IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 3 December 2022, accepted 20 January 2023, date of publication 30 January 2023, date of current version 2 February 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3240433

SURVEY

Self-Organization in Smart Manufacturing–Background, Systematic Review, Challenges and Outlook

LUIS A. ESTRADA-JIMENEZ, TERRIN PULIKOTTIL, SANAZ NIKGHADAM-HOJJATI, (Member, IEEE), AND JOSÉ BARATA, (Member, IEEE)
UNINOVA—Centre of Technology and Systems (CTS), FCT Campus, 2829-516 Caparica, Portugal
Faculdade de Ciencias e Tecnologia, Departamento de Engenharia Electrotecnica, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal

Corresponding author: Luis A. Estrada-Jimenez (lestrada@uninova.pt)

This research is supported by the Digital Manufacturing and Design Training Network (DiManD) project funded by the European Union through the Marie Skłodowska-Curie Innovative Training Networks (H2020-MSCA-ITN-2018) under grant agreement no. 814078.

ABSTRACT The concept of smart manufacturing has attracted huge attention in the last years as an answer to the increasing complexity, heterogeneity, and dynamism of manufacturing ecosystems. This vision embraces the notion of autonomous and self-organized elements, capable of self-management and self-decision-making under a context-aware and intelligent infrastructure. While dealing with dynamic and uncertain environments, these solutions are also contributing to generating social impact and introducing sustainability into the industrial equation thanks to the development of task-specific resources that can be easily adapted, re-used, and shared. A lot of research under the context of self-organization in smart manufacturing has been produced in the last decade considering different methodologies and developed under different contexts. Most of these works are still in the conceptual or experimental stage and have been developed under different application scenarios. Thus, it is necessary to evaluate their design principles and potentiate their results. The objective of this paper is threefold. First, to introduce the main ideas behind self-organization in smart manufacturing. Then, through a systematic literature review, describe the current status in terms of technological and implementation details, mechanisms used, and some of the potential future research directions. Finally, the presentation of an outlook that summarizes the main results of this work and their interrelation to facilitate the development of self-organized manufacturing solutions. By providing a holistic overview of the field, we expect that this work can be used by academics and practitioners as a guide to generate awareness of possible requirements, industrial challenges, and opportunities that future self-organizing solutions can have towards a smart manufacturing transition.

INDEX TERMS Cyber-physical production systems, smart manufacturing, self-organization, complexity theory, artificial intelligence, biologicalisation.

I. INTRODUCTION

In the past decades, the high market dynamicity in addition to globalization, fast change in customer preferences, high rate of personalization of products (short life cycle), and increasing need for customer satisfaction have brought the need for companies to change their business strategies to stay competitive. This situation requires the development of novel manufacturing control approaches where resources need to be ready to change, production delays are not allowed and opportunities to increase performance should be part of a constant process adaptation.

Industry 4.0 or Smart manufacturing (from this point they will be used interchangeably) was coined back in 2010 as a new revolutionary industrial paradigm driven by the German government [1]. This vision supported by emerging computational concepts i.e., digitalization or Cyber-Physical Production Systems (CPPS) [2] aims to

The associate editor coordinating the review of this manuscript and approving it for publication was Sunil Karamchandani.

provide the agility and flexibility required to fulfill these new industrial requirements. Although preliminary supporting ideas were already introduced in the early 2000s with the concepts of Evolvable Production Systems (EPS) [3], [4], Holonic Manufacturing Systems (HMS) [5], [6] and Bionic Manufacturing Systems (BMS) [7].

Today, this *digital innovation* and *smartification* in the manufacturing sector is associated with sustainability policies (to minimize effects on environmental impact) and it is pushing circular and shared economy as there is a link towards the reusability of resources [8], [9]. A direct target is manufacturing industries as they are responsible for a significant contribution to greenhouse emissions [10]. In 2021, in the U.S., the manufacturing industry only was responsible for around 23% of CO2 emissions according to the Environmental Protection Agency [11]. Also, in Europe industry emits annually around 880 million tones of CO2 [11]. High relevance has the concept of sustainability and its application in manufacturing that a recent report by Deloitte states that *significant change is afoot [in manufacturing] and it necessitates bigger thinking. Those unprepared may find themselves being left behind* [12].

Hand in hand with sustainability, higher levels of automation are supporting smart manufacturing, too. The World Economic Forum states 3 main reasons why automation matters in an industry 4.0 context [13]. First of all, to lift industrial productivity: requiring less manual labor in operations, and reducing commissioning and installation expenses. Second, by providing the workforce with tools that allow operators to work remotely and from a safe distance, and third, by reducing the impact of industry on the environment, highly related to the concept of sustainability previously introduced.

Besides automation and autonomous systems, from a business perspective, several factors should be taken into account to reach the desired level of sustainability. Some examples to consider are: the creation of value from waste (circular economy, sharing assets) and delivering functionalities rather than ownership (using product service systems: rental, lease, and share equipment and technology) [9].

Autonomous manufacturing systems with the capacity of self-management (characterized by self-x behaviors i.e., self-organization) are in line with the aforementioned manufacturing requirements (i.e., sustainability, digitalization, and smartification). Independent task-specific modules can be re-used and shared thanks to a collaborative and smart infrastructure. Thus, reducing the manual engineering effort of configuration and reconfiguration and bringing also a high adaptation capacity to the system.

The interest in the design of self-organizing manufacturing approaches has been growing in the last years. Probably initial ideas in the field date back to the conception of the HMS in the early 90s [6]. From that point, a wide variety of research has been produced. Some of them have provided conceptual ideas about the concept of self-organization in manufacturing: challenges and opportunities [14], the role of collective intelligence [15], status and the relation with industry 4.0 [16], agents (main enablers of self-organizing approaches) [17] and contribution of holonic systems in industry 4.0 [18].

Generally speaking and under the umbrella of self-organized manufacturing, there is a lack of a comprehensive review that explains the main background and concepts behind the field, the different mechanisms that are being used, the status of implementation they have, the different technological enablers that potentiate its implementations, and some of the challenges and potential research directions.

Thus, the main objective and contribution of this work go towards that direction. By means of a systematic review and three research questions, we comprehensively analyze the main mechanisms used, the current status of implementation, and some of the future research directions. Future researchers and practitioners can use the result of this work as a generic guide to design and implement new self-organized manufacturing solutions.

The rest of this paper is organized as follows. *Section II* presents relevant concepts and definitions in the context of smart manufacturing (i.e., manufacturing automation, flexibility, intelligent product-driven manufacturing, Cyber-Physical Production Systems). *Section III* presents relevant concepts and definitions in the context of self-organization and complex systems (i.e., complex systems, complex adaptive systems, self-organization, emergence, biologicalisation, swarm intelligence). *Section IV* presents the objective and method of the research. *Section V* presents a summary of the mechanisms utilized. *Section VI* introduces an overview of the current status (i.e., readiness level, automation level, the context of the application, and technological enablers). *Section VII* presents challenges and implications for future research. *Section VIII* presents an outlook of the work. *Section IX* presents some limitations of the methodology of the literature review and finally, *Section X* presents the conclusions of this work.

II. SMART MANUFACTURING - BACKGROUND, CONCEPTS AND DEFINITIONS

This section introduces relevant concepts regarding automated and flexible manufacturing systems as well as a general overview and characterization of the fourth industrial revolution and CPPS.

A. MANUFACTURING AUTOMATION

Automation is required in a factory while manufacturing a product and in operations like assembling, inspection, and material handling. Automated processes are performed with a reduced level of human intervention [19]. Some examples include: automatic material handling, processing/assembling with industrial robots or automated storage systems [19]. Several benefits are driven by industrial automated solutions i.e., increasing productivity of factories, increasing human safety, and reducing environmental impact [13], [20].

B. FLEXIBILITY IN MANUFACTURING SYSTEMS

Increasing market dynamism and unforeseen events indicate that it is not always feasible to define in advanced behaviours that explicitly state how a manufacturing shop-floor should react in terms of configuration or organization.

Due to this level of uncertainty, it is important to have shop-floors with high levels of flexibility. Flexibility, as defined by [21], is *"the capacity of a system to change and assume different positions or states in response to changing requirements with little penalty in time, effort, cost or performance"*. Several types of flexibility can be derived by this definition in a manufacturing context e.g., machine flexibility, material handling flexibility, operation flexibility, process flexibility, product flexibility, routing flexibility, and expansion flexibility [21].

C. INTELLIGENT PRODUCT DRIVEN MANUFACTURING

An intelligent product as defined by D. McFarlane et al. [22], [23], [24] is *"a physical and information-based representation of an item for retail"* which fulfills characteristics like:

- Posses a unique identification.
- Can communicate with the environment.
- Can store data about itself.
- Has a language to display its production requirements.
- Can participate in the decision-making of the process.

In a product-driven manufacturing context, the potential for responsiveness and adaptation to disturbances can be handled by the product and the set of specifications it has [23]. This intelligence makes the system more proactive by handling the information from the product, identifying production problems, and notifying if relevant decisions are required [23]. Automatic identification technology can be used to track and manage products on the shop-floor. Intelligent products are also able to negotiate required operations with available resources in run time (see Fig. 1).

The current transition from mass customization to a mass personalization era where the satisfaction of individual requirements for personalizing goods and services need to be fulfilled [25] and the opportunities of batch size one operations are enabling the introduction of intelligent production models. Those present conceptual principles to generate adaptation and self-organization for new automation solutions.

D. EMERGING CONCEPTS ON SHOP-FLOOR AUTOMATION

Traditional manufacturing systems have rigid layouts and fixed conveyor systems. This can restrict the movement and capacity of adaptability of shop-floor elements; thus, new solutions should be more flexible and designed with dynamic control solutions. Novel ideas show a direction towards a higher level of mobility and transportation [26].

While categorizing various automation levels, it is suggested that industries are still far from reaching a high application maturity in terms of the mobility of resources and consumables. High complexity in the management

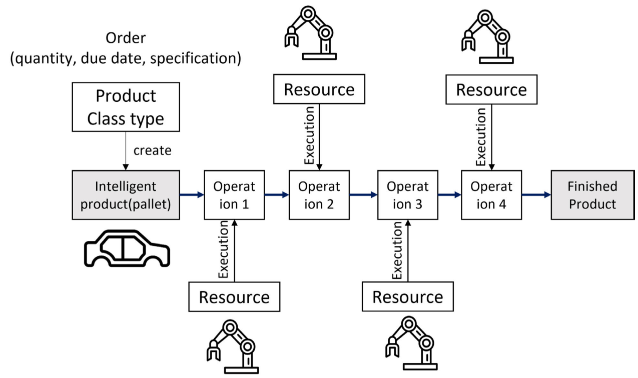


FIGURE 1. Intelligent product-driven manufacturing concept, from [24].

and heterogeneity of operational resources seems to be fundamental reason. Below is a detailed list of the automation levels considered by [26] and also detailed in Fig. 2.

- Level 0: Manufacturing operations are manual e.g., holes are drilled by hand.
- Level 1: Automated operations of workpieces e.g., with CNC machines.
- Level 2: There is a structure and automated handling of parts in fixed lines.
- Level 3: There is a complex handling and transportation of materials in flexible lines.
- Level 4: Mobile robots can perform operations of picking and preparation of parts, tools, and equipment.
- Level 5: Mobile robots autonomously perform complex production. Some repair tasks are also automated.

Mobile automation is an important enabler for the transition from current application design into levels 4 and 5, with such a degree of flexibility and engineering required, manufacturing solutions that can self-organize become imperative. Those can push higher levels of automation on the manufacturing shop-floor.

Some companies have already a vision of such future scenarios. The concept of *Factories of the Future* by Rexroth-Bosch [27] suggests that to achieve high product customization the only thing that should be static in the shop-floor are the walls, the floor, and the ceiling. All the other elements should be capable of moving. Following the same trend, the company KUKA has been already manufacturing robots with navigation capabilities [28]. Those can execute material handling activities autonomously. The separation of the intra-logistics and production, namely the Matrix Production is another vision proposed by KUKA, where categorized and standardized cells with product-neutral equipment are implemented in a grid shape layout [29].

The core idea of the Matrix Production is the separation of the shop-floor intra-logistics and production, avoiding fixed material flows and rigid links between stations. In this concept, the shop-floor consists of a grid (or matrix) of stations. Those are not product specific, i.e., they are not equipped with product-specific tools. A tool store provides the necessary equipment to customize the cells. Also, a warehouse provides

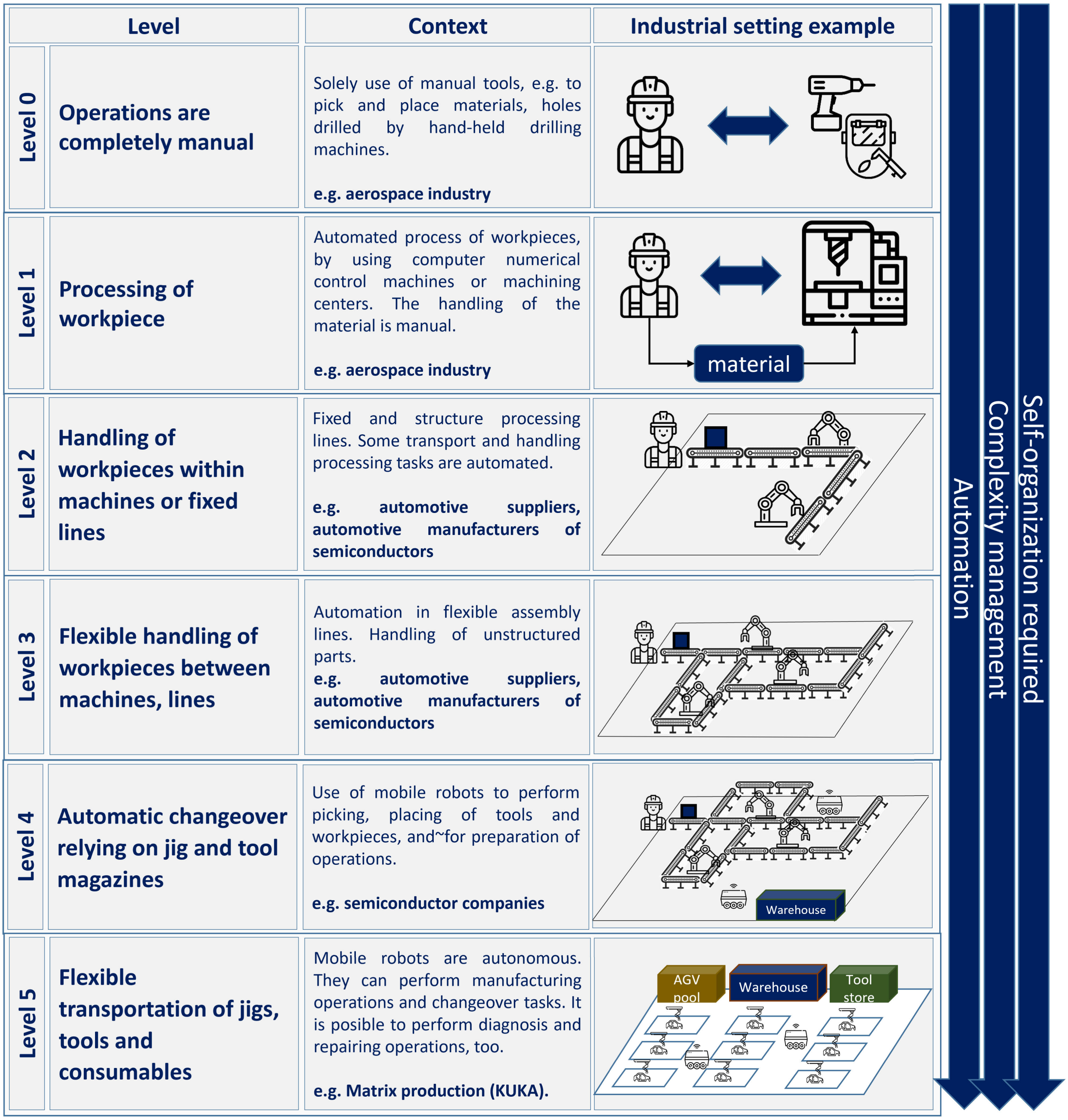


FIGURE 2. Level of automation, adapted from [26].

all necessary production parts and an Automated guided vehicle (AGV) store provides transportation means (i.e., AGVs) to transfer both tools and material into each of the stations. Thus, the system can convert itself, scale, and, control capacity utilization and bottlenecks. A sketch of the matrix production can be seen in Fig 3. As this concept is relatively new, it is suggested that its control logic is an open research question [30].

E. FOURTH INDUSTRIAL REVOLUTION

Manufacturing systems have undergone a huge transformation and evolution in the last decades to deal with the constant change of customer and market requirements and naturally going hand-in-hand with the technological evolution [4], [31]. In 2020, the Covid 19 pandemic affected a wide number of industries worldwide, obligating many of them to change their core manufacturing business. Many failed because of the lack of infrastructural or engineering capacity to adapt or change. This clearly shows the rigidity of mass production approaches which cannot cope with this level of production/market volatility.

Novel manufacturing solutions and ideas along with the introduction of information and communication technologies (ICT), Artificial intelligence (AI), collaborative robotics, high sensor availability, computational power, and faster

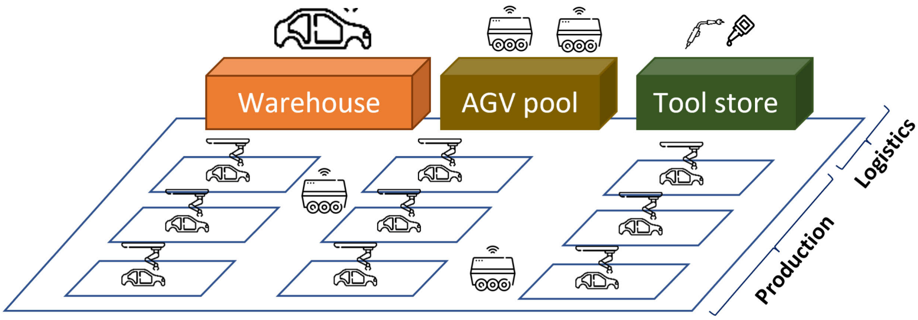


FIGURE 3. Matrix production concept by KUKA as a new concept of automation solution.

and more reliable networking infrastructures are currently pushing a new vision of the industry.

In general, Industry 1.0 was related to steam-powered systems, Industry 2.0 to the use of electric and electronic devices, and Industry 3.0 to the adoption of information and automation technologies.

Industry 4.0 aims to digitize physical assets on the shop-floor [32], providing an integral level of awareness, intelligence, and connectivity [33].

A vastly interconnected, integrated, and agile industrial environment will provide a competitive advantage to industrial stakeholders, sharing data, generating relevant knowledge, and efficiently and optimally controlling the manufacturing process. Those levels of integration can be summarized in [33], [34], and [35]:

- **Horizontal integration**: The integration of the manufacturing actors in the value chain, from the release of a new order, relation with suppliers, manufacturing operations, logistics, and final distribution elements.
- **End-to-end integration**: The digitization and integration of information of the product and set of operations during its life cycle.
- **Vertical integration**: At the shop-floor level, the integration of all the elements e.g., manufacturing resources, software, and people.

This overall integration allows the system to be more flexible and respond more agilely to disturbances.

F. CYBER-PHYSICAL PRODUCTION SYSTEMS

The concept of CPPS emerges from the integration of digital units (cyber) with their physical counterpart. These elements are autonomous and cooperative and are present across all the levels of the manufacturing life cycle. CPPS are characterized by having intelligence, connectivity, and responsiveness [2]. Intelligence to acquire information from the environment and to respond independently, connectivity to exchange information and to be easily integrated with other elements, and responsiveness to respond to external and internal changes.

With the advent of the internet of things (IoT) and the Industrial Internet of things era (IIoT) and with the high data availability, continuous and more efficient monitoring and control is possible [36].

This evolution comes hand in hand with the implementation and development of pilot use cases.

