** - Similarly to nature, crossover and mutation operators are employed to introduce diversity in the population so that the full extent of the solution space can be properly explored. Although most bio-inspired approaches use genetic operators to perform evolutionary adaptation, from a mechatronic perspective these operators could be used to evolve particular parameters and achieve individuals' adaptation. It is important to stress that this is not an essential property to enact an approach as bio-inspired.
2. **Large populations** - Biological systems are typically characterized by large populations of individuals. Group size is typically determined by the resulting advantage, where the size of the group affects its performance. Small populations imply a magnification of individual mistakes. Too large populations may generate a fearsome resource competition leading to the destruction of population members. Within the midrange is the optimal population size. In the mechatronic context processes and components redundancy should be optimized in order to provide the desired level of robustness, in case critical failures affect the system components.
3. **Homogeneity of the individuals** - Biological systems are generally composed by identical individuals. This ensures that coherent and semantic interaction patterns are established as a response to disturbances in the environment. Mechatronic components do not necessarily need to present similar physical properties. However, compatible interfaces should be defined so that a meaningful collective behavior is attained.
4. **Decoupled nature of the entities** - Biological entities usually present high levels of autonomy, in the sense that different individuals interact by using well defined interfaces rather than tightly depending on each other. This implies that the removal or addition of components should have little or no impact in the normal system behavior. In other words, each mechatronic entity should contribute to the collective behavior, whilst every entity should be as negligible as possible to the proper functioning of the system.
5. **Stochastic behavior** - In nature, as opposed to the engineering world, systems do not have any specific goal rather than reproduce and survive. Individual decisions that influence the overall function and dynamics of the collective are the result of an interplay between deterministic and stochastic events presented by the environment. Similarly, evolutionary adaptation is also the outcome of exposing living systems to some events of stochastic nature such as mutations, genetic drift and natural selection. In this sense, it is therefore important to have, in the mechatronic context, a limited amount of randomness in order to explore all possible, available and feasible solutions (the stochastic process can be virtually simulated [37]).
6. **Asynchronous and local interactions** - Local interactions are one of the key aspects in the emergence of coherent and meaningful biological collective behaviors. Notoriously, the regulatory principles that foster the emergence of the natural self-organizing mechanisms are supported by the asynchronous establishment, between population individuals, of semantic and efficient interaction patterns. Consequently, comparable interaction patterns need to be

devised in artificial systems in order to attain similar behavior. Furthermore, living systems are usually characterized by physical limitations that heavily constrain the individuals perception of the environment. This however implies that they are extremely responsive to environmental disturbances. Thus, despite the fact that self-organization in artificial systems does not necessarily preclude the use of global information, it seriously has a negative impact with the increasing size of the system. Therefore, in order to closely match the mechanisms of biological self-organization, a trade-off between the responsiveness of the system and the optimality of the decision needs to be found.

7. **No centralized knowledge or decision nodes** - Unlike the approach that has been typically followed by current state-of-the-art architectures, biological systems do not rely on entities with centralized knowledge and decision making capabilities. Instead, each individual is an autonomous decoupled entity that acts according to its internal and surrounding information. In this way, natural systems are able to, in a distributive manner, handle the disturbances or problems posed by the environment. This is a relevant differentiation aspect between natural and artificial distributed systems. Hence, a bio-inspired self-organizing system that presents the agility and robustness of biological systems can only be enacted with the full distribution of both knowledge and decision making capabilities.
8. **Emergence of collective behavior** - Emergent properties are a hallmark of collective animal behavior. In this context, the adequate implementation of the previous properties should foster the emergence of a robust, coherent, and meaningful collective behavior. Moreover, the system should present characteristics such as responsiveness, agility, robustness, scalability, pluggability, adaptability and evolutionary properties as result of the implemented bio-inspired self-organizing mechanisms.

## 6 Conclusions

Organizational sustainability and supply chain agility have become critical for the success of regular manufacturing enterprises. Companies with a pluggable, scalable and highly reconfigurable shop-floor have the ability to better cope with uncertainties and therefore have a faster response to new business opportunities. In this context, modern manufacturing paradigms play a crucial role, since they provide the methodology and background necessary to implement such systems. However, although the importance and validity of modern production paradigms is generally consensual, their implementation in real industrial systems has been, until now, minimal and only partially successful.

To some extent, this problem can be attributed to the fact that modern manufacturing systems heavily rely on biologically inspired concepts that are not properly considered and supported in the following development phases. Modern production systems, as envisioned by innovative paradigms, rely on modular independent constructs that naturally make the system a complex structure. However, the biological mechanisms that critically regulate collective living systems with similar structure are still faced simply as a desirable characteristic of the systems, but not as the main control mechanism. A more holistic integration of these mechanisms in the manufacturing context could possibly not only foster systems autonomy, scalability and reconfigurable ability but also its distributed problem resolution capabilities, enabling the system to more efficiently respond to changes and uncertainties in the environment. It is the authors' belief that considering the highlighted challenges and identified properties is a small step towards that goal.

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