Those rely on the application of emerging ICT technologies i.e., Multi-Agent Systems (MAS), Web services, Cloud computing, Big Data, Digital Twins, human-machine interaction, wireless communication, etc. As CPPS are still far from being in a mature implementation stage, such technological applications can showcase industrial stakeholders about the real business advantage.

The Industrial Internet of Things (IIoT) is clearly supporting the design and implementation of CPPS. Those rely on technologies such as Radio-frequency identification (RFID), Wireless Sensor Networks (WSN), (network of sensors to sensor and monitor), Internet (IPV6), 3G/4G, ZigBee, WiMax, Social Networks, Near field communication, Web services, Cloud computing, Barcodes, Smartphones, AutoID, ITU, Bluetooth [37].

While the introduction of IIoT technologies has motivated the design of CPPS, the intelligence of smart factories has been the result of the development of smart devices and smart sensors. Those, besides having infrastructure communication capacity, have computing and perception power [38] and are equipped with signal conditioning features, intelligent algorithms, and interfaces that provide self-awareness, self-diagnostic, and self-identification [38].

G. CPPS RESEARCH CHALLENGES

CPPS have brought a lot of attention from the research community, yet many recent publications discussed gaps and challenges for the development of future CPPS [2], [18], [32], [39], [40], [41], [42], [43], [44]. Most of the later reviews agree on the confluence of the following general clusters:

- **Self-organizing, complex, and autonomous behaviour:** adaptability, robustness, and new ways of collaboration will make CPPS capable of dealing with dynamic changes in more complex environments.
- **Learning-based systems:** A proper data processing and acquisition, the consideration of human-in-the-loop decision making, and implementation of proper artificial intelligence techniques.

- **Control and standardization:** Low-level control (shop-floor) and the inclusion of standards as well as the inclusion of enabling technologies will foster the implementation of use cases and the industrial adoption of CPPS.
- **Human machine interaction:** Methodologies for the cooperation and collaboration between humans and machines, collaborative decision making, collaborative learning. Keywords such as operator 4.0 or industry 5.0 are usually associated with this concept.

Fig. 4 shows a sketch that presents a summary of this section alongside the industrial evolution. This paper is mainly concerned with the first set of research challenges. Self-organization and related concepts are explained in the next section.

III. SELF-ORGANIZATION AND COMPLEX SYSTEMS - BACKGROUND, CONCEPTS AND DEFINITIONS

Below, several concepts are introduced referring to self-organization and complex systems. Those are thereafter put in the context of smart manufacturing.

A. COMPLEX SYSTEMS

Complexity science deals with the study of complex systems. Complex systems consist of several heterogeneous and interdependent elements which are in constant interaction [45], [46]. In these systems, the change in the behavior of one of their elements leads to a change in the behavior of others by indirect interactions. They are said to have *"freedom to act in ways that are not always totally predictable"* [47]; therefore, it is not feasible to reduce their global behavior as the result of the sum of their elementary internal interactions.

Examples of complex systems are chemical reactions, cells (including the interactions with different microorganisms), human societies or stock markets [45].

B. COMPLEX ADAPTIVE SYSTEMS

Complex adaptive systems (CAS) are complex systems characterized by adaptation and learning [46]. These properties allow a continuous improvement in the interactions and behaviors of a system and in its internal units.

CAS refer also to the Darwinian evolutionary theory [48] where natural organisms physiologically evolve to survive over generations, improving their suitability and survival in the environment. This biological capacity denotes a continuous adaptation.

The study of complexity science and complex systems covers a wide range of interdisciplinary fields e.g., evolutionary theory, collective behaviour, self-organization, etc. Those are the basis to analyze, model and understand the behavior of complex systems.

C. SELF-ORGANIZATION

Self-organization has been extensively researched in software engineering [49] and swarm robotics [50]. It is referred to as *"a process where a system changes its internal organization to adapt to changes in its goals and the environments without explicit external control. Self-organization often results in emergent behavior that can be either desirable or undesirable. Thus, we define self-organization as the mechanism or the process enabling a system to change its organization without explicit external command during its execution time"* [51]. Fig. 5 depicts a self-organizing and emergent process as a result of local interactions.

Various properties (mandatory and optional) that complement the understanding of self-organizing systems are [49], [51], and [53]:

1) **Decentralized control**: The control of the process is distributed along all the elements i.e., every single unit contributes to the organization of the system.
2) **Dynamic adaptation**: Systems that self-organize are capable of changing their organization dynamically fulfilling a specific objective and the conditions and restrictions of their environment.
3) **Lack of external control**: Systems that self-organize do not have an external entity that has global awareness and control. All changes that occur in the system are the result of internal interactions.
4) **Robustness**: Robust systems are the ones that can work in normal conditions even if one of the constitutive elements fails or if it is removed.

Important examples of self-organization can be found in nature. Life exhibits self-organization. Animals like a school of fish, a colony of ants, or a flock of birds self-organize to survive. Several disciplines like robotics or software engineering have taken biological inspiration to solve complex problems.

D. EMERGENCE

This concept was originally studied by the ancient Greeks and appears in several fields e.g., philosophy, physics, thermodynamics, etc [51]. Close to its definition is the saying that *"the whole is greater than the sum of its parts"*.

Emergent phenomena are characterized by the irreducibility of the properties of their parts at least from a high-level perspective. The process entails a certain degree of novelty in the sense that a product, process, or in general something new is released that was not expected.

This does not mean to have inconsistent behaviour, the final outcome should have coherence. An example of this can be observed in a society of ants, where the self-organizing process of pheromone depositing leads to the whole organization of the ant colony (finding new sources of food). For the concept of emergence, we highlight the definition provided by [54]. *"A system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system"*.

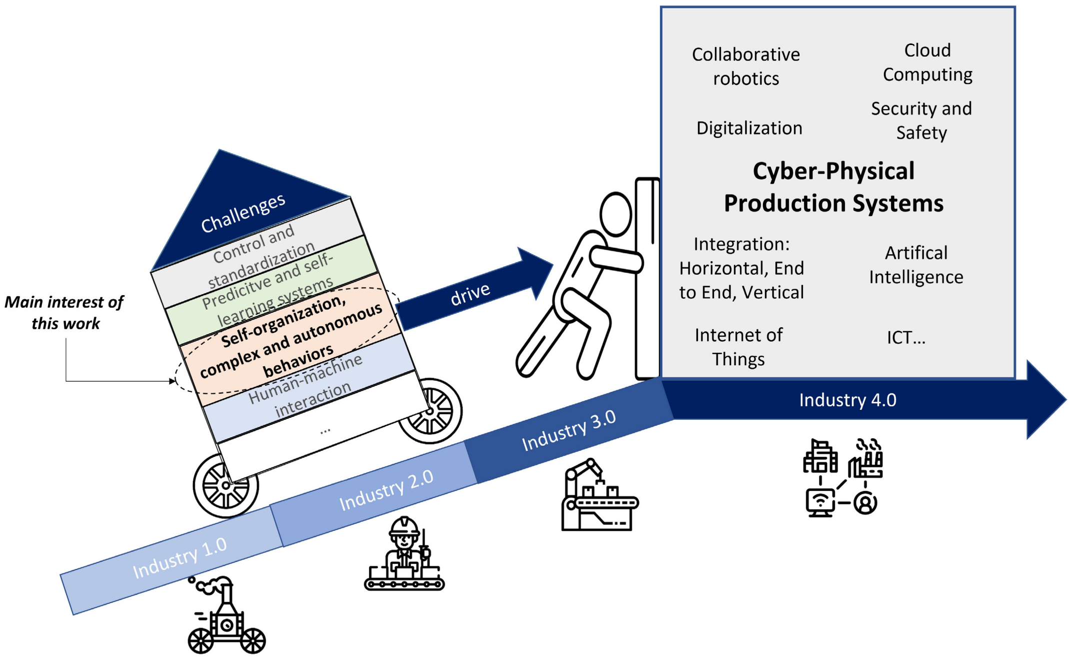


FIGURE 4. Challenges towards the fourth industrial revolution transition.

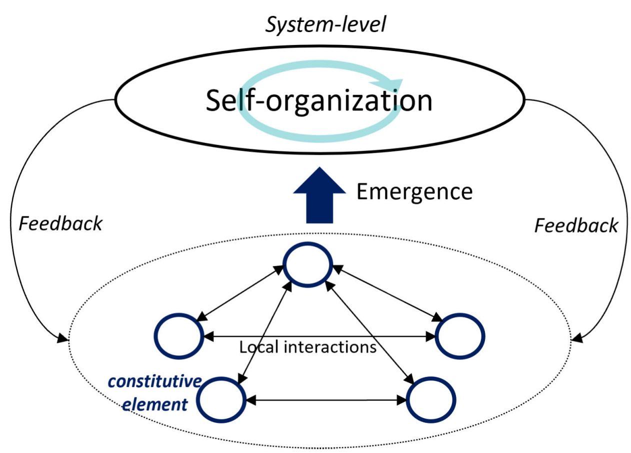


FIGURE 5. Self-organization and emergence representation, adapted from [52].

E. CONFLUENCE OF SELF-ORGANIZATION, COMPLEXITY AND SMART MANUFACTURING

The future of smart manufacturing systems is highly influenced by digitalization, enabling technologies, an increasing information acquisition capacity as well as the enormous inter-connectivity required, within a factory and with the entire value chain is producing new levels of complexity not seen before [55]. Traditional reductionist methods are not prepared for this new level of complexity because they can only work for tasks they were pre-program to do; hence, new methodologies that promote high adaptability and self-organization should be designed and implemented [55]. To this end, complexity science and self-organizing systems bring interesting sources of inspiration that even though implemented to some extent, have not been highly exploited [55]. Future cyber-physical entities should be capable of self-organization without any external control, to the extent that new global behavior can emerge. This means that manufacturing components do not need to be reprogrammed, but they can have the needed abilities to respond to specific situations, which implies very high levels of adaptability and robustness.

Smart manufacturing systems and more specifically product-driven manufacturing can represent a source of application for self-organizing design. Physical processes (manufacturing tasks) are driven by a layer of collaboration either digital or physical (by means of perception) or a combination of both. In run-time conditions, the intelligent product can find its path toward a resource without predefined engineering conditions. This means that if new resources are added or removed, if one of them fails, or if a different product is launched, the system is able to autonomously or at least partially autonomously reconfigure and adapt. This explanation concept is illustrated in Fig. 6.

F. BIOLOGICALISATION IN MANUFACTURING

Considering new, smart and sustainable advanced manufacturing technologies, and the integration of biological and bio-inspired principles, the term ''Biologicalisation in Manufacturing'' was conceived. It is defined as [56] *''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''*.

At the shop-floor level, important focus areas of biologicalisation in manufacturing include: manufacturing system design and manufacturing process and assembly operations [56]. Transversal to these fields is the idea of

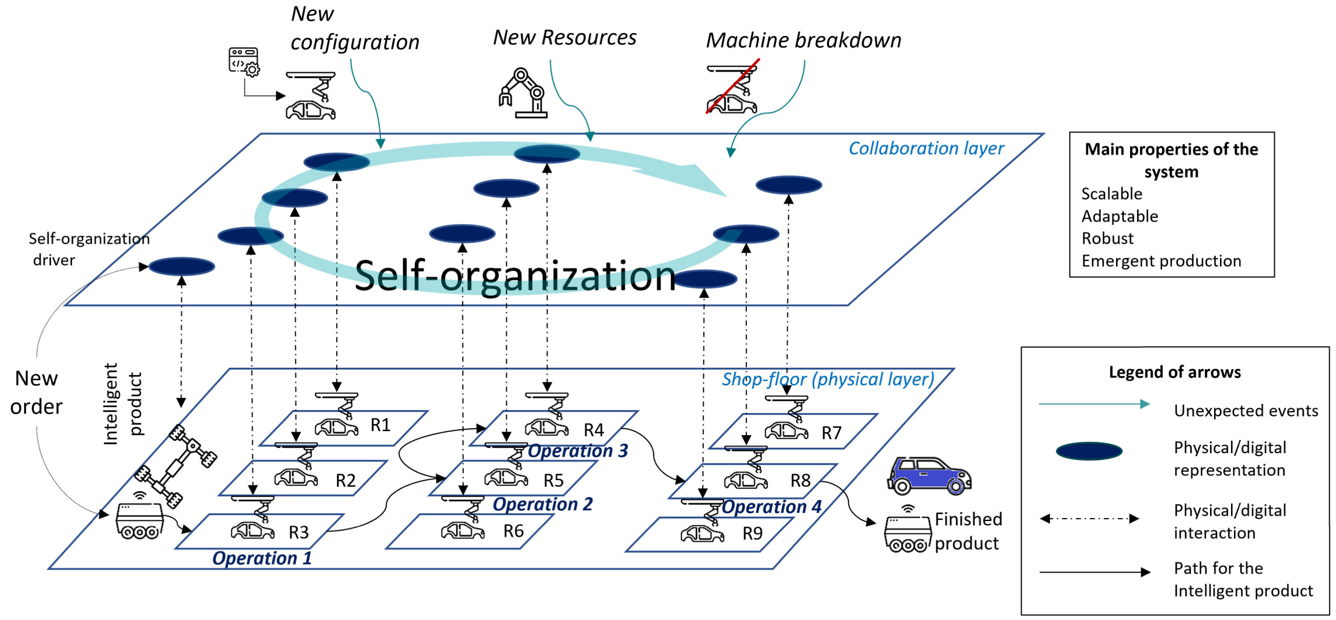


FIGURE 6. Self-organization in a product-driven manufacturing context.

looking back at natural principles and understanding how those can be used to solve new complex design problems and the alternatives they provide compared to more traditional solutions.

Some bio-inspired solutions include [56] the use of heuristic optimization approaches (e.g., to optimize parameters during a manufacturing process) like genetic algorithms or particle swarm optimization. Production self-assembly can be instantiated by the self-assembly of molecules or cellular formation. Novel assembly concepts also include the use of decentralized swarm of robots. Similar to what ants do in nature to allocate their work. Immune systems and collective systems are also being utilized for fault detection and recovery using distributed intelligence.

Several approaches of biologicalisation in manufacturing are in the research phase [56]. Various biological solutions and principles are paving the way towards a new technology pull. Those are proving various solutions at the production stage.

G. SWARM INTELLIGENCE

One of the key factors behind the success of social insects/animals is their capacity for cooperation. Even if it seems that all individuals have their own agenda, the whole colony/community/group seems to be very organized. What is more fascinating is that nobody is in charge in that organization [57].

Many characteristics of the behavior of social insects represent self-organization. The macroscopic pattern and complex behaviour of the group appear as the result of the simple behaviour of individuals [57]. Social insects are therefore a promising source of inspiration to design intelligent computational and robotics systems.

Several properties are of fundamental interest for researchers [57], [58] e.g.:

1) *Adaptability/Flexibility:* Capacity of a swarm to adapt to different environments.
2) *Robustness:*The ability of a swarm to recover its global functionality even if one individual agent is lost or has failures.
3) *Scalability:* The addition or removal of various swarm members does not affect the global interest of the group.
4) *Simple behaviour:* As social insects have limited cognitive capabilities, the modelling of their behaviour should be simple.

Within the previous context, swarm intelligence is defined as *"an attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies"* [57].

Swarm intelligence has been applied in robotics. A swarm robotics system usually describes a swarm of mobile robots (a large number of individuals) whose collective behaviour is based on or inspired by swarm intelligence algorithms [59]. Their control is distributed and decisions are mostly based on local interactions. Individual robots have sensing, processing, acting and communication capabilities [60]. They can share information with each other. Interactions of swarm robotic systems range from basic behaviours for sensing and acting to more elaborated and complex decision-making.

IV. OBJECTIVE AND METHOD

As a starting point to understand the state of the art of self-organized manufacturing applications at the shop-floor level, a systematic literature review was conducted. Thus, this section provides a review of related applications as well as trans-disciplinary ideas that will complement the objective of the paper.

Several works are analyzed under the umbrella of smart manufacturing and under the concept of product-driven manufacturing as described in Section II-C.

It is imperative to identify and characterize tendencies in the application of concepts of self-organization in smart manufacturing; as well as to understand the integration with current emerging technologies, their technological and industrial readiness, and potential future research directions. In this section, we conduct a systematic review, performed based on the following research questions (RQs).

- **RQ1:** What are the main mechanisms and design principles of self-organization in product-driven smart manufacturing applications?
- **RQ2:** What is the current status of self-organization in product-driven smart manufacturing?
- **RQ3:** What are the main challenges and future research directions?

These questions will guide hereafter the development of this review.

A. METHODOLOGY

The literature review followed a systematic approach. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [61] was used. This methodology was chosen as it provides predefined and well-established steps to conduct a transparent and complete reporting of research work.

B. OBJECTIVES

The objectives of this review are threefold and are aligned with the research questions presented above.

- In terms of *RQ1*: What are the main design principles of self-organization in product-driven smart manufacturing applications? The main interest is to understand (1) the mechanisms used and (2) to have an insight into implementation details as well as its characteristics.
- In terms of *RQ2*: What is the current status of self-organization in product-driven smart manufacturing? the main interest is to understand (1) the type of applications at the shop-floor level, (2) the shop-floor automation level of the application, (3) the emerging technologies applied, and (4) the readiness of implementations.
- Finally, the *RQ3* is related to understanding what are some of the challenges and potential future research directions.

C. STUDY IDENTIFICATION, SCREENING, AND ELIGIBILITY

A set of keywords has been chosen considering relevant terminology in the area. Core concepts reflected here are ''self-org'', ''product-driven'' and ''product-oriented''. Those are accompanied by industrial terminology i.e., ''manufact*'', ''industr*'', ''shop-floor''. Group 1 and Group 2 are linked with the operator *AND*, whereas internally they are linked by the operator *OR*. Table 2 presents the research string utilized for this review.

TABLE 1. String of key words adopted for the review.

Group 1	Group 2
"self-org*"	"manufact*"
"product-driven"	"industr*"
"product-oriented"	"shop-floor"

The research string was applied in the electronic databases *Web of Science (WOS)* and *Scopus* as they are well-known and large academic scientific repositories.

The identification of articles started with the identification of records using the specified keywords. Also, a set of 10 articles were manually added as it was believed by the authors that contributed to the main goal of the review.

The screening phase contemplates the identification of relevant articles after an exclusion criteria considering papers written just in the English language, journal publications, the exclusion of non-related fields (e.g., Environmental Sciences, Biology), and the consideration of articles published after 2010. As a result, 1650 articles were obtained. After removing duplicates, 377 articles were removed, leaving 1273 articles for further consideration. Papers in the eligibility phase are the ones that after a fast checking of the Title and Abstract presented some relevance considering the 3 RQs. Also at this phase, an emphasis on the selection was given to articles that were exploring solutions at the shop-floor level or that were following a product-driven approach. Thus, in the Eligibility phase, 173 articles were further considered. The last criteria included a more detailed screening of the content of the paper, going for instance for fast reading of the text. The articles that were conceptual or just discussions without concrete use case representation were removed (52 articles included). From this point, different clusters and ideas were collected aiming to answer RQs of this section. Fig.7 summarizes all steps of the systematic review.

D. RESULTS

A total of 52 related papers have been analyzed. A *Summary* of their contributions, *Potential future research*, Automation level (*AL*) and Readiness level (*TRL*) is presented in Table 5 in the Appendix of this work.

Sections V, VI, and VII will provide insight to answer the research questions presented in this section. Fig. 8 presents a histogram with the distribution of works and years considered in this review.

V. MECHANISMS AND DESIGN PRINCIPLES

This section presents a collection of mechanisms used by state-of-the-art works. Emphasis is given to methods already defined by software engineering and artificial life community e.g., Stigmergy, Immune-based systems, Holonic systems, and Generic Architectures as described by [16], [53], and [62].

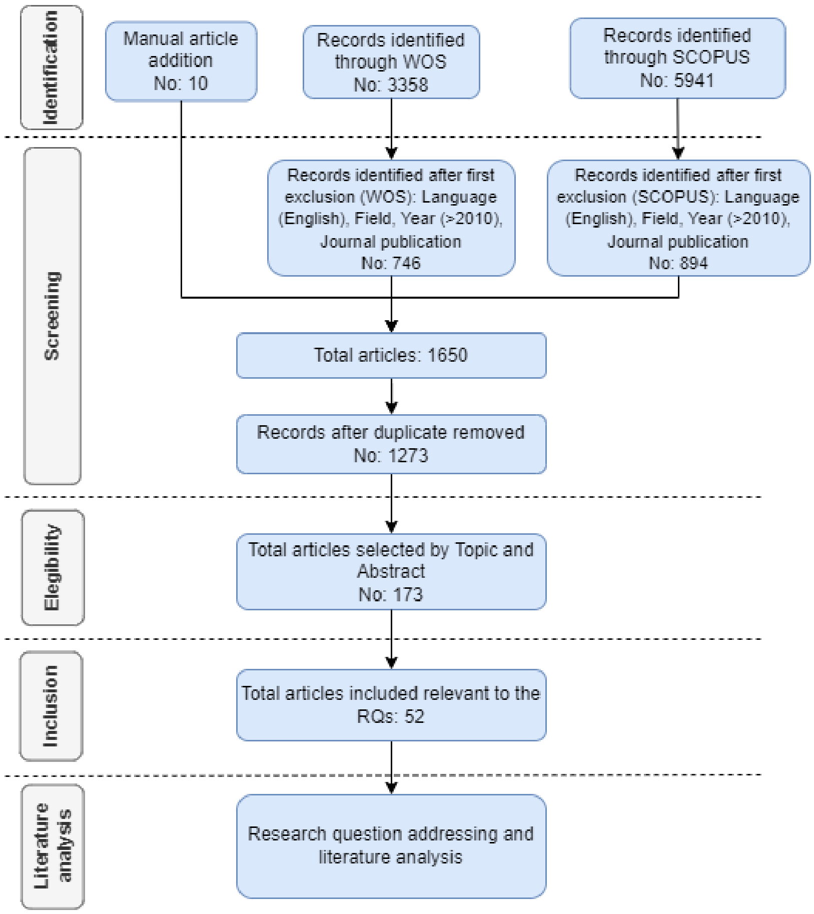


FIGURE 7. **Methodology followed in the literature review.**

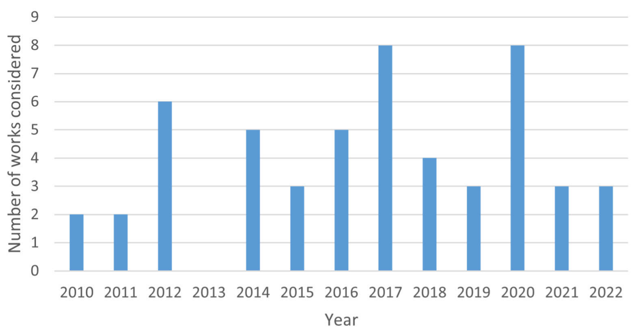


FIGURE 8. **Distribution of works over the years considered in the review.**

Fig. 9 presents a summary of some of the mechanisms used, general characteristics, and some lessons learned for its utilization.

A. MULTI-AGENT SYSTEMS

Most of the work on manufacturing self-organization includes the use of Multi-Agent Systems (MAS). Agents represent autonomous units with characteristics of autonomy, collaboration, reactivity, pro-activity, and learning [67]. Different actors, objects, and processes can be abstracted and represented as agents, e.g., product agent, resource agent, transport agent [68]. Those represent the digital part of the cyber-physical system. Usually, agents have local policies and negotiate (contract net protocol) and collaborate with others to fulfill a specific global behaviour e.g., manufacturing of a product [68]. Agents make use of semantic knowledge to understand each other (have a common language). Also, ontologies have been used with MAS to create reasoning mechanisms with the necessary knowledge, rules, policies general information to model agents' behaviour [66], [69].

Self-organization using agents has been implemented in different contexts and is supported by various technological enablers e.g., web services and cloud-based systems [70] (see next section). They can form coalitions [4], [68] and create aggregated and more complex functionalities. An example of coalitions as an aggregated group of agentified manufacturing components is the CoBASA architecture (Coalition Based Approach for Shop floor Agility) [4]. In CoBASA, agents form contracts that regulate the process of adaptability of the agentified modules on the shop-floor.

Agents instantiate intelligent products [71]. They negotiate the transportation and specific manufacturing tasks with available resources. This negotiation produces self-organized manufacturing. In extreme conditions, excessive negotiation of agents can cause bottlenecks or communication delays. Excessive complexity management and specification of

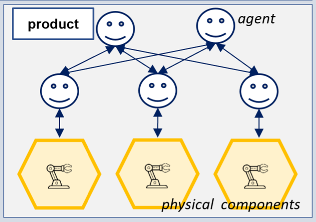
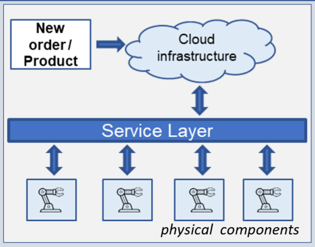
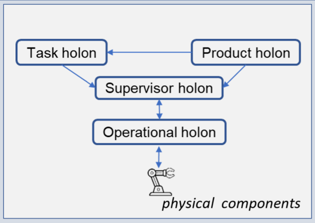
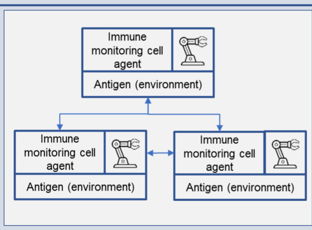
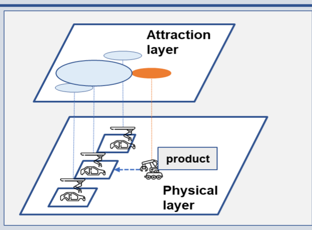
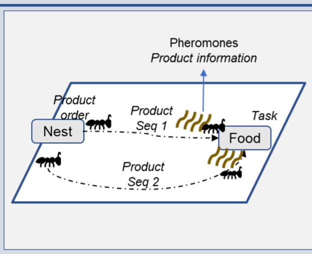
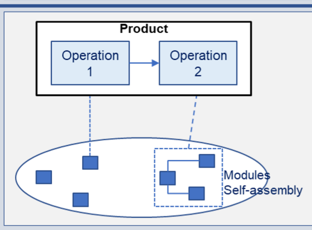
	Mechanism (example)	Characteristics	Lessons Learned in Manufacturing
Multi-Agent Systems		• Computational or digital units in an environment. • Agents have autonomous capabilities. • Rely on the use of interactions and negotiation to satisfy preferences.	• Are Used to instantiate holonic systems. • Abstract physical components i.e. machines, products, transportation equipment, and people. • Abstract digital components: orders, plan, coalitions, monitor, orchestration. • The product agent knows what it needs and can negotiate with manufacturing equipment according to specific requirements. • Autonomous decisión-making.
Cloud and Service-based Systems		• Services are object-oriented software that can be accessed via the internet via standardized message protocols.	• Services facilitate the consumption and production of functionalities or skills of manufacturing resources. • The orchestration and composition of services provide the self-organization of production. • Cloud infrastructures can be used to manage manufacturing services and as a mean to coordinate and control resources.
Holonic Systems		• Holon is something that is a whole and a part of a constitutive system. • A holarchy is a hierarchy of holons (which are self-regulating and autonomous entities) with dependency on higher holarchy levels. • Main focus in holonic systems is the description of social organizations and living organisms.	• Different hierarchical divisions of holons describe various levels in a manufacturing plant and their interdependence in a holarchy (planning, management, co-ordinational, operational, and physical levels). • Usually holons are instantiated using agent technology. • Examples of holons are task, product, supervisor, and operational. Each one has specific responsibilities and knowledge.
Artificial Immune System		• The Artificial immune system (AIS) is adaptive and distributed. A negative selection mechanism is used to protect against pathogens that can attack the body. • B-cells react against pathogens. They work according to a theory that describes how lymphocytes can learn, adapt and remember such pathogens (memory).	• Mechanisms based on negative selection can be used to protect the manufacturing system against malfunctions. • AIS can automatically and distributivity coordinate the production tasks by instantiating autonomous agents. • Autonomous monitoring, diagnosis, memory, and decision-making are the main properties driven by AIS in manufacturing.
Potential Fields and Firefly algorithm		• Artificial potential fields generate a source of luminescence to attract or repel certain objects. • Fireflies use flashing patterns to attract mating partners, and potential prey. It is also used to avoid predators. • Light intensity of the light source is inversely proportional to the square of the distance.	• Manufacturing resources can serve as a luminescence source and can attract objects indirectly (parts of subassemblies). • Each resource has different types of luminescence according to the service they can provide. • These mechanisms suggest an indirect material handling routing and task allocation of resources. • Some approaches use hierarchical structures on top of the luminescence approach to provide global optimization.
Stigmergy		• Ants forage randomly for food, starting from the nest. • Once food has been found, they come back to the nest while depositing pheromones. • Other ants are attracted to this pheromone trail, this causes an increase in the pheromone deposit. • After some time pheromones are evaporated and the attraction to the path is lost.	• Mobile agents can be used to represent ants (order agents) that are randomly looking for products or resources. They travel virtually. • The order of a product can represent the nest, the task by itself, the food source, and various product sequences (i.e., alternative paths for the ant). • Pheromones or ant agents can store information e.g., routing or historical data, process time, etc. • Pheromones are used as a communication medium between agents. They can be evaporated (eliminated).
Chemical Reaction Model		• Molecules in a solution react with each other according to specific rules. • When a rule is launched, molecules are replaced or modified until all rules are used and the system is stable. • Rules are launched simultaneously and distributely i.e., molecules self-assembly or self-organize.	• Molecules can represent various manufacturing modules providing simple or complex skills. • A set of rules represent a possible combination of modules. • When a new product is launched, the dynamic composition of manufacturing modules as well as composite skills is initiated.

FIGURE 9. State of the art of self-organizing mechanisms - *Some figures presented have been adapted from various works in the literature: Holonic Systems [16], Artificial Immune Systems [63], Firefly and Potential fields [64], Stigmergy [65], Chemical reaction model [66].

policies or rules can be a drawback for the agent-based implementations for highly dynamic shop-floors [55].

B. CLOUD AND SERVICE-BASED SYSTEMS

Services and cloud computing mechanisms provide the necessary infrastructure to generate production self-organization. This infrastructure supports centralized or supervisory control that coordinates or monitors industrial networks [72], [73] or even a network of interconnected agents. Cloud infrastructures can be also used to coordinate external actors in the production process. Agents can make use of web services. Services can encapsulate the functionality or skill that a manufacturing agent can provide [66], [74]. Services provide a greater level of interoperability. The functionalities of machines or manufacturing resources can be published on the network or cloud and be used when required [16], [70]. The challenge lies in the dynamic service orchestration and composition. Those are supported by various self-organizing methods.

C. HOLONIC SYSTEMS

The term holon was first proposed by A. Koestler in 1968 in the book "The ghost in the machine" [75] while studying the behaviour of biological and social systems. Koestler describes a holon as something that is a whole (autonomous entity) and part of a bigger whole (which is cooperative). Koestler also defines a holarchy as a hierarchy of interconnected holons which coordinate their parts, are dependent on their coordinators, and interact with the environment.

These ideas have been adopted by the manufacturing community (i.e., HMS [6]) to describe all manufacturing activities and their interrelation, considering holonic objects as distributed and autonomous manufacturing elements. Usually, they represent a physical asset and/or an abstract information unit.

A lot of current research [76] is based on the ideas of the PROSA (Reference architecture for holonic manufacturing systems) [6] and ADACOR (A holonic architecture for agile and adaptive manufacturing control) [5]. The acronym PROSA stands for product-resource-order-staff architectures [77]. In terms of production control, each holon can represent different aspects e.g., the production planning, the allocation of resources, or the management of the logistics.

New works under the umbrella of holonic manufacturing systems have potentiated these interactions and infrastructure concepts by proposing hybrid interactions [76] i.e., hierarchical or stationary state and heterarchical or transient state depending on the perturbation generated. Bio-inspiration is also considered e.g., stigmergy as a way of indirect communication between the holons [76]. Holons have been instantiated using Agent technology [78] or web services [79].

D. ARTIFICIAL IMMUNE SYSTEMS

The immune system plays an interesting role in the regulation and protection of the body in presence of infectious agents or antigens which induce an immune response (protection in the body) [80].

The metaphor of the immune system consists of the adaptation of the mechanism to protect invaders that can affect their normal health conditions. The self-organization of the immune system is the result of high-distributed entities, i.e., antibodies that without a centralized control can cooperate, adapt and learn from previous infections (memory) [81]. A basic idea in the context of software engineering considers the request of an event as an antigen (or stimulation) and a response or answer as antibodies. Given the highly distributed design, the immune system can be used to decompose complex decision-making [81]. This organizational design makes it ideal the utilization of multi-agent systems as technological enablers to design immune-based systems.

In [63], the authors propose an agent-based immune monitoring model to create adaptability during the control of a manufacturing system. An immune monitoring cell is proposed. Its architectural design contemplates six agents that mimic the immune response e.g., decision-making, diagnosis, recognition, perception, memory, and state monitoring. Its behaviour is dependent on the condition of the antigen (environmental status). The immune monitoring cell can exchange information with others and thus generate a distributed immune control.

E. POTENTIAL FIELDS

The artificial potential field concept has been presented by [82] for applications like path planning and obstacle avoidance in robotics. The metaphor consists of generating fields that can indirectly guide the movement of an entity, repelling it from obstacles or attracting it to specific targets [83]. From a social interaction and distributed control perspective, each robot can sense a resultant potential field generated from different components and act under the influence of the generated force [84].

Artificial potential fields have been used in manufacturing shop-floor operations, specifically during material handling or intralogistics. The route of a product can be dynamically built based on the interaction of various attraction fields.

In [85] a potential field approach is proposed based on fixed and mobile resources. Products are mobile and are attracted to resources that can provide one or more services. Products can sense the resource workload and the services they provide. The attraction is based on the quality of the resource. This approach is said to have an easier design and engineering process and an easy-to-manage reactive behaviour [86]. Due to the inherent reactivity of potential fields, this approach has been combined with a switching mechanism to provide also global optimization (in terms of scheduling) when required [87]. In [88], a potential field approach is utilized along with energy consumption considerations as a decision criterion to activate and deactivate the fields of the resources. A switching mechanism based on energy optimization allows this transition.

F. FIREFLY ALGORITHM

The firefly algorithm developed by Xin-She Yang in 2007 [89] has been used as a metaheuristic optimization solution. The algorithm is based on two key ideas: the light intensity that each firefly emits and the level of attractiveness between two fireflies. The flashing patterns are mainly used to attract mating partners, and potential preys as a warning mechanism [89]. The light intensity of the light source is inversely proportional to the square of the distance. The previous formulation is used as the objective function in optimization problems.

As a result of a PhD research, a bio-inspired self-organized method for a manufacturing shop-floor was developed [64], [90]. It has been instantiated using the firefly algorithm. The approach has some similarities to the concept of attractiveness with the potential field model. In this concept female firefights are attracted to male ones. The analogy considers male objects as static entities which generate a mechanism based on attraction based on the skill or functionality each resource has. Female entities consider a transport element and the part. The architecture is said to be highly decoupled and with a high level of reactivity.

G. STIGMERGY

The concept of stigmergy was proposed by Grasse in 1959. The mechanism suggests indirect coordination as a result of the change of environmental variables (i.e., pheromones). In ant colonies, when ants are looking for food sources, foraging ants emit a pheromone trail on their way home, so that other ants can follow the food path (positive reinforcement). Coordination based on stigmergy offers advantages such as the recruitment of other foragers looking for sources of food, and the selection of the shortest path between the food source and the nest of the colony [91]. If the reinforcement stops, after some time the pheromone trails evaporate. As a result, less efficient paths or empty sources of food are not reinforced until they disappear.

Stigmergy provides an efficient way to achieve coordination and self-organization. There is no need to plan, communicate (directly), impose sequences, or for agents to be centrally controlled [92]. Simple rules lead to robust collective behaviours [91].

Several applications for self-organizing control have been proposed in the last years that apply stigmergy or ant-based algorithms e.g., for dynamic routing and task allocation [93].

In [94], the analogy of food-foraging ants is considered. Here, the concept of an ant agent is conceived as referring to an agent that has the capacity of releasing pheromones (i.e., production data). Pheromones are shared through a cooperative environment in form of a message mediator that influences agent decision-making. It is suggested that ant agents can travel virtually to disseminate information (using a service bus) and continuously update shop-floor information e.g., the capabilities of agents or production data.

In [65] the analogy considers the launching of a product as the representation of the nest, the task to be performed as the food source, and the various possible sequences to manufacture the product as the various alternative paths for the ant to go from the nest to the food source. Pheromones or ant agents can store information e.g., routing or historical data, process time, etc. Pheromones can be used as a communication mediator. Similarly in [95], the concept of digital pheromone is used as a form of indirect communication (a short message). Those are stored in a pheromone container. Examples of pheromones include feasibility pheromones that present a list of services that a specific resource provides or reservation pheromone that is used to reserve a specific path for the passage of an AGV.

In [76] the concept of pheromones is considered to establish influence in the re-organization of an holonic architecture. The representation of stigmergy is based on how far it can be dissipated (having a range of influence in the holonic system).

H. CHEMICAL REACTION MODEL

In 1986 the Gamma chemical reaction model was introduced [96]. It was developed taking into account a chemical reaction metaphor. It can be considered as a different approach to sequential programming. In this case, a program is modeled as *(Reaction, Condition and an Action)*. There is a continuous execution of the programs in the reaction condition, replacing them with the product of the action. This process continues until no more reactions can be executed [97].

In the context of a self-organizing assembly process, this methodology has been applied in [66], [74], and [97]. The self-assembly of molecules is used as a metaphor to generate a composition or aggregation of manufacturing modules. Without a central control and considering various rules/policies two or more modules can be aggregated to each other to generate coalitions and therefore more complex tasks, functionalities, and skills. Such aggregation is dynamically done and it is launched after the execution of a new production order.

I. FUNCTIONAL MODELLING

Complementary to self-organizing approaches, we also consider works that show adaptability on the shop-floor. Even though they are not strictly under the umbrella of self-organization, they are described here because they provide adaptability and autonomy to production activities. Those can be labeled as functional modeling. *A functional model shows how the general goal of a system is achieved by the realization of sub-goals via the sub-functions in the system* [98]. This requires the decomposition of the activities of a process as well as the required services for execution. In other words generating the decision design principles (e.g., rules or policies) between the system requirements and the components specification [98]. This process is also transversal to all self-organizing mechanisms as all of them require an analysis of reasoning mechanisms and structural decomposition.

TABLE 2. Mechanisms used in the works analyzed.

Mechanism	Reference
Multi-Agent Systems	[66], [68]–[73], [76], [95], [101]–[107]
Cloud and service based	[69], [69], [79], [101], [108]
Stigmergy	[65], [76], [94], [95], [104], [109]–[112]
Functional modelling	[99], [100], [112]–[117]
Holonic systems	[76], [78], [79], [111], [111], [118]–[120]
Artificial Potential Fields	[85]–[87], [121]
Chemical Reaction model	[66], [97]
Artificial Immune System	[63]
Firefly Algorithms	[90]

Some examples include the definition of a function behaviour structure mechanism as described by Sanderson et al [99]. A function represents the product to be assembled and its requirements, the behaviour is the set of tasks required to assemble it, and the structure defines the components of the shop-floor and its interconnection.

In [100] production self-organization utilizes the analytical target cascading method (ATC). With this method, system requirements can be translated into single-component problems. Different nodes of the ATC model are used to implement collaboration (hierarchy-based). In this work, an autonomous matching between the product requirement and services available is formed.

Knowledge representation and reasoning are imperative for process self-organization. In some cases, they can provide tools for autonomous decision making as in the case of [69] where agents (products and machining) and knowledge reasoning from ontologies are provided.

This process can be dependent on the adaptation of the specific rule/policy considered in the context of the problem. A summary of the distribution of works considering the type of mechanism/design principle used is shown in Fig. 10. We did not include functional modeling in the description of Fig. 10 due to the high variety of possibilities for their representation.

VI. CURRENT STATUS

The current section presents the results in terms of readiness level, automation level, context, type of application and various technological enablers utilized in the works analyzed.

A. READINESS LEVEL

Considering the level of implementation, the majority of works (52%) are still in a conceptual or simulation stage, 38% have a partial demonstration at a laboratory level, and around 10% have an industrial implementation. Probably a big roadblock for practical implementations in the last decades has been the lack of computational power and infrastructure development. The same has slowed down the development of the industrial implementation of CPPS, but that now is tending to increase thanks to the different European and world manufacturing strategies.

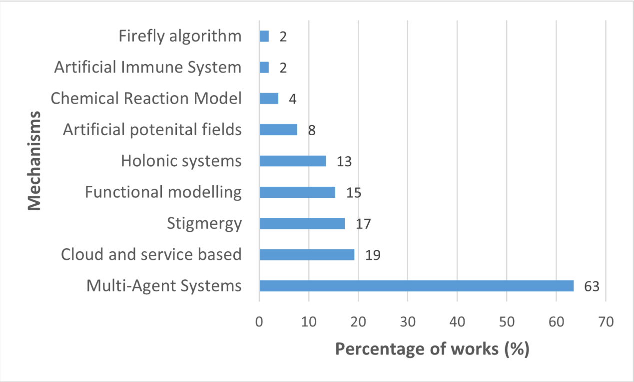


FIGURE 10. Distribution and percentage of mechanisms used in the works analyzed.

A lot of current work has been done in the development of reference architectures. Future research should start showcasing the industrial potential of these works attracting in this way industrial stakeholders that can understand the real potential benefits that self-organizing systems have. Fig. 11 shows the summary of the readiness level of the literature analyzed.

B. AUTOMATION LEVEL

Considering the automation level as detailed in Section II-D, none of the works consider levels 0 and 1, probably because these levels have a very reduced level of flexibility which is required for manufacturing self-organization.

The vast majority of works and their applications are around levels 2 and 3. Most of the use cases consider assembly lines with fixed conveyor systems. Even if they have a degree of flexibility, they are usually restricted to the pre-defined layout they have.

Less works consider mobility with applications using AGVs or mobile robots, i.e., [111] and in some cases, they are still in a very conceptual implementation stage [90]. In [107], it is presented an approach based on multi-agent negotiation that showcases production self-organization in a smart workshop, AGVs are in charge of the transportation of material from the warehouse to production cells.

Fig. 12 shows the summary of the level of automation of the works considered. Some works have been categorized into more than one cluster of automation as it was generally hard to categorize them in a specific one.

C. CONTEXT AND TYPE OF APPLICATION

Regarding the types of applications, the confluence of five differentiating areas allows us to understand the general focus of current research. This list is not strict and some works may fall into various contexts. However, they can be used as a baseline to understand where self-organizing approaches have a strong focus. A summary of the classification of the works and a frequency diagram can be seen in Table 3 and Fig. 13 respectively. Some works have been clustered in more than one group of applications.

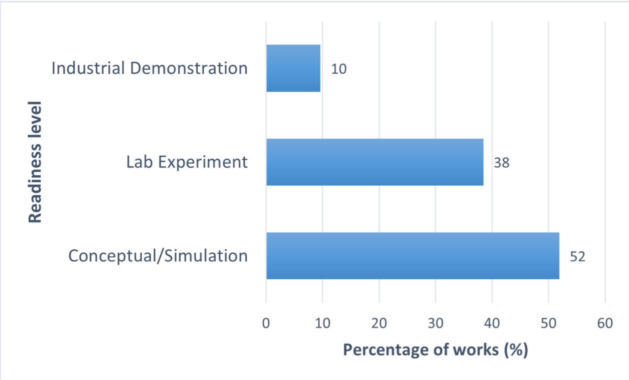


FIGURE 11. Distribution and percentage of readiness level of the works analyzed.

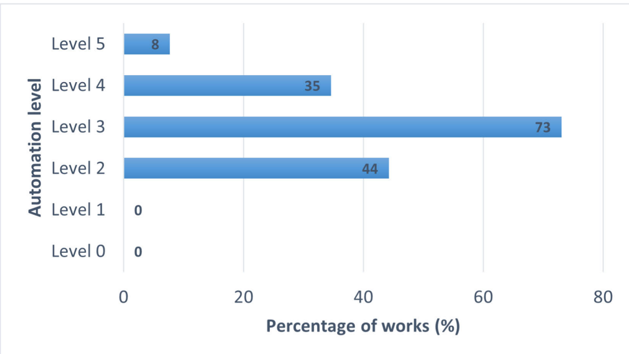


FIGURE 12. Distribution and percentage of the automation level of the works analyzed.

- **Generic/Manufacturing control**: Usually presented as reference architectures. Those have a high-level abstraction of the operations and resources that are part of the shop-floor, and provide a series of constructs that allow the monitoring, diagnosis, and control of a manufacturing process. Normally, they are not associated with a specific activity. Self-organization consists of a series of interactions and negotiations between each of those constitutive entities. In [76] a holonic-based architecture presents various constructs to generate reconfigurability and self-organization.
- **Planning/Scheduling/Task allocation**: Usually associated with optimization activities considering tasks to be executed (operations, jobs, manufacturing parts), number and type of resources available, manufacturing constraints and performance indicators (e.g., time, quality).
- **Routing/Intralogistics/Material handling**: The focus of these works is at the shop-floor level. Normally they consider the product or parts of the product, tools, and resources as elements that can move. Self-organization considers the necessary interaction that allows the transportation or movement (manually, with AGVs, with cranes, and conveyors) of goods to specific places (e.g., for executing an operation). A material handling architecture based on MAS is presented in [105].

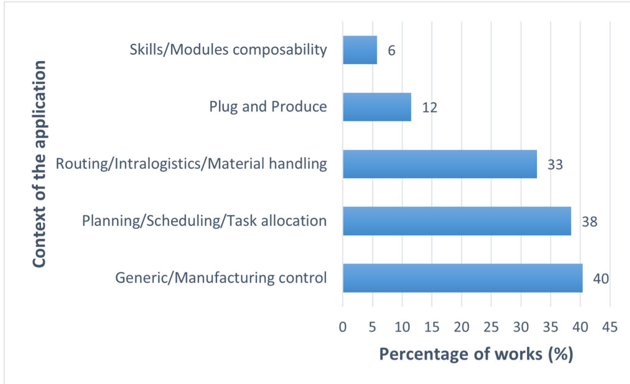


FIGURE 13. Distribution and percentage of the context of the application of the works analyzed.

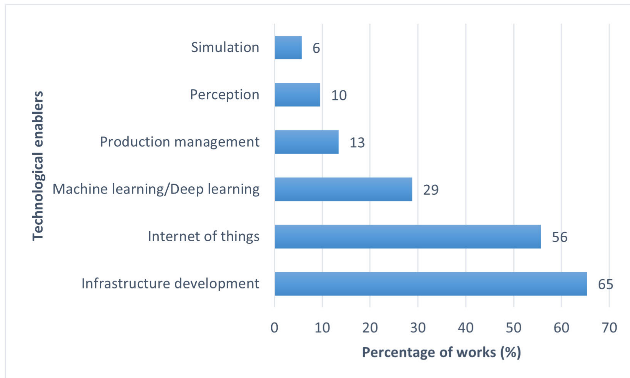


FIGURE 14. Distribution and percentage of the technological enablers of the works analyzed.

TABLE 3. Context of the application of the works analyzed.

Context of the application	Reference
Generic/Manufacturing Control	[63], [65], [69], [70], [72], [73], [76], [79], [94], [97], [103], [104], [104], [108], [110], [114], [117]–[119], [122], [122]–[125]
Planning/Scheduling/Task allocation	[69], [70], [78], [85], [87], [99], [102], [107], [109], [112], [113], [115], [120], [121], [123], [126]–[130]
Routing/Intralogistics/Material Handling	[71]–[73], [78], [85], [86], [90], [95], [99], [100], [103], [105], [106], [111], [129]
Plug and Produce	[66], [68], [90], [97], [106], [116]
Skills/Modules composability	[66], [68], [97]

- **Plug and Produce:** At the shop floor level, the hardware and software (i.e., mechatronic component) of a production resource can be added without extra engineering effort and without modification of hardware. This brings a lot of scalability and robustness to the system. Self-organization occurs when new resources are connected, initiated, and automatically integrated into the system. The industrial demonstrator of the IDEAs (European project) [68] is an example of a plug-and-produce system. The control software is in charge of coordinating and configuring each of the modules.

- **Skills/Modules composability:** When there is a certain level of granularity in the system, elementary elements may have specific skills or functionalities. The dynamic association or composition of such skills (self-assembly) represents another way of self-organization. e.g., in the work presented in [66], the self-organization occurs when a gripper (which individual skills are drag and drop), and a robotic axis (individual skill is moving in a 3d plane) are dynamically arranged (self-organized) to perform the task of pick and place.

D. TECHNOLOGICAL ENABLERS

In terms of technological enablers, most of the research (at least 65% of the works in this review) discusses technologies related to infrastructure development. This means basic technologies to make the system functional and to establish a minimum level of communication with its constituent elements. Clear examples represent MAS, cloud computing, and web services. This goes in line with the current trend in digitalization along with IoT and IIOT development and the benefits that connecting all the resources on the internet may have. Interesting to mention is the utilization of the FIPA agent communication language.

Another technology widely used is represented by the internet of things devices (at least 56%). The inclusion of sensors and actuators but especially microcomputers i.e., raspberry pis has been extended in the last years aiming to give a certain level of computation and intelligence to the shop-floor elements e.g., RFID technology (to store information on the status of the product). Sensors allow also the monitoring of variables i.e., energy consumption. Such information can be used for optimization or self-organization activities.

To a lesser extent (around 29% of the works), consider machine learning and deep learning algorithms. This includes also data analytics and big data. Data extraction, storage, and processing in some hierarchical systems can be used to improve process self-organization [103]. Reinforcement learning has been also used as an optimization mechanism in scheduling problems.

Production management technologies i.e., Enterprise resource planning (ERP), Manufacturing Execution Systems (MES), or Supervisory control and data acquisition (SCADA) systems do not have a wide scope of consideration (around 13%). This makes sense as the main focus of the research was on shop-floor operations. However, its consideration on hierarchical self-organizing systems is imperative in industrial applications as they provide the means of integration with the business area of a company.

As the number of AI technologies has not been widely extended, the same causes an even reduced number of works that consider perception detailed methodologies (around 10% of the works). This means how robots, machines, and in general manufacturing resources can identify their environment and generate valuable cognitive information that can be used to provide self-awareness in manufacturing systems. Most of the works have a limited consideration of measurement of process variables i.e., temperature, vibration, acoustic, and fewer works consider camera-based systems for object tracking or Lidar sensors. In general, the perception of mobile robots is not widely considered. Probably the high focus on infrastructure development is the cause of such reduced integral research. Less works have used Robot Operating System (ROS) for control and simulation of robotic operations. Interesting will be to have simulation in self-organization applications as a way to understand possible unexpected behaviours based on the emergence occurrence.

TABLE 4. Type and area of interest of the technological enablers of the works analyzed.

Type	Area of interest	Reference
Infrastructure development	Cloud computing, Edge computing, Multi-agent Systems, ROS, LAN, Sockets, Service bus	[63], [66], [68]–[73], [76], [78], [79], [94], [95], [100], [101], [103]–[105], [107]–[110], [114], [122], [126], [128]–[131]
Internet of things	RFID, Sensors, Wifi, Raspberry pi, MQTT, Bluetooth, infrared communication	[68], [70]–[73], [78], [85], [87], [94], [100], [101], [103], [104], [106], [107], [110], [111], [113], [117], [118], [122], [123], [125], [126], [130], [131]
Machine learning	Big data, Natural language processing, Deep Reinforcement Learning, Q learning, k-nearest neighbors	[72], [73], [100], [101], [103], [107], [114], [116], [119], [122], [130]
Production management	ERP, MES, SCADA	[69], [101], [104], [117]
Perception	Vision (e.g., camera tracking), Acoustic, Temperature, Vibration	[71], [85], [100], [121], [123]
Simulation	ROS/Gazebo	[108], [126]

VII. CHALLENGES AND IMPLICATIONS FOR FUTURE RESEARCH

Results from the review carried out reveal several lines of research under the scope of manufacturing self-organization at the shop-floor level. Those summarize the main aspects presented in Table 5 in the appendix at the end of this work. Fig. 15 presents an overview of the percentage of challenges and potential future research presented.

A. COMPLEXITY AND DYNAMICITY OF SHOP-FLOORS

Widely mentioned is the increasing complexity and dinamicity of both shop-floor structures and the high level of product individualization. In the first case, the assumption of static layouts with limited topological changes and reduced mobility certainly reduces the complexity of self-organization process modeling but also can limit the capacity of adaptation of the shop-floor. Future use cases should have an applicability that goes beyond Level 4 and reach Level 5 of automation as presented in Section VI-B in Fig. 2 and why not adopt future and more concrete visions of industry.

An interesting example to consider is the Matrix production concept proposed by KUKA and several commercial mobile manipulation systems already in the market [132]. In the second case, the assumption of use cases that consider not just a single product or a single family of products should be avoided. Companies should be prepared to drastically change their production business if they want to survive. During the Covid pandemic, various companies had to change their core business models e.g., from automotive products to health care (e.g., ventilators) [133]. This certainly takes out some level of determinism that approaches under the scope of manufacturing self-organization generally have. This argument is highlighted by some research in the field where the concept of mobility is an important focus, i.e., [111].

B. PERCEPTION/COGNITIVE/LEARNING IN SELF-ORGANIZED APPLICATIONS

A second point of consideration is the use of AI, learning techniques, and sensory perception systems for individual manufacturing resources. This has been generally avoided as concluded in the previous section. The reason is probably that a lot of current research is mostly centered on the infrastructure development of CPPS. However, from a more individual/resource point of view, the integration of such research can enhance the self-awareness of individual elements and at the same time improve the self-organization policies, which will take into account not just internal states but also their interdependence with the environment and with other elements. This clearly shows the need for integration with Robotics, Mechatronics, and mobile robotic systems and the integration of sensors (IIoT) in both logistics and production as well as real-time and low-level computation capabilities (edge computing, microcomputers). From a low-level perspective, and in the context of mobile robotics some works have used camera-based tracking systems e.g., for task allocation of resources [121]. Under the same context, interesting could be the concept of an embodiment for self-organized robotics [50]. This implies embodying a physical system with sensors, actuators, and a neural model that can represent its physical interaction with the environment. Also, as we are heading towards an increased level of mobility, interesting is the consideration of ideas from the vehicular autonomous navigation point of view i.e., behavioral reflex-based navigation which does not necessarily require a centralized planning phase for navigation purposes [134]. Autonomous vehicles are guided basically by a layer of perception and intelligent decision-making. Machine learning and deep learning techniques can complement the perception mechanisms [135] and therefore in a manufacturing context self-organization may occur in transport entities.

C. DECENTRALIZATION, COMPLEXITY THEORY AND SELF-ORGANIZATION-BASED CONCEPTS

Many authors mention the need of having decentralized systems without a central point of coordination (due to the fact that it can be considered also a central point of failure) that can adapt and react faster. This goes hand in hand also with the introduction of self-organization with its inherent characteristics (e.g., emerging behaviour, complexity, complex adaptive systems) as mentioned for example by [49], [51], [53], and [136] (see the section III) of this work. We believe the study and application of ideas of these ''non-conventional'' fields can generate a higher level of autonomy as done at some point with established paradigms i.e., EPS [3], [4], HMS [5], [6] and BMS [7]. Indeed, many works do not introduce or explore these concepts when they talk about self-organized manufacturing. This can result in the design of traditional centralized approaches.

D. BIOLOGICALISATION, SWARM INTELLIGENCE AND MORE CREATIVE SOLUTIONS

With the previous context in mind and considering also the need of having more ''creative solutions'' for self-organized manufacturing systems as suggested by [74], it is natural the consideration of Biologicalisation [56], collective behaviour and swarm intelligence [137], [138]. Collective biological systems offer characteristics that are needed to fulfil the concept of Industry 4.0 and a high level of individualization i.e., scalability, robustness, adaptability, flexibility and simple behaviours design [57], [58]. Not so many works in the literature have been focused on this type of solution (i.e., see results in section V), which is why it is imperative to potentiate the current ones i.e., make them less abstract, create necessary information modelling for their implementation and make tangible experiments or industrial demonstrators (additional challenges and implication for future research). The inclusion of technical enablers will push forward this type of solutions and will create awareness for industrial practitioners to understand their potential benefits. Important principles have been already established for bio-inspired manufacturing solutions [64], [90], [111]. Interesting will be to potentiate them with current technological enablers and showcase them with modern industrial vision. New principles can be derived from new sources of inspiration of natural-inspired principles. An interesting guideline for this can be found in [139] in the work: ''Distributed systems – from natural to engineered: three phases of inspiration by nature''. The main steps to design natural systems considered are the understanding of the natural system, the lab experimentation with such understanding and finally, the implementation with the consideration of industrial constraints.

E. TECHNOLOGICAL ENABLERS AND REAL-TIME COMPUTING POWER

While a lot of research work is showing the application of technological enablers (see section VI-D), especially in terms of infrastructure development and IoT implementation, fewer works are considering complementary aspects that could potentiate their development. Some examples are machine learning techniques to generate cognitive learning agents that can learn new policies while self-organizing. This could be used to create smart autonomous navigation systems that can find their way to take tools, materials and specific resources. Interesting will be also the inclusion of reinforcement learning methods in a self-organized simulation environment, where the policies can be learned by different simulation iterations and just after that applied to a real manufacturing plant. This could drastically reduce the design effort for self-management and coordination in this type of applications. Future potential research when focusing on higher levels of mobility may include coordination not just based on digital negotiation but on smart perception. Thus, a combination of sensors, and smart and fast edge computing devices need to be considered.

F. SELF-HEALING, SELF-MONITORING, AND INTEGRATION WITH OTHER SELF-CAPABILITIES

It is important to mention the integration of self-organizing manufacturing methodologies with other self-x capabilities [140] to build integral solutions. This means the incorporation of monitoring, diagnosing, and even healing mechanisms into these approaches with the aim of finding a wider scope of applicability. There are several examples in biological systems where this type of ideas can take inspiration from e.g., the artificial immune system [141] or with the concept of reciprocal altruism applied in a society of vampire bats i.e., bats who have eaten can recognize and help hungry ones [142]. An example of the applicability of this idea could be the sharing of energy or spare parts between AGVs or robots when one of them requires it.

Other interesting considerations could be the application of optimization techniques for collaborative self-organization by means of digital twins as explained in [143]. Here, various key performance indicators and a production plant can be used to generate different scenarios for shop floor reconfiguration and self-organization.

G. HUMAN IN THE LOOP FOR SELF-ORGANIZED MANUFACTURING

Although the purpose of having self-organized manufacturing applications is the design of autonomous manufacturing systems, we should highlight recent efforts under initiatives like industry 5.0 that suggest the reintroduction of the human operator into the center of the process [144]. Thus, several remarks need to be reconsidered under this context i.e., What would be the role of the human during this type of ''autonomous operations''? How to model this mutual operator-resource relationship? What ethical issues should be considered? and how can we create mutual collaboration? i.e., How can we take advantage of the experiences of the operator (decisions) to enhance the autonomous process? Under the umbrella of self-organized manufacturing, this has been generally elusive; however, new approaches should integrate such ideas. Human holons under the context of HMS

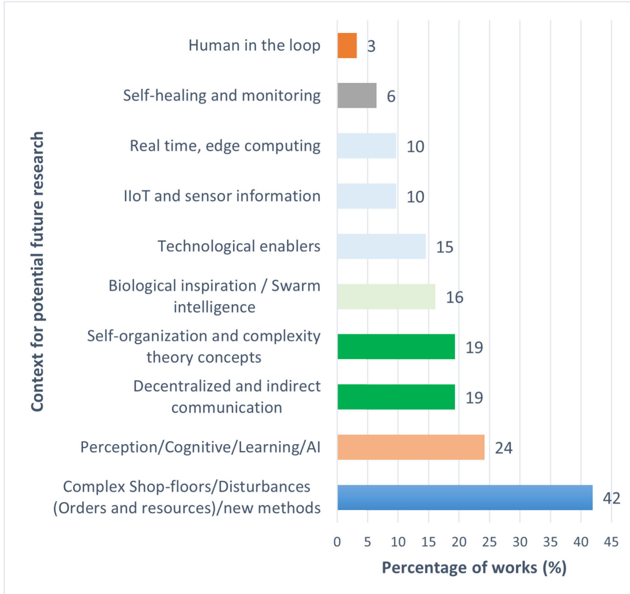


FIGURE 15. Distribution and percentage of the potential future research mentioned in the works analyzed. The cluster in dark green is described in section VII-C. The cluster in light blue is described in section VII-E.

are an interesting example [18]. Those have to interact with other holons, negotiate, and at the same time understand that humans have to be aware of the context of the process. Also, the industrial system should realize that the decisions of the operator are not perfect and mechanisms should be developed to recognize and provide the necessary feedback.

VIII. OUTLOOK

The results of this work are used in this section to provide an outlook of important considerations when designing a self-organized manufacturing solution. This is dived into four generic stages from the conception of the solution to its application.

A. CONCEPTION

Drivers of these solutions are aligned with the generation of revenue, added value, or change in business models of a company/shop-floor. Self-organized manufacturing can ensure sustainability by means of the re-usability of resources/machines and in general assets that require a certain level of reconfiguration which can be replaced by smart task-specific resources. Smart infrastructures can ensure higher levels of automation not just on the shop-floor, but also in the monitoring, planning, and supervision layers. This ensures agility of the process, reducing the time to market and in many cases optimizing process variables (e.g., energy) contributing also to reducing manufacturing environmental impact. There is a wide scope of applications to consider depending on the perspective of the process, resources, and technologies available. From a high-level manufacturing control perspective, planning and scheduling where process variables can be optimized and optimally coordinated to a

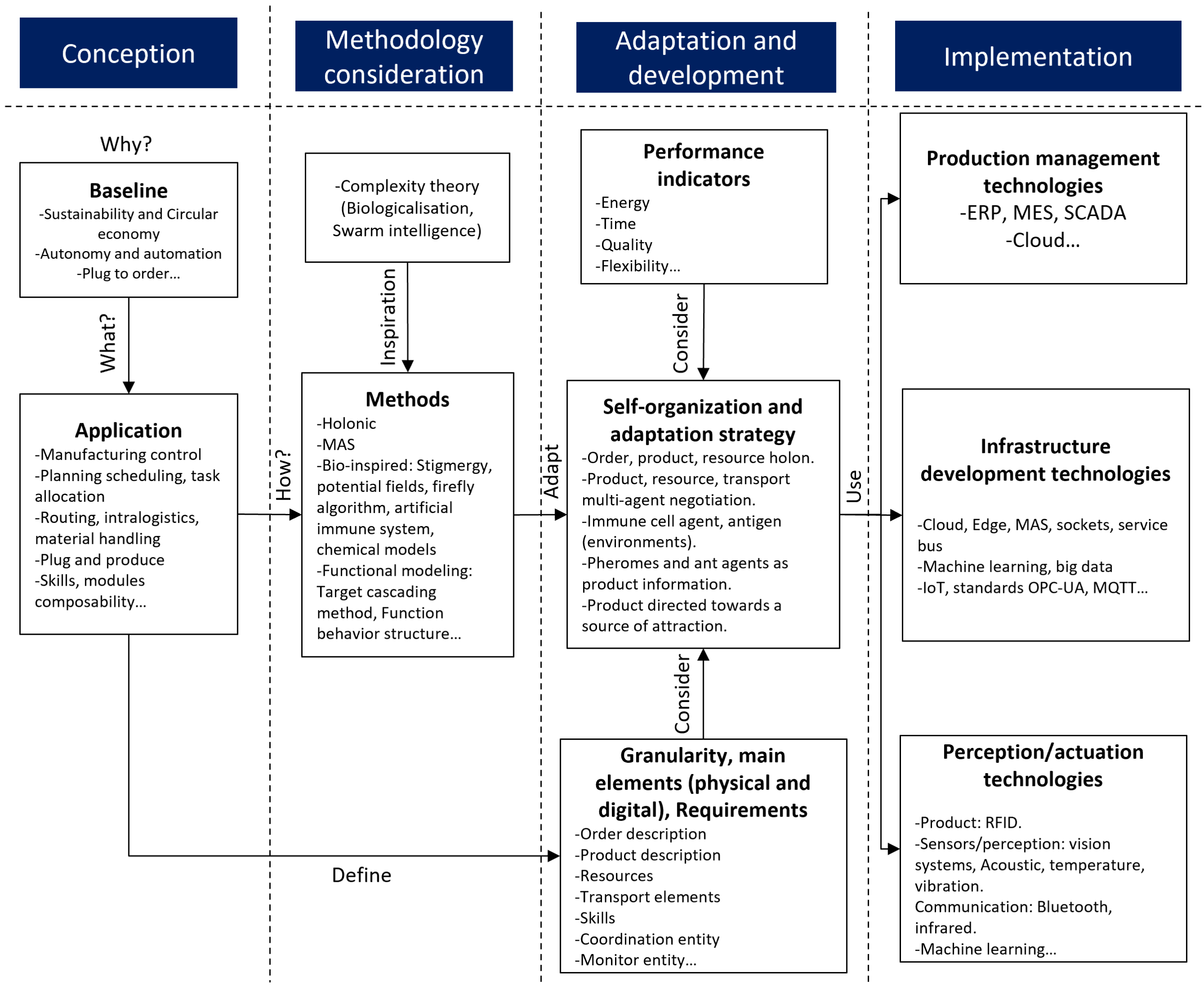


FIGURE 16. Outlook of important considerations for self-organized smart manufacturing solutions.

low-level one (shop-floor), where smart process modules can form coalitions, or products can find their way intelligently towards a specific resource.

B. METHODOLOGY CONSIDERATION

From an understating of the task, a methodology aligned with its objectives should be generated. The chosen methodology can take into account some of the ones revised in this review and will definitely depend on the main business objectives and technologies available, e.g., a more traditional supervision and monitoring control approach can be based on HMS supported by MAS. Solutions that are based on higher levels of flexibility or that have mobility included can consider less traditional approaches e.g., some that may require physical perception (firefly algorithm or potential fields). A more detailed analysis and comparison (out of the scope of this work) will definitely be necessary to evaluate the possible method used.

C. ADAPTATION AND DEVELOPMENT

This stage suggests the formalization and adaptation of a strategy combining the chosen mechanism with a granularity definition, requirements specification, and desired performance indicators. The granularity definition takes into account which actors have relevance in the targeted application. Some examples are the order, the product, resources, transport elements, tools, an understating of how they are interrelated, and a set of requirements and assumptions necessary to showcase the main objective of the application considered. The adaptation of the specific strategy will take into account those elements to generate analogies or design patterns that satisfy such requirements. Besides the well-known design patterns of multi-agent manufacturing systems, less traditional works (in a bio-inspired context) like [64] do this job considering male fireflies as active resources and female fireflies as passive products that can move and are attracted to a specific resource.

D. IMPLEMENTATION

In the final stage, the implementation is carried out considering the strategy developed based on the application of specific technological enablers. Three main aspects are considered here. First, the necessary infrastructure to coordinate, communicate, and integrate the physical assets, including also a supervisor and monitoring entities (could be digital). Second, the integration of perception and actuating technologies to embed a smart physical capability in low-level resources, smart controllers, and manufacturing products. Finally, important is to consider the inclusion of supervisory and enterprise technologies e.g., ERP, MES, and SCADA systems. This could be included in a cloud-based environment to increase the scalability and interoperability of the solution.

Fig. 16 presents a summary of the outlook and important considerations of the work to generate a self-organized smart manufacturing solution.

Future research work on the self-organization of smart manufacturing can consider the guidelines presented in this section to design and implement new solutions.

IX. LIMITATIONS

The exclusion criteria used while doing this literature review may have left some relevant publications out of the analysis. This is true due to the high variability of buzzwords generated under the context of smart manufacturing and self-organizing applications. However, the number of works considered as well as its dispersion during 12 years time are a good representative sample of the research carried out. A way to prevent this limitation was the inclusion of 10 works that were found after an empirical research in the field. Another detail to consider is the exclusion of articles that were not in the English language, this could have left some relevant publications out of the cluster, too.

Also, due to the limited research to characterize self-organized smart manufacturing systems, several sections represent the result of an analysis of empirical evidence found in the literature e.g., technological enablers or context of the applications. They provide a holistic view of the field as well as core representative elements and clusters. The next stages of the work should head towards a conceptual framework development that can deal with specific manufacturing applications overcoming also industrial current roadblocks.

Finally, as this field of research tends to be highly volatile, especially in regards to technological enablers, strategies to generate autonomy, and taking into account the conceptual level of implementation of the works presented, it is possible that the results shown in the work can change in the future.

X. SUMMARY AND CONCLUSION

The current work presents a systematic review of smart manufacturing and more specifically of self-organization in smart manufacturing applications considering two important scientific databases i.e., Web of Science and Scopus. The main objective of the work was threefold. First, to provide a brief overview of related concepts and background in the field (see *Section II* and *Section III*). Second, to characterize the current landscape of research through a PRISMA analysis based on three research questions, and finally to present an outlook considering the results of the work.

The description of mechanisms and main design principles as an answer to *RQ1* has been identified in *Section V*, resulting in eight identified methodologies. Multi-agent systems have been widely considered in the literature while biological-inspired mechanisms have had less attention (i.e., artificial immune systems, firefly algorithm, stigmergy, chemical abstract machines). Other mechanisms popularized consider the use of hierarchies based on holonic systems. Functional modeling techniques complement the development of these frameworks by providing goals and subgoals that require the decomposition of manufacturing activities and the design of rules that design such behaviour.

The current status as an answer to *RQ2* is presented in *Section VI* providing details on readiness level, automation level, the context of the application, and the various technological enablers used. Generally speaking, most of the works (approx. 52%) are still in a conceptual/simulation stage, others have a lab experiment demonstrator (approx. 38%) and fewer have a demonstration in an industrial setting (10%). Flexible lines with fixed conveyor systems are presented as use cases in most of the works, giving less attention to material handling using AGVs for example. Also, several works are focused on the development of manufacturing control architectures and often they do not go towards specifications on how to achieve pluggability at the shop-floor level and even less often go towards the composability of manufacturing modules. Most of the papers consider technologies in terms of infrastructure development (approx. 52%) (e.g., MAS, cloud computing, web services) and IoT (e.g., RFID, sensors). Fewer works focus on the perception and management of intelligence at the low level, simulation, or the inclusion of production management technologies.

A discussion of the challenges and the potential future research directions as an answer to *RQ3* is presented in *Section VII*. From the literature analyzed, seven clusters have been considered in this section highlighting the complexity and dynamicity of shop-floors in terms of mobility of resources, the application of biologicalisation, and more creative solutions to deal with current design challenges, the embodiment of learning, cognitive and perceptive techniques in low-level resources and the introduction of the operator as an important actor of the self-organized manufacturing process.

The last part of the paper presents an outlook that summarizes important considerations when designing self-organized smart manufacturing solutions *Section VIII*. As we believe we are still in the initial stage to have self-organized solutions totally functional in an industrial setting, we expect the outcomes of this work can facilitate the transition to develop new ideas towards a smart manufacturing transition.

TABLE 5. Summary of references considered.

Ref	Summary	Potential future research
[72], 2016	A generic architecture is proposed to show the self-organization of a smart factory. The main focus is industrial networks, cloud, shop-floor devices, and big data analytics that provides feedback and coordination. *AL:* L2-L3 — *TRL:* Concept/Simulation	The work focuses on vertical integration with an emphasis on emerging technologies. It suggests that MAS in manufacturing applications still cannot handle the complexity of a manufacturing environment. Thus, technological enablers can support the development of smart factories.
[73], 2016	A central coordinator is suggested to manage and coordinate a self-organized manufacturing system. It is based on MAS. Distributed decision-making by negotiation and deadlock prevention for smart objects are implemented. *AL:* L2 - L3 — *TRL:* Concept/Simulation	Main requirements of a smart factory should combine smart objects with big data and industrial networks. Such objects should be able to dynamically reconfigure and should be highly flexible. Through cooperation, having social abilities and without global intervention, the smart factory can be implemented.
[70], 2016	Self-organization consists of optimal task matching of resources services, and tasks. Self-adaptation is implemented in run time. Mechanisms implemented are conflict resolution and optimal configuration (based on metrics evaluation). Machines can be configured based on a Gray relational analysis (GRA). *AL:* L2 - L3 — *TRL:* Lab Experiment	Claims the need for integration of Cyber-Physical Systems with lower-level manufacturing resources to improve real-time sensing capabilities and mechanisms for proactive task allocation and resource self-organization. There is a need to extend the study to more complex environments.
[76], 2015	2-dimensional self-organization: structural and behavioral. Composed of hybrid architecture: (hierarchical and heterarchical), modules for learning (behaviors), and a nervousness stabilizer. *AL:* L3-L4 — *TRL:* Lab Experiment	Suggests that most of the works in the context of self-organization consider just partial concepts of complex systems, evolutionary theory, or self-organization. Centralized control approaches are becoming obsolete because they cannot cope with disturbances and perturbations. The consideration of advanced behaviours of self-organization is discussed.
[100], 2018	Cooperation between production and logistics. Tasks and resources are virtualized as services and a self-organized configuration layer based on intelligent tasks and a logistics decomposition process. It uses the Analytical target cascading (ATC) model. *AL:* L3 - L4 — *TRL:* Lab Experiment	In self-organization of production and logistics, less attention has been given to IIoT-based synchronization to address logistics problems, i.e., how to model the perception and intelligent behaviour of resources, how to optimize the collaboration and global interaction of tasks, and a real-time analysis, considering conflicts and diagnosis of machines.
[69], 2017	A cloud-assisted and hierarchical self-organized framework is presented based on MAS and cloud to communicate and negotiate. A set of ontological and knowledge-based reasoning is provided to improve the decision-making of agents. A dynamic scheduling application, as well as various communication methods are implemented. *AL:* L2 - L3 — *TRL:* Lab Experiment	It is suggested that reconfigurability in industrial processes is not adopted yet. Also, highlights the need of having agents in a hierarchy to reduce the complexity of the design process.
[101], 2017	Presents different components of a smart factory and the network to integrate them with external systems e.g., logistical networks, consumers, and banks. Also, a schema for inter-layer interaction is presented. On the shop-floor, a multi-agent-based negotiation process is established to determine the operations of the machine. *AL:* L2 - L3 — *TRL:* Lab Experiment	Despite huge technical advancements, the concept of a smart factory is not yet implemented. There is still the need to implement new frameworks, algorithms, and also standards that can take advantage of previous research and technology (i.e., Cloud).
[78], 2014	Two strategies for the control of a manufacturing cell are proposed. The first one considers the intelligence of the product (product-driven manufacturing) and the second one is an holonic manufacturing concept. Through the network, computer systems can access and update information about the agents that represent orders, products, and resources. *AL:* L2 - L3 — *TRL:* Lab Experiment	High customization requires centering the automation of the product in the product itself. Also, the implementation of distributed intelligence allows high responsiveness over multiple entities and, therefore; higher autonomy and adaptivity. Current networking and instrumentation capacity should be considered as part of future research.
[102], 2014	A hierarchical architecture for planning and scheduling of control of manufacturing systems is proposed. It is based on a multi-agent based negotiation approach between the product and resources. *AL:* L2 - L3 — *TRL:* Concept/Simulation	New control architectures able to represent complex environments, while being decentralized and with planning and scheduling should be implemented. Mechanisms to avoid disturbances have to be considered.
[79], 2016	A methodology for product-driven applications is proposed. Manufacturing services are proposed and modeled under the Holonic manufacturing framework (PROSA). Service ontologies are created to define various operations and skills. Decomposition and encapsulation of manufacturing services provide process flexibility. *AL:* L2-L3 — *TRL:* Concept/Simulation	It is suggested that a formal description of informational elements for manufacturing services is still missing. Thus, it is important to generate models where architectures can be developed properly.
[109], 2014	Describes a negotiation mechanism for dynamic scheduling based on swarm intelligence and agent collaboration. Algorithms such as Particle swarm optimization, Artificial bee colony, and Ant colony optimization are tested to minimize the make-span (completion time of jobs) and machine utilization. *AL:* NA — *TRL:* Concept/Simulation	There is increasing research in decision support systems that include self-organizing ideas to handle complex manufacturing problems. Dynamic scheduling and collective intelligence are an alternative to be used for complex manufacturing systems (different operations and components). Dynamic environments and perturbations need to be tested.
[122], 2020	Introduces the social internet of things idea by presenting a smart work and exposing it on the web. Autonomous interactions are created with workpieces and machines by proactive discovery mechanisms. Various contextual awareness mechanisms are created from the perception of physical activities. A case study is explained where the production of a shaft is carried out by generating product requirements and creating task decomposition based on granular computing. *AL:* L2-L3 — *TRL:* Concept/Simulation	The development of CPPS needs to handle heterogeneous complexity and the various contextual data involved i.e., how to integrate different smart entities and several contexts from environment and prosumers. Empirical studies must be developed to understand the consequences of social internet interactions. Automated mining of knowledge from such interactions can enhance this process.

TABLE 5. ***(Continued.)*** **Summary of references considered.**

Ref	Summary	Potential future research
[85], 2012	Introduces the potential field concept for Flexible Manufacturing Systems. Products request services to resources sensing fields that are emitted by them. Products can choose the field that better satisfies their requirement. The work was simulated in Netlogo. Different nodes provide various field types. Performance criteria considered are optimal (make-span), reactivity (respond to non-available resources), scalable and realistic behavior. Real experimentation was developed by instrumenting a product with a network computer and infrared technology. *AL:* L2-L3 — *TRL:* Lab Experiment	Hierarchical-dependent applications are not able to manage unpredictable situations and mass customization of products. Heterarchical approaches, i.e., negotiation and bio-inspired mechanisms can react and adapt faster. Negotiation mechanisms led to challenges, i.e., deadlock avoidance and performance. Future implementations should consider the use of simulation to predict and estimate the global dynamics of the system.
[103], 2017	The solution considers cloud-based interaction for robot negotiation. Various architectural layers are described, i.e., client, cloud and big data, and self-organized smart entities. The negotiation is designed for self-organized production with RFID-tagged products. The negotiation process can determine proper machines, convey routes and prevent deadlock thanks to cloud coordination. The framework has been tested in a candy packaging application. *AL:* L2-L3 — *TRL:* Lab Experiment	The technical limits of a smart factory include constraints in the computation and communication capabilities and the need of having dynamic reconfiguration. IoT, AI, and cloud computing offer alternatives to implement flexible production.
[104], 2019	Proposes a model and technologies to generate a smart CPPS. It has characteristics such as self-organization, healing, and diagnosis. CPS use agent technology with cognitive capabilities i.e., perception, reasoning, learning, and cooperation. It is mainly focused on the integration and interoperability of resources. *AL:* NA — *TRL:* Lab Experiment	New manufacturing requirements need to implement autonomous behaviors based on the inspiration of living systems and nature. To improve such characteristics, cognitive agents have to be implemented. Current works usually focus on data model architectures and networking. Thus bio-inspired and cognitive technology as well as swarm intelligence and ubiquitous computing should be considered.
[95], 2018	Proposes a MAS mechanism for coordination and control of AGVs. Mechanisms such as path load, road pheromones, and composite pheromones are used to cope with anticipated events and to deal with coordination issues. The evaporation mechanism and permanent search create a system that can predict near-future states. A proof of concept is implemented for the coordination of unidirectional AGVs using the Ella software. *AL:* L4-L5 — *TRL:* Concept/Simulation	One directional AGVs are guided by magnetic tapes. Such system guidance restricts the movement, which can result in coordination problems: collisions or deadlocks, This requires new ways of coordination. The dynamic localization of AGVs is not defined (it is taken for granted). Negotiation mechanisms cannot be used to predict future system states.
[121], 2014	Presents a self-organized multi-robot task allocation system using the concept of attractive field. Sensing and communication capabilities are done using camera tracking and a centralized communication system. Results show improved performance in terms of task trough, communication overhead, and energy consumption. *AL:* L4-L5 — *TRL:* Lab. Experiment	Self-organized solutions are more robust than planned-based systems, but they are difficult to design. They have been suggested to solve problems related to scalability and global communication. Local communication can be beneficial thanks to the reduction in communication latency.
[94], 2017	Proposes a control system method with indirect coordination based on ant colony intelligence (Stigmergy) for cooperation with MAS and RFID technology. The work is showcased in a flexible assembly line in a gas oven factory. Results of the simulation show that the proposed solution has better performance than direct coordination mechanisms i.e. immediate response. *AL:* L2-L3 — *TRL:* Concept/Simulation	Direct mechanisms for the coordination of MAS can increase processing time. Indirect coordination inspired by nature can be introduced to enhance manufacturing self-organizing systems. Social insects represent a complex collective behaviour. Indirect coordination decouples actors, time, and space of interaction. The work will consider more dynamic use cases as well as the inclusion of learning from bidding history and self-tuning.
[105], 2015	Proposes a reference architecture based on MAS and graph models to deal with re-routing, and dynamic scheduling. The re-routing mechanism is based on the abstraction of a conveyor system. By tracking the topology of the system and the state of resources and by using the Dijkstra algorithm it is possible to find the shortest and lowest cost transportation path. *AL:*L2-L3 — *TRL:*Concept/Simulation	Fully decoupled architectures do not have a central point of failure. Agility and adaptivity should be considered more than global optimization for architectural design patterns. The system behaviours under topological changes have been elusively explored. Incremental information from sensors may help to choose better routes for transportation. More heterarchical architectures should be adopted to decrease the long decision times of traditional ones.
[90], 2018	Fully bio-inspired architecture. Self-organization based on the firefly algorithm. Resources attract mobile parts based on an attraction mechanism (each resource has a template of available operations). The decision of allocation stays in the product that selects the source of maximum attraction. The approach is tested in a flow line scenario and a job shop-like scenario. *AL:* L3-L4 — *TRL:* Concept/Simulation	Consideration of methodologies close to collective biological systems. Analogies should be created for their design. Bio-inspiration is usually lost from the analogies and ends up designing typical negotiation or cooperation approaches limited to bio-inspired heuristics. Increasing autonomy, evolutive characteristics, and scalability are some of the emerging biological characteristics that are suggested for smart manufacturing concepts. More dynamic scenarios should be tested.
[97], 2010	Proposes a solution for the design of a self-organized assembly system using the Chemical abstract machine method. The main idea is that industrial robots and modules can self-assemble depending on specific chemical rules. *AL:* L2-L3 — *TRL:* Concept/Simulation	Approaches in the context of flexible and agile manufacturing systems do not consider the interrelation between product, process, and system. From an engineer's point of view, the assembly layout is designed manually and programs are manually written.

TABLE 5. ***(Continued.)*** **Summary of references considered.**

Ref	Summary	Potential future research
[110], 2012	Focuses on product-driven systems i.e., decisions to be allocated to the product based on a stigmergic approach. It is centered on projecting a stigmergic pattern in the control of a manufacturing system. In this interpretation, the product is the common work (has a set of attributes), and the various actors interact with it by means of pheromones. The proposed method applies these features based on a subscription/notification mechanism. *AL:* L2-L3 — *TRL:* Lab Experiment	Bio-inspired systems (swarm intelligence) are novel and can be used to achieve decentralized control with very simple agents. Swarm behavior seems very useful to cope with a high production variance and can have memory capabilities. Indirect mechanisms can be used as a way of coordination. Future work includes interactions between products and the development of reinforcement policies for product attributes.
[123], 2020	Proposes a cyber-physical approach to manage and control a manufacturing system. A model integrates production planning, scheduling, and control and enables the self-organization of the shop-floor. This is implemented by means of connectivity, digitization, and intelligent decision-making. It takes into account current tasks and new tasks to self-organize the agenda at the operational level. *AL:* L2-L3 — *TRL:* Concept/Simulation	Current research in the field of management and control of CPPSs offers innovative ideas, but they are not yet implemented in industrial environments. A proper methodology should integrate various levels of decision-making in an enterprise that will enable adaptive control.
[126], 2020	This study shows a product-driven manufacturing architecture. Intelligent entities are represented by products, machines, and routing agents that cooperate and share information with each other. Infotronic technology i.e., RFID and wireless are integrated to ensure real-time communication. *AL:* L3-L4 — *TRL:* Lab Experiment	The new generation of production needs to focus on distributed scheduling. New approaches should be able to cope with unpredictable and complex environments. Product-driven systems can be enhanced with enabling concepts of Cyber-Physical systems i.e., MAS, discrete event simulation, and RFID technology.
[111], 2021	It presents production mechanisms that deal with frequent layout changes. It is inspired by self-organization based on stigmergy. The structure is based on the reinforcement of local interactions without having centralized control and with the applicability of mobile resources. A 3-layer MAS is also proposed: a physical layer, an information layer, and a virtual layer (the one that uses stigmergy as a coordination mechanism). A use case is presented for the self-reconfiguration of shop floors in personalized shoes. *AL:* L4-L5 — *TRL:* Concept/Simulation	A challenge in manufacturing control is routing different products in various resources and the management of layout configurations (adaptation in real-time). Previous approaches are normally based on conveyor systems and static production resources. This limits the flexibility of the shop floor. Material handling should be replaced with mobile and intelligent robots. One or a combination of bio-inspired mechanisms can be useful methods for complex shop-floors.
[127], 2021	Proposes a dynamic dispatching rule to generate adaptive scheduling. It is designed based on 3 aspects: role definition of self-organization units, negotiation mechanisms on self-organization units, and decision methods. Products can be scheduled to multiple resources. Those could be dynamically allocated as resources are mobile. A use case is simulated in a semiconductor manufacturing system. The approach performs better than common heuristic dispatching rules. *AL:* L3-L4 — *TRL:* Concept/Simulation	Scheduling methods should adapt quickly to real-time work disruptions. Traditional heuristic scheduling solutions cannot adjust to load state. Normally they cannot adjust to non-linear processes.
[128], 2020	Presents a hybrid architecture for a smart assembly shop floor, including enabling technologies. The conception of a smart assembly unit to encapsulate physical processes and implementation of a MAS-based architecture. A 3-layer architecture is designed: a physical, field networking, and controlling and computing layer. It is showcased using a multi-joint robot assembly application and the JADE framework. *AL:* L3-L4 — *TRL:* Concept/Simulation	Regardless of advances in CPPS, there are some challenges that are still open i.e., dynamic reorganization (plug-and-play capabilities), time constraints, and ubiquitous networking. Future works include the integration of cloud and edge computing capabilities and enhanced learning algorithms, i.e., reinforcement learning.
[129], 2019	Proposes a decentralized agent-based self-organization approach for large structure assembly problems using mobile robots. Compared to a hybrid approach, this model has higher responsiveness. *AL:* L3-L5 — *TRL:* Concept/Simulation	Centralized scheduling has an issue of rigidity due to considerable changes in software. Decentralized systems have an advantage over hybrid models in terms of computational effort, dealing faster with complexity, and being more adaptable. Decentralized systems have also a disadvantage considering the time required for negotiation. Mobile systems can overcome many limitations of fixed automation. For large mobile manufacturing systems, it is worth it to use a decentralized model. Noisy and dynamic environments should be investigated.
[63], 2017	Presents an agent-based biological-immune system for coordination and fault diagnosis of manufacturing systems. The simulation and adaptation of the immune mechanisms can monitor, diagnose, and learn from the faults that the system encounters. An immune monitoring cell agent is proposed as a mechanism to model the interaction and cognition of a manufacturing cell. *AL:* L2-L4 — *TRL:* Lab Experiment	It is necessary to integrate fault diagnosis and condition monitoring approaches to have control and adaptivity of a manufacturing plant.
[108], 2016	Presents a solution for multi-robot cooperation for welding operations. It uses the ROS framework for communication and interaction between them (MoveIt services). The focus is self-organization and autonomous path planning for synchronization of activities, coordination, and collision avoidance. Optimization criteria based on "minimum path length" is considered. *AL:* NA — *TRL:* Concept/Simulation	Motion planning, collision avoidance, environmental perception, and searching are being applied for system designs and advanced robotic technology. Less consideration of mobile robotics has been done in industrial applications. There is complex coordination, i.e., distributed workload between robots. Issues of interoperability and heterogeneity also should be considered. Cognitive functions and autonomy can open new perspectives to create intelligent machines.

TABLE 5. ***(Continued.)*** **Summary of references considered.**

Ref	Summary	Potential future research
[112], 2020	Four design patterns for self-organization are introduced i.e., Agent–artifact coupling, Product model expertise, process supervision, and Stigmergy. Basic metamodels (in form of UML classes) definitions and relationships are explained in this work. The definition of self-organized manufacturing is given by considering Agents with the capacity of operating in different configurations. Those can change due to changes in orders, and failures in machines. *AL:* NA — *TRL:* Concept/Simulation	Implementation of technological enablers. Contextual reasoning has been recently complemented to MAS design probably because of the increasing availability of sensors. Agents should have the ability to look around and adapt; this could be done by using an artificial perception range. The dependent data set is an issue that should be considered. Not all data can reach the cloud level. Finally, a high level of self-organization should be the result of the emergence of collective behavior under reinforcement learning.
[124], 2022	Proposes a smart manufacturing concept based on fractals. It includes simulations and the use of big data extraction. 3 methods for reconfiguration are tested: a Goal decision model, a negotiation model, and a sustainability assessment method. The fractal structure is composed of a highest-level fractal and a sub-level fractal. The latest one is composed of five agents, i.e., observer, reporter, analyzer, resolver, and organizer. *AL:* L2-L4 — *TRL:* Concept/Simulation	Distributed control systems (e.g., Fractals) normally do not take into account data-driven systems i.e., use of big data (information from the environment, knowledge base), and are a clue for the self-decision-making to implement autonomous facilities.
[65], 2012	Presents AntControl, a methodology based on the ant colony approach. Orders take the analogy of ants foraging for food. The order represents the nest, and the order completion represents the food source. The various paths represent the possible flow sequences of operations. Pheromones are used to evaluate the outcomes of the different paths. Various concepts and simulation tools have been developed and integrated into the already existing Osim tool using activity networks as models and triggers of a manufacturing system. *AL:* NA — *TRL:* Concept/Simulation	Most of the current research deals with deterministic scheduling, i.e., times are fixed and process times are predefined. Also, most current control approaches are limited to static planning without considering disruptions, most control actions are limited to specific actions. Methods of swarm intelligence can be used for distributed systems. These types of approaches are mostly used for static problems; however, their greatest potential can be seen when having highly dynamic domains or just local information available.
[106], 2020	Present a modular self-organized solution for a conveyor-base CPS. It is based on MAS which runs on a raspberry pi. Conveyor agents need to interact with each other to establish their position and to execute the transference of the parts in the right sequence. They use a mechanism based on tokens to determine the position of the conveyors to add, remove and swap conveyors. Messages of the MAS are exchanged using WIFI technology. Motors and sensors constitute a fundamental part of the physical system. Each agent can collect and transmit this information. The MAS model was implemented using the FIPA protocol in JADE. Agents also have been implemented with ML capabilities to prevent malicious attacks. *AL:* L3-L4 — *TRL:* Lab Experiment	The self-organized characteristics of MAS can be enhanced with simple bio-inspired mechanisms, translating them case by case to the CPPS environment. Those can be potentiated with AI techniques to support their dynamic evolution. Such approaches have not really been adopted because industrial stakeholders have not seen real demonstrators (tangible benefits). This is changing thanks to the development of low-cost computers, IoT solutions, and embedded and advanced AI techniques for monitoring and reconfiguration.
[71], 2015	Proposes a Multi-agent-based solution for product-driven manufacturing. Provides self-adaptation and optimization of production while improving energy efficiency and production quality. Agents considered are product type, resource, and interdependent. The main functionalities of the intelligent product are presented as intelligent services. Some adaptation mechanisms include the monitoring of quality, adjustment of the functional plan, and the customization of parameters of the onboard controller. *AL:* L3-L4 — *TRL:* Industrial Demo	Potential deployment challenges for intelligent products include collection and handling of proper data, storage, and retrieval (semantics), use of private infrastructure for storage retrieval, intelligent algorithms for the reasoning of intelligent products, human-in-the-loop considerations, and the hostage of proper intelligence in low-cost electronic devices.
[86], 2012	This work presents a bio-inspired architecture for reconfigurable manufacturing. The use case presents a dynamic task allocation based on potential fields, generating attractive and repulsive fields, according to the services they provide and their availability. Potential fields are usually emitted in all directions, and the decision of allocation stays in the product that goes to the resources with the greatest potential field. *AL:* L3-L4 — *TRL:* Concept/Simulation	Current paradigms e.g., HMS, usually do not consider self-organization. MAS have partially inherited certain ideas from biology. These ideas can be enhanced with other biological concepts i.e., swarm intelligence. Self-organization provides insights into manufacturing in terms of self-configuration, optimization, and healing. Bio-inspired methods should be carefully matched to manufacturing requirements. Those are more adequate for unpredictable problems and easy to engineer. Future work should be done to understand how bio-inspired solutions can ensure robustness, scalability, flexibility, and reconfigurability.
[99], 2019	Considers the design of an ontological modeling of the system based on a function-behavior-structure methodology. The product development relies on a recipe that formalizes its design features. *AL:* L3-L4 — *TRL:* Concept/Simulation	Main issues related to self-adaptive manufacturing frameworks are 1. Most current works only address single-product or a single family of products rather than a system with a drastic change, 2. They are not focused on self-adaptation but on product design systems or static systems. 3. Most of the design are very abstract or knowledge-intensive.
[125], 2018	Approach to monitoring various states and components of the system reacting autonomously or informing the user of possible deviations. It is divided into autonomous cooperative objects (ACO) that can communicate with each other. They have social behavior (communication with other ACO). They can share experiences and understand their environment. In the case that adaptation is needed, each ACO can create dynamic associations or clusters with other ACOs for knowledge propagation and negotiation of local and global needs. *AL:* NA — *TRL:* Concept/Simulation	What most of the research on adaptable, scalable, and robust solutions has in common is the proposition of a central point of control or hierarchies. Instead, new solutions should try the introduction of local propagation to cope with constant changes in interconnected devices. The provision of self-awareness can integrate self-adaptation and self-optimizing solutions.

TABLE 5. ***(Continued.)*** **Summary of references considered.**

Ref	Summary	Potential future research
[68], 2012	Presents the concept of EPS and more specifically the concept of plug and produce. A multi-agent architecture allows the communication between resources, products, and transport systems *AL:* L3-L4 — *TRL:* Industrial Demo	In the context of complex manufacturing systems, concepts of self-organization and emergence are important for the right control and coordination of systems where working conditions can dynamically change. Evolvable Assembly Systems differ deeply from other paradigms (i.e., HMS) in the granularity in which the manufacturing components are considered.
[113], 2020	Autonomous manufacturing task orchestration. Based on a Hidden Markov model to determine the most optimal machine sequence after a production task has been launched. Processes are shown as observable states based on probabilities to perform an adequate autonomous work in progress. For decision-making, it considers historical and real-time data. A process flow for shaft sealing sleeves is considered as a demonstrative case study. *AL:* NA — *TRL:* Concept/Simulation	Autonomous task orchestration problems in manufacturing can be divided into 3 challenges: methodologies to extract key information and knowledge from historical data, methodologies to initiate a sequential production flow, and methodologies to make a dynamic adjustment considering production data and real-time information.
[66], [74] 2011	Self-organization of tasks in creation time (chemical reaction basis) and adaptation in runtime. Automatic layout generation according to available modules and ontological-based decision-making. Modules self-organize and form coalitions and thus can offer composite skills. *AL:* L3-L4 — *TRL:* Concept/Simulation	For the current approach, metrics for self-organization may be considered. Also, strategies to deal with conflict policies and mechanisms at production time e.g., for monitoring, sensing, and coordination of the workspace. The author suggests the exploration of more creative solutions for self-organization with fewer specifications and constraints. self-organization can benefit from learning from experience, by remembering solutions that have been found (i.e., layouts) and applying them if the context appears again.
[120] 2017	A dynamic hybrid control system that integrates a switching mechanism to alter hierarchical and heterachical architectures according to a governance parameter. Two behavioral characteristics are included: predictive schedule and reactive control policies. The approach is tested in a dynamic job shop considering a scheduling problem. *AL:* NA — *TRL:* Lab Experiment	Current challenges are represented by the correct way to dynamically optimize various architectures taking advantage of hierarchical or centralized architecture and fully heterarchical ones. Few works have considered the switching at the structural and behavioral levels at the same time. Those which have, normally are bound to pre-defined configurations and do not explore different alternatives of production optimization. Current works require a balance between the optimization required and the execution time of the switching mechanism.
[87], 2014	Proposes a hybrid architecture for dynamic adaptation with the capacity to handle a predictive behavior and a reactive one. The design is divided into 3 layers: a global one with a global point of view of the system, and a local one with a local optimizer. Each local entity is linked to a physical part. In normal conditions the system operates as a hierarchy, but if a perturbation is detected local optimizers will take control of the orders. The heterarchical part is modeled using the potential field concept. The architecture is instantiated in a scheduling problem in a flexible job-shop problem. *AL:* NA — *TRL:* Lab Experiment	Hybrid architectures with dynamic adaptation and heterogeneous control have been less explored due to the complexity of their design and the high focus on dynamic optimization of architectures with homogeneous control. Authors also suggest that some constraints are due to the oversimplification of scheduling problems, transportation variables (e.g., time, transportation resources), machines (e.g., processing time, unlimited storage capacity) green manufacturing aspects e.g., energy consumption. Also, it is suggested to carry out more experiments with more variables e.g., cell typology, perturbations, etc.
[114], 2022	Proposes an approach for product-driven control to learn how to make control decisions while reacting to disturbances. The approach includes the use of Analytic Hierarchy Process with expert rules for a Multi-agent discrete event simulation model. The approach is validated using an industrial assembly process in tackling the dispatching problem. *AL:* L3 — *TRL:* Lab Experiment	Product-driven control is a complex and open-ended problem with few works that succeeded in developing an approach for decentralized control capabilities on smart products allowing them to have a role in decision processes (react to disturbances and operational risk)
[107], 2022	Multi-agent manufacturing system based on deep reinforcement learning and Edge computing to intelligently generate optimal production strategy for task allocation and improve the decision-making performance *AL:* L3-L4 — *TRL:* Industrial Demo	Traditional dispatching rules and heuristic algorithms cannot work well in a changeable workshop environment when encountering a large number of stochastic disturbances of orders and resources. Traditional scheduling methods do not have robust & efficient production requirements in a changing & disturbance-prone workshop environment
[115], 2021	A novel Hyper-Heuristic based approach to switch scheduling rules with smart products is presented in the current work where the product-driven control systems is based on the design of the smart products. *AL:* L4-L5 — *TRL:* Concept/Simulation	There exists a challenge in defining and improving behavior in a Product-Driven Control System while facing the risk of inefficient decision-making due to the myopia effect
[130], 2020	A decentralized multi-layer peer-to-peer network model designed for handling manufacturing exceptions for resources. This model improves the existing scheduling models including features for reducing complexity, accuracy, and quick identification. The proposed methodology could be implemented in achieving self-x behaviours like self-organization and self-diagnosis. These features were achieved using understanding patterns & features along with rule-based reactions. *AL:* L2-L3 — *TRL:* Industrial Demo	Detection and identification of exceptions in complex manufacturing systems are becoming increasingly hard. The existing scheduling models do not incorporate the required features for timely identification and recovery. Hence, there is a need for a rule-based methodology for addressing manufacturing exceptions.

TABLE 5. ***(Continued.)*** **Summary of references considered.**

Ref	Summary	Potential future research
[118], 2017	The paper presents a generic control architecture for self-organization with industrial robots and workers in a re-configurable Manufacturing System. The work is achieved by combining adaptive holonic control with the existing ISA-95 architecture in the context of the self-organization of a manufacturing system that could rearrange in an effective way. The solution is validated using a case study for a centrifugal pump assembly process. *AL:* L2-L3 — *TRL:* Concept/Simulation	Achieving self-organization in a timely and cost-effective manner is a challenging task. The challenge increases in a chaotic environment like Worker - Industrial robot collaboration. There is a need for an effective Control & communication model to achieve self-organization in a such chaotic environment.
[116], 2017	The paper presents a self-learning technique for automated experience-based learning to adjust to changes in production due to new requirements or disruptions like maintenance. Automated learning is achieved by generalizing the operational knowledge and acquiring experience on the change to develop an experience model and self-learning system for modular assembly and plug & produce system. *AL:* L2-L3 — *TRL:* Concept/Simulation	There is a need for generalized operational knowledge to aid the operators and transfer this knowledge-based on experience to a new environment. The existing techniques do not formalize the decision for change and hence cannot be transferred among operators / new environments
[131], 2012	The work presents a two-layer system with a distributed control architecture for a product-driven production process. The first layer - the deliberative layer controls the managerial part of the control system and the lower layer - the reactive layer controls the shop-floor. The control system is achieved through a two-step priority calculation alignment method. *AL:* L3 — *TRL:* Lab Experiment	In a product-driven system, the coordinated control of all the decision entities is important in achieving an efficient control system, especially in a highly dynamic environment like a logistics center. The drawback of the existing distributed decision-making systems is the lack of a control system in which the defined guidelines are followed by all decision entities for the shop-floor to manager level.
[119], 2011	A holonic module-based framework for manufacturing control, self-organization, and simulation through fuzzy Q-learning is presented. The framework could be used for a reconfigurable manufacturing system and aid in the design, simulation, and analysis of a manufacturing system with uncertainties. *AL:* L3-L4 — *TRL:* Lab Experiment	In the quest for restructuring an existing factory to a holonic factory, most existing MAS/HMS architectures are at the conceptual level and there is a need for an effective and executable modeling framework supporting design, analysis, and simulation
[117], 2010	Proposes a discrete-event coordination architectures approach for automated manufacturing system based on a synthesis approach. The approach presents imperative control command sequences and discrete-event supervisors. The command conditions are designed to achieve the manufacturing product procedure using the synthesized supervisors. This guarantees the robustness of the equipment controllers during production changes. *AL:* L2-L3 — *TRL:* Lab Experiment	In supervisory control architectures, there is a need to recalculate product supervisors while changing supervisors at lower levels and hence there is a need to change the equipment controllers while producing different products. Also, global controllability and product manufacaturability is not considered by the product supervisor.
End of Table		

** TRL: Readiness level; AL: Automation level; NA: Not applied*

APPENDIX

Table 5 presents a summary of the works and potential future research obtained from the systematic literature review.

ACKNOWLEDGMENT

The icons used in certain figures were provided by www.flaticon.com and made by juicy_fish, smalllikeart, Freepik, Pixel perfect, berkahicon, Vectoricons, Eucalyp, and Andrejs.

REFERENCES

[1] Y. Lu, "Industry 4.0: A survey on technologies, applications and open research issues," *J. Ind. Inf. Integr.*, vol. 6, pp. 1–10, Jun. 2017.

[2] L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, and K. Ueda, "Cyber-physical systems in manufacturing," *CIRP Ann.*, vol. 65, no. 2, pp. 621–641, 2016.

[3] M. Onori, "Evolvable assembly systems: A new paradigm?" in *Proc. 33rd Int. Symp. Robot.*, 2002, pp. 1–15.

[4] J. Barata and L. M. Camarinha-Matos, "Coalitions of manufacturing components for shop floor agility—The CoBASA architecture," *Int. J. Netw. Virtual Organisation*, vol. 2, no. 1, pp. 50–77, 2003.

[5] P. Leitão and F. Restivo, "ADACOR: A holonic architecture for agile and adaptive manufacturing control," *Comput. Ind.*, vol. 57, no. 2, pp. 121–130, Feb. 2006.

[6] H. Van Brussel, J. Wyns, P. Valckenaers, L. Bongaerts, and P. Peeters, "Reference architecture for holonic manufacturing systems: PROSA," *Comput. Ind.*, vol. 37, no. 3, pp. 255–274, Nov. 1998.

[7] A. Tharumarajah, "Comparison of the bionic, fractal and holonic manufacturing system concepts," *Int. J. Comput. Integr. Manuf.*, vol. 9, no. 3, pp. 217–226, Jan. 1996.

[8] R. Cioffi, M. Travaglioni, G. Piscitelli, A. Petrillo, and A. Parmentola, "Smart manufacturing systems and applied industrial technologies for a sustainable industry: A systematic literature review," *Appl. Sci.*, vol. 10, no. 8, p. 2897, Apr. 2020.

[9] A. Maffei, S. Grahn, and C. Nuur, "Characterization of the impact of digitalization on the adoption of sustainable business models in manufacturing," *Proc. CIRP*, vol. 81, pp. 765–770, Jan. 2019.

[10] M. Burstein. *Sustainability in the Manufacturing Industry is a Work in Process*. Accessed: Nov. 23, 2022. [Online]. Available: https://www.forbes.com/sites/forbestechcouncil/2022/05/20/sustainability-in-the-manufacturing-industry-is-a-work-in-process/?sh=78f66899310e

[11] World-Economic-Forum. *From Remanufacturing to Recycling: How Manufacturing Can Raise the Bar on Global Climate Goals*. Accessed: Nov. 23, 2022. [Online]. Available: https://www.weforum.org/agenda/2021/06/manufacturing-industry-climate-change-goals/

[12] J. CoyKendall. *Sustainable Manufacturing: From Vision to Action*. Accessed: Nov. 23, 2022. [Online]. Available: https://www.deloitte.com/global/en/Industries/energy/perspectives/sustainable-manufacturing.html

[13] *3 Reasons Why Industrial Automation Matters*, World-Economic-Forum, Cologny, Switzerland, 2022.

[14] P. Leitão, "Self-organization in manufacturing systems: Challenges and opportunities," in *Proc. 2nd IEEE Int. Conf. Self-Adapt. Self-Organizing Syst. Workshops*, Oct. 2008, pp. 174–179.
[15] P. Leitão, J. Queiroz, and L. Sakurada, "Collective intelligence in self-organized industrial cyber-physical systems," *Electronics*, vol. 11, no. 19, p. 3213, Oct. 2022.
[16] J. Zhang, X. Yao, J. Zhou, J. Jiang, and X. Chen, "Self-organizing manufacturing: Current status and prospect for industry 4.0," in *Proc. 5th Int. Conf. Enterprise Syst. (ES)*, Sep. 2017, pp. 319–326.
[17] P. Leitão, S. Karnouskos, L. Ribeiro, J. Lee, T. Strasser, and A. W. Colombo, "Smart agents in industrial cyber–physical systems," *Proc. IEEE*, vol. 104, no. 5, pp. 1086–1101, May 2016.
[18] W. Derigent, O. Cardin, and D. Trentesaux, "Industry 4.0: Contributions of holonic manufacturing control architectures and future challenges," *J. Intell. Manuf.*, vol. 32, no. 7, pp. 1797–1818, Oct. 2021.
[19] M. P. Groover, *Automation, Production Systems, and Computer-Integrated Manufacturing*. London, U.K.: Pearson, 2016.
[20] IBERDROLA. *Industry 4.0: Which Technologies Will Mark the Fourth Industrial Revolution?* Accessed: Nov. 23, 2022. [Online]. Available: https://www.iberdrola.com/innovation/fourth-industrial-revolution
[21] H. A. E. Maraghy, "Flexible and reconfigurable manufacturing systems paradigms," *Flexible Service Manuf. J.*, vol. 17, no. 4, pp. 261–276, 2006.
[22] D. McFarlane, S. Sarma, J. L. Chirn, C. Y. Wong, and K. Ashton, "The intelligent product in manufacturing control and management," *IFAC Proc. Volumes*, vol. 35, no. 1, pp. 49–54, 2002.
[23] G. G. Meyer, K. Främling, and J. Holmström, "Intelligent products: A survey," *Comput. Ind.*, vol. 60, no. 3, pp. 137–148, Apr. 2009.
[24] D. McFarlane, "Product intelligence: Theory and practice," *IFAC Proc. Volumes*, vol. 45, no. 6, pp. 9–14, May 2012.
[25] Y. Wang, H.-S. Ma, J.-H. Yang, and K.-S. Wang, "Industry 4.0: A way from mass customization to mass personalization production," *Adv. Manuf.*, vol. 5, no. 4, pp. 311–320, 2017.
[26] R. Berger. *Rise of the Machines—How Robots and Artificial Intelligence Are Shaping the Future of Autonomous Production*. Accessed: Apr. 4, 2022. [Online]. Available: https://www.rolandberger.com/en/Insights/Publications/Autonomous-production-Rise-of-the-machines.html
[27] Rexroth-Bosch. *Factories of the Future*. Accessed: Apr. 4, 2022. [Online]. Available: https://apps.boschrexroth.com/rexroth/en/factory-of-the-future/
[28] KUKA. *KMR IIWA: Autonomous and Extremely Flexible*. Accessed: Apr. 4, 2022. [Online]. Available: https://www.kuka.com/en-gb/products/mobility/mobile-robots/kmr-iiwa
[29] KUKA. *Matrix Production: An Example for Industrie 4.0*. Accessed: Apr. 4, 2022. [Online]. Available: https://www.kuka.com/en-de/industries/solutions-database/2016/10/matrix-production
[30] N. Schmidtke, A. Rettmann, and F. Behrendt, "Matrix production systems-requirements and influences on logistics planning for decentralized production structures," in *Proc. 54th Hawaii Int. Conf. Syst. Sci.*, 2021, p. 1665.
[31] L. Ribeiro and J. Barata, "Re-thinking diagnosis for future automation systems: An analysis of current diagnostic practices and their applicability in emerging IT based production paradigms," *Comput. Ind.*, vol. 62, no. 7, pp. 639–659, Sep. 2011.
[32] R. A. Rojas and E. Rauch, "From a literature review to a conceptual framework of enablers for smart manufacturing control," *Int. J. Adv. Manuf. Technol.*, vol. 104, nos. 1–4, pp. 517–533, Sep. 2019.
[33] V. Alcácer and V. Cruz-Machado, "Scanning the industry 4.0: A literature review on technologies for manufacturing systems," *Eng. Sci. Technol., Int. J.*, vol. 22, no. 3, pp. 899–919, Jun. 2019.
[34] M. Ghobakhloo, "The future of manufacturing industry: A strategic roadmap toward industry 4.0," *J. Manuf. Technol. Manage.*, vol. 29, no. 6, pp. 910–936, Jul. 2018.
[35] L. A. Estrada-Jimenez, T. Pulikottil, N. N. Hien, A. Torayev, H. U. Rehman, F. Mo, S. N. Hojjati, and J. Barata, "Integration of cutting-edge interoperability approaches in cyber-physical production systems and industry 4.0," in *Design, Applications, and Maintenance of Cyber-Physical Systems*. Hershey, PA, USA: IGI Global, 2021, pp. 144–172.
[36] H. Yang, S. Kumara, S. T. S. Bukkapatnam, and F. Tsung, "The Internet of Things for smart manufacturing: A review," *IISE Trans.*, vol. 51, no. 11, pp. 1190–1216, Jan. 2019.
[37] L. Da Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.
[38] T. Kalsoom, N. Ramzan, S. Ahmed, and M. Ur-Rehman, "Advances in sensor technologies in the era of smart factory and industry 4.0," *Sensors*, vol. 20, no. 23, p. 6783, Nov. 2020.
[39] O. Cardin, "Classification of cyber-physical production systems applications: Proposition of an analysis framework," *Comput. Ind.*, vol. 104, pp. 11–21, Jan. 2019.
[40] S. Karnouskos, L. Ribeiro, P. Leitao, A. Luder, and B. Vogel-Heuser, "Key directions for industrial agent based cyber-physical production systems," in *Proc. IEEE Int. Conf. Ind. Cyber Phys. Syst. (ICPS)*, May 2019, pp. 17–22.
[41] H. Panetto, B. Iung, D. Ivanov, G. Weichhart, and X. Wang, "Challenges for the cyber-physical manufacturing enterprises of the future," *Annu. Rev. Control*, vol. 47, pp. 200–213, 2019.
[42] J. Tavcar and I. Horvath, "A review of the principles of designing smart cyber-physical systems for run-time adaptation: Learned lessons and open issues," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 1, pp. 145–158, Jan. 2019.
[43] L. Ribeiro and M. Björkman, "Transitioning from standard automation solutions to cyber-physical production systems: An assessment of critical conceptual and technical challenges," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3816–3827, Dec. 2018.
[44] P. Leitão, A. W. Colombo, and S. Karnouskos, "Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges," *Comput. Ind.*, vol. 81, pp. 11–25, Sep. 2016.
[45] H. Haken, *Information and Self-Organization: A Macroscopic Approach to Complex Systems*. Cham, Switzerland: Springer, 2006.
[46] J. H. Holland, "Complex adaptive systems and spontaneous emergence," in *Complexity and Industrial Clusters*. Cham, Switzerland: Springer, 2002, pp. 25–34.
[47] L. M. Holden, "Complex adaptive systems: Concept analysis," *J. Adv. Nursing*, vol. 52, no. 6, pp. 651–657, Dec. 2005.
[48] S. G. Tzafestas, *Energy, Information, Feedback, Adaptation, and Selforganization: The Fundamental Elements of Life and Society*, vol. 90. Cham, Switzerland: Springer, 2018.
[49] G. Di Marzo Serugendo, M.-P. Gleizes, and A. Karageorgos, *Self-Organising Software: From Natural to Artificial Adaptation*. Berlin, Germany: Springer, 2011.
[50] R. Pfeifer, M. Lungarella, and F. Iida, "Self-organization, embodiment, and biologically inspired robotics," *Science*, vol. 318, no. 5853, pp. 1088–1093, 2007.
[51] G. D. M. Serugendo, M.-P. Gleizes, and A. Karageorgos, "Self-organization in multi-agent systems," *Knowl. Eng. Rev.*, vol. 20, no. 2, pp. 165–189, 2005.
[52] S. Van Der Leeuw, *Social Sustainability, Past and Future: Undoing Unintended Consequences for the Earth's Survival*. Cambridge, U.K.: Cambridge Univ. Press, 2020.
[53] G. Di Marzo Serugendo, M.-P. Gleizes, and A. Karageorgos, "Self-organisation and emergence in MAS: An overview," *Informatica*, vol. 30, no. 1, pp. 1–10, 2006.
[54] T. De Wolf and T. Holvoet, "Emergence versus self-organisation: Different concepts but promising when combined," in *Proc. Int. Workshop Eng. Self-Organising Appl.* Cham, Switzerland: Springer, 2004, pp. 1–15.
[55] L. A. Estrada-Jimenez, T. Pulikottil, R. S. Peres, S. Nikghadam-Hojjati, and J. Barata, "Complexity theory and self-organization in cyber-physical production systems," *Proc. CIRP*, vol. 104, pp. 1831–1836, Jan. 2021.
[56] G. Byrne, D. Dimitrov, L. Monostori, R. Teti, F. van Houten, and R. Wertheim, "Biologicalisation: Biological transformation in manufacturing," *CIRP J. Manuf. Sci. Technol.*, vol. 21, pp. 1–32, May 2018.
[57] E. Bonabeau, *Swarm Intelligence: From Natural to Artificial Systems*. Oxford, U.K.: Oxford Univ. Press, 1999.
[58] M. Schranz, G. A. Di Caro, T. Schmickl, W. Elmenreich, F. Arvin, A. Şekercioğlu, and M. Sende, "Swarm intelligence and cyber-physical systems: Concepts, challenges and future trends," *Swarm Evol. Comput.*, vol. 60, Feb. 2021, Art. no. 100762.
[59] S. Kernbach, *Handbook of Collective Robotics: Fundamentals and Challenges*. Boca Raton, FL, USA: CRC Press, 2013.
[60] M. Schranz, M. Umlauft, M. Sende, and W. Elmenreich, "Swarm robotic behaviors and current applications," *Frontiers Robot. AI*, vol. 7, p. 36, Apr. 2020.

[61] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, and G. Prisma, "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *Ann. Internal Med.*, vol. 151, no. 4, pp. 264–269, 2009.
[62] G. D. M. Serugendo, M.-P. Gleizes, and A. Karageorgos, *Self-Organising Software: From Natural to Artificial Adaptation*. Cham, Switzerland: Springer, 2011.
[63] L. Wang, C. Luo, J. Cai, and M. Li, "An efficient agent-based biological immune system approach to adaptive manufacturing system control," *Int. J. Robot. Autom.*, vol. 32, no. 1, pp. 78–86, 2017.
[64] J. Dias-Ferreira, "Bio-inspired self-organising architecture for cyber-physical manufacturing systems," Ph.D. dissertation, KTH Roy. Inst. Technol., Stockholm, Sweden, 2016.
[65] P. Stock and G. Zülch, "Reactive manufacturing control using the ant colony approach," *Int. J. Prod. Res.*, vol. 50, no. 21, pp. 6150–6161, Nov. 2012.
[66] R. Frei and G. Di Marzo Serugendo, "Self-organizing assembly systems," *IEEE Trans. Syst., Man, Cybern., C, Appl. Rev.*, vol. 41, no. 6, pp. 885–897, Nov. 2011.
[67] M. Wooldridge, *An Introduction to Multiagent Systems*. Hoboken, NJ, USA: Wiley, 2009.
[68] M. Onori, N. Lohse, J. Barata, and C. Hanisch, "The IDEAS project: Plug & produce at shop-floor level," *Assem. Autom.*, vol. 32, no. 2, pp. 124–134, Apr. 2012.
[69] H. Tang, D. Li, S. Wang, and Z. Dong, "CASOA: An architecture for agent-based manufacturing system in the context of industry 4.0," *IEEE Access*, vol. 6, pp. 12746–12754, 2018.
[70] Y. Zhang, C. Qian, J. Lv, and Y. Liu, "Agent and cyber-physical system based self-organizing and self-adaptive intelligent shopfloor," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 737–747, Apr. 2017.
[71] P. Leitão, N. Rodrigues, J. Barbosa, C. Turrin, and A. Pagani, "Intelligent products: The grace experience," *Control Eng. Pract.*, vol. 42, pp. 95–105, Sep. 2015.
[72] S. Wang, D. Li, J. Wan, and C. Zhang, "Implementing smart factory of industrie 4.0: An outlook," *Int. J. Distrib. Sensor Netw.*, vol. 12, no. 1, 2016, Art. no. 3159805.
[73] S. Wang, J. Wan, D. Zhang, D. Li, and C. Zhang, "Towards smart factory for industry 4.0: A self-organized multi-agent system with big data based feedback and coordination," *Comput. Netw.*, vol. 101, pp. 158–168, Jun. 2016.
[74] R. Frei, "Self-organisation in evolvable assembly systems," Ph.D. dissertation, Nova Univ. Lisbon, Lisbon, Portugal, 2010.
[75] A. Koestler, *The Ghost in the Machine*. U.K.: Hutchinson, 1967, p. 381.
[76] J. Barbosa, P. Leitão, E. Adam, and D. Trentesaux, "Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution," *Comput. Ind.*, vol. 66, pp. 99–111, Jan. 2015.
[77] J. Jarvis, D. Jarvis, R. Rönnquist, and L. C. Jain, "Holonic manufacturing systems," in *Holonic Execution: A BDI Approach*. Berlin, Germany: Springer, 2008, pp. 7–16.
[78] T. Borangiu, S. Raileanu, D. Trentesaux, I. Iacob, and T. Berger, "Distributed manufacturing control with extended CNP interaction of intelligent products," *J. Intell. Manuf.*, vol. 25, no. 5, pp. 1065–1075, Oct. 2014.
[79] F. G. Quintanilla, O. Cardin, A. L'Anton, and P. Castagna, "A modeling framework for manufacturing services in service-oriented holonic manufacturing systems," *Eng. Appl. Artif. Intell.*, vol. 55, pp. 26–36, Oct. 2016.
[80] J. Timmis, P. Andrews, and E. Hart, "On artificial immune systems and swarm intelligence," *Swarm Intell.*, vol. 4, no. 4, pp. 247–273, Dec. 2010.
[81] V. Hilaire, A. Koukam, and S. Rodriguez, "Immune systems," in *Selforganising Software*. Cham, Switzerland: Springer, 2011, pp. 227–249.
[82] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots," in *Proc. IEEE Int. Conf. Robot. Autom.* Cham, Switzerland: Springer, 1986, pp. 396–404.
[83] P. Dunias, "Autonomous robots using artificial potential fields," Ph.D. dissertation, Eindhoven Univ. Technol., Eindhoven, The Netherlands, 1996.
[84] J. H. Reif and H. Wang, "Social potential fields: A distributed behavioral control for autonomous robots," *Robot. Auto. Syst.*, vol. 27, no. 3, pp. 171–194, May 1999.
[85] N. Zbib, C. Pach, Y. Sallez, and D. Trentesaux, "Heterarchical production control in manufacturing systems using the potential fields concept," *J. Intell. Manuf.*, vol. 23, no. 5, pp. 1649–1670, Oct. 2012.
[86] P. Leitão, J. Barbosa, and D. Trentesaux, "Bio-inspired multi-agent systems for reconfigurable manufacturing systems," *Eng. Appl. Artif. Intell.*, vol. 25, no. 5, pp. 934–944, Aug. 2012.
[87] C. Pach, T. Berger, T. Bonte, and D. Trentesaux, "ORCA-FMS: A dynamic architecture for the optimized and reactive control of flexible manufacturing scheduling," *Comput. Ind.*, vol. 65, no. 4, pp. 706–720, May 2014.
[88] C. Pach, T. Berger, Y. Sallez, T. Bonte, E. Adam, and D. Trentesaux, "Reactive and energy-aware scheduling of flexible manufacturing systems using potential fields," *Comput. Ind.*, vol. 65, no. 3, pp. 434–448, Apr. 2014.
[89] X.-S. Yang, *Nature-Inspired Metaheuristic Algorithms*. Beckington, U.K.: Luniver Press, 2010.
[90] J. Dias-Ferreira, L. Ribeiro, H. Akillioglu, P. Neves, and M. Onori, "BIOSOARM: A bio-inspired self-organising architecture for manufacturing cyber-physical shopfloors," *J. Intell. Manuf.*, vol. 29, no. 7, pp. 1659–1682, Oct. 2018.
[91] C. Bourjot, D. Desor, and V. Chevrier, "Stigmergy," in *Self-Organising Software*. Cham, Switzerland: Springer, 2011, pp. 123–138.
[92] F. Heylighen, "Stigmergy as a universal coordination mechanism I: Definition and components," *Cognit. Syst. Res.*, vol. 38, pp. 4–13, Jun. 2016.
[93] T. Berger, Y. Sallez, B. Valli, A. Gibaud, and D. Trentesaux, "Semi-heterarchical allocation and routing processes in FMS control: A stigmergic approach," *J. Intell. Robot. Syst.*, vol. 58, no. 1, pp. 17–45, Apr. 2010.
[94] A. V. Barenji and R. V. Barenji, "Improving multi-agent manufacturing control system by indirect communication based on ant agents," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 231, no. 6, pp. 447–458, Jul. 2017.
[95] B. Micieta, M. Edl, M. Krajcovic, L. Dulina, P. Bubenik, L. Durica, and V. Binasova, "Delegate MASs for coordination and control of one-directional AGV systems: A proof-of-concept," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 1–4, pp. 415–431, Jan. 2018.
[96] J.-P. Banâtre, P. Fradet, and D. L. Métayer, "Gamma and the chemical reaction model: Fifteen years after," in *Proc. Workshop Membrane Comput.* Cham, Switzerland: Springer, 2000, pp. 17–44.
[97] R. Frei, G. Di Marzo Serugendo, and T. F. Şerbănuţă, "Ambient intelligence in self-organising assembly systems using the chemical reaction model," *J. Ambient Intell. Humanized Comput.*, vol. 1, no. 3, pp. 163–184, Sep. 2010.
[98] M. S. Erden, H. Komoto, T. J. van Beek, V. D'Amelio, E. Echavarria, and T. Tomiyama, "A review of function modeling: Approaches and applications," *Artif. Intell. Eng. Des., Anal. Manuf.*, vol. 22, no. 2, pp. 147–169, 2008.
[99] D. Sanderson, J. C. Chaplin, and S. Ratchev, "A function-behaviour-structure design methodology for adaptive production systems," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 9, pp. 3731–3742, Dec. 2019.
[100] Y. Zhang, Z. Guo, J. Lv, and Y. Liu, "A framework for smart production-logistics systems based on CPS and industrial IoT," *IEEE Trans. Ind. Informat.*, vol. 14, no. 9, pp. 4019–4032, Sep. 2018.
[101] S. Wang, J. Wan, M. Imran, D. Li, and C. Zhang, "Cloud-based smart manufacturing for personalized candy packing application," *J. Supercomput.*, vol. 74, no. 9, pp. 4339–4357, Sep. 2018.
[102] N. He, D. Z. Zhang, and Q. Li, "Agent-based hierarchical production planning and scheduling in make-to-order manufacturing system," *Int. J. Prod. Econ.*, vol. 149, pp. 117–130, Mar. 2014.
[103] S. Wang, C. Zhang, C. Liu, D. Li, and H. Tang, "Cloud-assisted interaction and negotiation of industrial robots for the smart factory," *Comput. Electr. Eng.*, vol. 63, pp. 66–78, Oct. 2017.
[104] N. H. Tran, H. S. Park, Q. V. Nguyen, and T. D. Hoang, "Development of a smart cyber-physical manufacturing system in the industry 4.0 context," *Appl. Sci.*, vol. 9, no. 16, p. 3325, Aug. 2019.
[105] L. Ribeiro, A. Rocha, A. Veiga, and J. Barata, "Collaborative routing of products using a self-organizing mechatronic agent framework—A simulation study," *Comput. Ind.*, vol. 68, pp. 27–39, Apr. 2015.
[106] P. Leitão, J. Barbosa, G. Funchal, and V. Melo, "Self-organized cyber-physical conveyor system using multi-agent systems," *Int. J. Artif. Intell.*, vol. 2020, pp. 1–15, Feb. 2020.

[107] Y. Zhang, H. Zhu, D. Tang, T. Zhou, and Y. Gui, "Dynamic job shop scheduling based on deep reinforcement learning for multi-agent manufacturing systems," *Robot. Comput.-Integr. Manuf.*, vol. 78, Dec. 2022, Art. no. 102412.

[108] G. Starke, D. Hahn, D. P. Yanez, and L. U. Leal, "Self-organization and self-coordination in welding automation with collaborating teams of industrial robots," *Machines*, vol. 4, no. 4, p. 23, Nov. 2016.

[109] A. Madureira, I. Pereira, P. Pereira, and A. Abraham, "Negotiation mechanism for self-organized scheduling system with collective intelligence," *Neurocomputing*, vol. 132, pp. 97–110, May 2014.

[110] R. Pannequin and A. Thomas, "Another interpretation of stigmergy for product-driven systems architecture," *J. Intell. Manuf.*, vol. 23, no. 6, pp. 2587–2599, Dec. 2012.

[111] R. Ogunsakin, C. A. Marin, and N. Mehandjiev, "Towards engineering manufacturing systems for mass personalisation: A stigmergic approach," *Int. J. Comput. Integr. Manuf.*, vol. 34, no. 4, pp. 341–369, Apr. 2021.

[112] V. Charpenay, D. Schraudner, T. Seidelmann, T. Spieldenner, J. Weise, R. Schubotz, S. Mostaghim, and A. Harth, "MOSAIK: A formal model for self-organizing manufacturing systems," *IEEE Pervasive Comput.*, vol. 20, no. 1, pp. 9–18, Jan. 2021.

[113] K. Ding, J. Lei, F. T. S. Chan, J. Hui, F. Zhang, and Y. Wang, "Hidden Markov model-based autonomous manufacturing task orchestration in smart shop floors," *Robot. Comput.-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101845.

[114] A. Attajer, S. Darmoul, S. Chaabane, Y. Sallez, and F. Riane, "An analytic hierarchy process augmented with expert rules for product driven control in cyber-physical manufacturing systems," *Comput. Ind.*, vol. 143, Dec. 2022, Art. no. 103742.

[115] W. Bouazza, Y. Sallez, and D. Trentesaux, "Dynamic scheduling of manufacturing systems: A product-driven approach using hyper-heuristics," *Int. J. Comput. Integr. Manuf.*, vol. 34, no. 6, pp. 641–665, Jun. 2021.

[116] D. Scrimieri, N. Antzoulatos, E. Castro, and S. M. Ratchev, "Automated experience-based learning for plug and produce assembly systems," *Int. J. Prod. Res.*, vol. 55, no. 13, pp. 3674–3685, Jul. 2017.

[117] A. Sanchez, E. Aranda-Bricaire, F. Jaimes, E. Hernandez, and A. Nava, "Synthesis of product-driven coordination controllers for a class of discrete-event manufacturing systems," *Robot. Comput.-Integr. Manuf.*, vol. 26, no. 4, pp. 361–369, Aug. 2010.

[118] A. Sadik and B. Urban, "Combining adaptive holonic control and ISA-95 architectures to self-organize the interaction in a worker-industrial robot cooperative workcell," *Future Internet*, vol. 9, no. 3, p. 35, Jul. 2017.

[119] H. Lee and A. Banerjee, "Executable design and control framework using reconfigurable manufacturing holons and its evolution algorithm," *Int. J. Prod. Res.*, vol. 49, no. 5, pp. 1405–1423, Mar. 2011.

[120] J. F. Jimenez, A. Bekrar, G. Zambrano-Rey, D. Trentesaux, and P. Leitão, "Pollux: A dynamic hybrid control architecture for flexible job shop systems," *Int. J. Prod. Res.*, vol. 55, no. 15, pp. 4229–4247, Aug. 2017.

[121] M. O. F. Sarker, T. S. Dahl, E. Arcaute, and K. Christensen, "Local interactions over global broadcasts for improved task allocation in self-organized multi-robot systems," *Robot. Auto. Syst.*, vol. 62, no. 10, pp. 1453–1462, 2014.

[122] J. Leng, P. Jiang, C. Liu, and C. Wang, "Contextual self-organizing of manufacturing process for mass individualization: A cyber-physical-social system approach," *Enterprise Inf. Syst.*, vol. 14, no. 8, pp. 1124–1149, 2018.

[123] E. Hozdić, D. Kozjek, and P. Butala, "A cyber-physical approach to the management and control of manufacturing systems," *J. Mech. Eng.*, vol. 66, no. 1, pp. 61–70, Dec. 2019.

[124] S. Lee and K. Ryu, "Development of the architecture and reconfiguration methods for the smart, self-reconfigurable manufacturing system," *Appl. Sci.*, vol. 12, no. 10, p. 5172, May 2022.

[125] L. C. Siafara, H. Kholerdi, A. Bratukhin, N. Taherinejad, and A. Jantsch, "SAMBA—An architecture for adaptive cognitive control of distributed cyber-physical production systems based on its self-awareness," *E Elektrotechnik Informationstechnik*, vol. 135, no. 3, pp. 270–277, Jun. 2018.

[126] B. Mihoubi, B. Bouzouia, K. Tebani, and M. Gaham, "Hardware in the loop simulation for product driven control of a cyber-physical manufacturing system," *Prod. Eng.*, vol. 14, no. 3, pp. 329–343, Jun. 2020.

[127] Q. Yu, H. Yang, K.-Y. Lin, and L. Li, "A self-organized approach for scheduling semiconductor manufacturing systems," *J. Intell. Manuf.*, vol. 32, no. 3, pp. 689–706, Mar. 2021.

[128] Q. Tan, Y. Tong, S. Wu, and D. Li, "Towards a next-generation production system for industrial robots: A CPS-based hybrid architecture for smart assembly shop floors with closed-loop dynamic cyber physical interactions," *Frontiers Mech. Eng.*, vol. 15, no. 1, pp. 1–11, Mar. 2020.

[129] S. Ljasenko, P. Ferreira, L. Justham, and N. Lohse, "Decentralised vs partially centralised self-organisation model for mobile robots in large structure assembly," *Comput. Ind.*, vol. 104, pp. 141–154, Jan. 2019.

[130] C. Qian, W. Sun, and Y. Zhang, "ResourceNet: A collaboration network among decentralised manufacturing resources for autonomous exception-handling in smart manufacturing," *IET Collaborative Intell. Manuf.*, vol. 2, no. 3, pp. 109–114, Sep. 2020.

[131] J. de las Morenas, A. G. Higuera, and P. G. Ansola, "Product driven distributed control system for an experimental logistics centre," *Int. J. Innov. Comput. Inf. Control*, vol. 8, no. 10, pp. 7199–7215, 2012.

[132] M. A. Roa, D. Berenson, and W. Huang, "Mobile manipulation: Toward smart manufacturing [TC spotlight]," *IEEE Robot. Autom. Mag.*, vol. 22, no. 4, pp. 14–15, Dec. 2015.

[133] L. Ulrich. *Automakers Pivot to Produce Ventilators, Respirators, and Face Masks*. Accessed: Nov. 23, 2022. [Online]. Available: https://spectrum.ieee.org/coronavirus-news-automakers-ford-gm-pivot-produce-ventilators-respirators-face-masks

[134] J. Van Brummelen, M. O'Brien, D. Gruyer, and H. Najjaran, "Autonomous vehicle perception: The technology of today and tomorrow," *Transp. Res. C, Emerg. Technol.*, vol. 89, pp. 384–406, Apr. 2018.

[135] J. Fayyad, M. A. Jaradat, D. Gruyer, and H. Najjaran, "Deep learning sensor fusion for autonomous vehicle perception and localization: A review," *Sensors*, vol. 20, no. 15, p. 4220, Jul. 2020.

[136] M. García and J. Aguilar, "Emergent control in the context of industry 4.0," *Int. J. Comput. Integr. Manuf.*, vol. 35, no. 3, pp. 247–262, Mar. 2022.

[137] M. K. Heinrich, M. D. Soorati, T. K. Kaiser, M. Wahby, and H. Hamann, "Swarm robotics: Robustness, scalability, and self-X features in industrial applications," *Inf. Technol.*, vol. 61, no. 4, pp. 159–167, Aug. 2019.

[138] J. Wen, L. He, and F. Zhu, "Swarm robotics control and communications: Imminent challenges for next generation smart logistics," *IEEE Commun. Mag.*, vol. 56, no. 7, pp. 102–107, Jul. 2018.

[139] R. Frei and J. Barata, "Distributed systems-from natural to engineered: Three phases of inspiration by nature," *Int. J. Bio Inspired Comput.*, vol. 2, nos. 3–4, pp. 258–270, 2010.

[140] R. Frei, R. McWilliam, B. Derrick, A. Purvis, A. Tiwari, and G. Di Marzo Serugendo, "Self-healing and self-repairing technologies," *Int. J. Adv. Manuf. Technol.*, vol. 69, nos. 5–8, pp. 1033–1061, Nov. 2013.

[141] A. D. Rocha, P. Lima-Monteiro, M. Parreira-Rocha, and J. Barata, "Artificial immune systems based multi-agent architecture to perform distributed diagnosis," *J. Intell. Manuf.*, vol. 30, no. 4, pp. 2025–2037, Apr. 2019.

[142] G. S. Wilkinson, "Food sharing in vampire bats," *Sci. Amer.*, vol. 262, no. 2, pp. 76–83, 1990.

[143] A. D. Rocha and J. Barata, "Digital twin-based optimiser for self-organised collaborative cyber-physical production systems," *Manuf. Lett.*, vol. 29, pp. 79–83, Aug. 2021.

[144] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and industry 5.0—Inception, conception and perception," *J. Manuf. Syst.*, vol. 61, pp. 530–535, Oct. 2021.

LUIS A. ESTRADA-JIMENEZ received the B.Sc. degree in electronic and control engineering from Escuela Politecnica Nacional, Ecuador, in 2016, and the M.Sc. degree in mechatronics engineering from the University of Oviedo, Spain, in 2019. He is currently pursuing the Ph.D. degree in electrical and computer engineering with the Nova University of Lisbon, Portugal. His master's thesis was developed at the Department of Modular Automation, FESTO, Germany. He is also working with the UNINOVA Research Institute, and also working as an Early Stage Researcher with the Digital Manufacturing and Design Training Network (DIMAND), funded by the European Union. His research interests include self-organization and automation in smart manufacturing systems and the application of artificial intelligence in industrial environments.

TERRIN PULIKOTTIL received the bachelor's degree in manufacturing engineering from the College of Engineering, Guindy Campus, Anna University, Chennai, India, in 2012, and the master's degree in mechanical engineering with specialization in industrial production from the Politecnico di Milano, Italy, in 2016. He is currently pursuing the Ph.D. degree in electrical and computer engineering with the Nova University of Lisbon. After his under graduation, he worked as a Technical Deputy Manager at Carborundum Universal Ltd., India, from 2012 to 2014, where he is responsible for supporting production and QA. He worked as a Research Fellow at the National Research Council of Italy, Institute for Intelligent Industrial Technologies and Systems for Advanced Manufacturing (STIIMA), from 2017 to 2020. He has been an Early Stage Researcher with UNNINOVA on H2020 DIMAND Project, since June 2020.

SANAZ NIKGHADAM-HOJJATI (Member, IEEE) received the Ph.D. degree in information technology management (Business Intelligence) from IAU, in 2017. She worked as a Postdoctoral Researcher at the Nova School of Science and Technology, Nova University of Lisbon, from 2018 to 2019. She worked as a University Invited Professor. She is currently a Senior Researcher with the UNINOVA Institute, Nova University of Lisbon, and also the Director of the Women in Science, Technology, Engineering, and Mathematics (WoSTEM) Program, UNINOVA. She has published several books and academic papers in a number of peer-reviewed journals and presented various academic papers at conferences. She has led and participated in several European Union projects, and Portuguese and Iranian National projects. Her research interests include computational creativity, affective computing, business intelligence, human behavior, emerging technologies, ICT, and innovation management.

JOSÉ BARATA (Member, IEEE) received the Ph.D. degree in robotics and integrated manufacturing from the NOVA University of Lisbon, in 2004. He is currently a Professor with the Department of Electrical Engineering, NOVA University of Lisbon, and a Senior Researcher with the UNINOVA—Instituto de Desenvolvimento de Novas Tecnologias. Since 2004, he has been leading the UNINOVA participation in EU projects, namely, EUPASS, self-learning, IDEAS, PRIME, RIVERWATCH, ROBO-PARTNER, and PROSECO. In the last years, he has participated actively researching SOA-based approaches for the implementation of intelligent manufacturing devices, such as within the Inlife Project. He has participated in more than 15 international research projects involving different programs, including NMP, IST, ITEA, and ESPRIT. He has authored or coauthored over 100 original papers in international journals and international conferences. His main research interest includes intelligent manufacturing, with an emphasis on complex adaptive systems, involving intelligent manufacturing devices. He is also a member of the IEEE Technical Committee on Industrial Agents (IES), Self-Organization and Cybernetics for Informatics (SMC), and Education in Engineering and Industrial Technologies (IES).