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A Review on the Characteristics of Cyber-Physical Systems for the future Smart Factories

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A Review on the Characteristics of Cyber-Physical Systems for the future Smart Factories

The emergence of new technologies is providing new ways to compete in the current context of changeable and unpredictable market requirements. The focus of this paper is on Cyber-Physical Systems (CPSs), as one of the most promising transformative technological concept of such a context, thus considered by literature as the building blocks of future smart factories. However, CPSs are still in their conceptualization phase. To this end, much literature effort has been put on their technological characterization, while there is a lack of knowledge on operations management characterization to manage such new systems. To contribute in this latter direction, this paper reviews literature in order to distinguish between technological characteristics of CPSs and operations management characteristics to build future CPS-based smart factories. This paper remarks the need for research on operations management characteristics as these may be the ones actually leading operations managers to the concrete implementation of CPS-based factories in manufacturing.

Keywords: Cyber-Physical System, Smart Factory, Digitalization

1 Introduction

Nowadays, manufacturing firms are facing the challenge of keeping their competitiveness despite a scenario whose protagonists are the unpredictability of market requirements and technological evolution [1–4]. In this context, fervent research activity is addressing the development of Cyber-Physical Systems (CPSs) in manufacturing: according to literature, CPSs can quickly adapt to unexpected changes [5,6], improving the competitiveness of firms [7–10].

More and more researchers agree that CPSs will become the building blocks of future factories [11–13]. Indeed, CPSs represent one of the most significant directions in the development of computer science and ICT in an industrial context. As such, CPSs are “systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet" [14]. To this end, CPSs are able to: (i) collect data referred to themselves and their environment, (ii) process and evaluate these data, (iii) connect and communicate with other systems, and (iv) initiate actions [15]. According to Garetti, Fumagalli and Negri [16], CPSs are made of collaborating computational elements (such as micro computing units, or embedded systems, interacting through a communication system) deeply connected to, and controlling, physical entities. To them, in CPSs many types of equipment (i.e. sensors, actuators, devices, machines and robots) are creating a smart community with the capability to capture data and take actions on the physical world. This capability is potentially built through different production levels (i.e. from sensors to machines/ robots, up to the whole factory). All in all, CPSs transfer raw data to actionable operations, assisting users to comprehend process information, and adding resilience to the manufacturing system through an evidence-based decision making [17,18]. To remark the application in manufacturing, many authors referred to Cyber-Physical Production Systems (CPPSs) instead of CPSs (see for example [19,20]). Thus, in this paper, the two nomenclatures have been considered as synonyms.

Manifold definitions traceable within the scientific community are an evidence of the strong interest in CPSs as a relevant technology-related concept to build future smart factories. Coherently, as CPS-related theory is in its initial stage of development, much literature effort has been put on the technological characterization of such systems; moreover, the technologies required to develop CPSs are already available for manufacturing firms. Nevertheless, the concrete application of these CPS-related technologies in order to enable the CPS-based smart factory is still far from turning into reality, as witnessed in currently published works. The introduction of CPSs leads to new requirements in the operations management of a factory. Operations managers should be made aware that there are some "technological" characteristics (in a broad sense, also involving specific competences, skills and functionalities offered by technology providers and production resources) that, by analogy with bricks to build constructions, should be the base to create a smart factory. Such smart factory differs from a traditional one because its inherent property is the capability to promptly evolve over time thanks to its “operations management” characteristics. To add a contribution in this direction, two research questions (RQs) are addressed in the paper:

- RQ1: What are the technological characteristics of CPSs in manufacturing emergent from existing literature?
- RQ2: What are the operations management characteristics to build CPSs-based smart factories?

To address the RQs, this paper reviews and sorts literature. Specifically, section 2 describes the adopted methodology. Section 3 digs into literature to identify and aggregate the characteristics of CPSs; section 4 answers to the two RQs by further aggregating and enriching characteristics, leading to their classification in characteristics of CPSs – i.e. technological (in a broad sense) ones – and characteristics to build CPS-based smart factories – i.e. operations management ones. Finally, section 5 draws the conclusions and the future developments of this research.

2 Adopted methodology

In order to identify and understand the characteristics of CPSs, a structured literature review was performed. Specifically, taking into account the peculiarities of the operations management field compared to other fields such as medicine, the guidelines provided by Durach, Kembro and Wieland [21] were followed as detailed in the remainder. Moreover, the review articles written by specific authors in this field [22,23] were taken as guidelines.

The review process has been synthesized in the following flow chart (Figure 1).

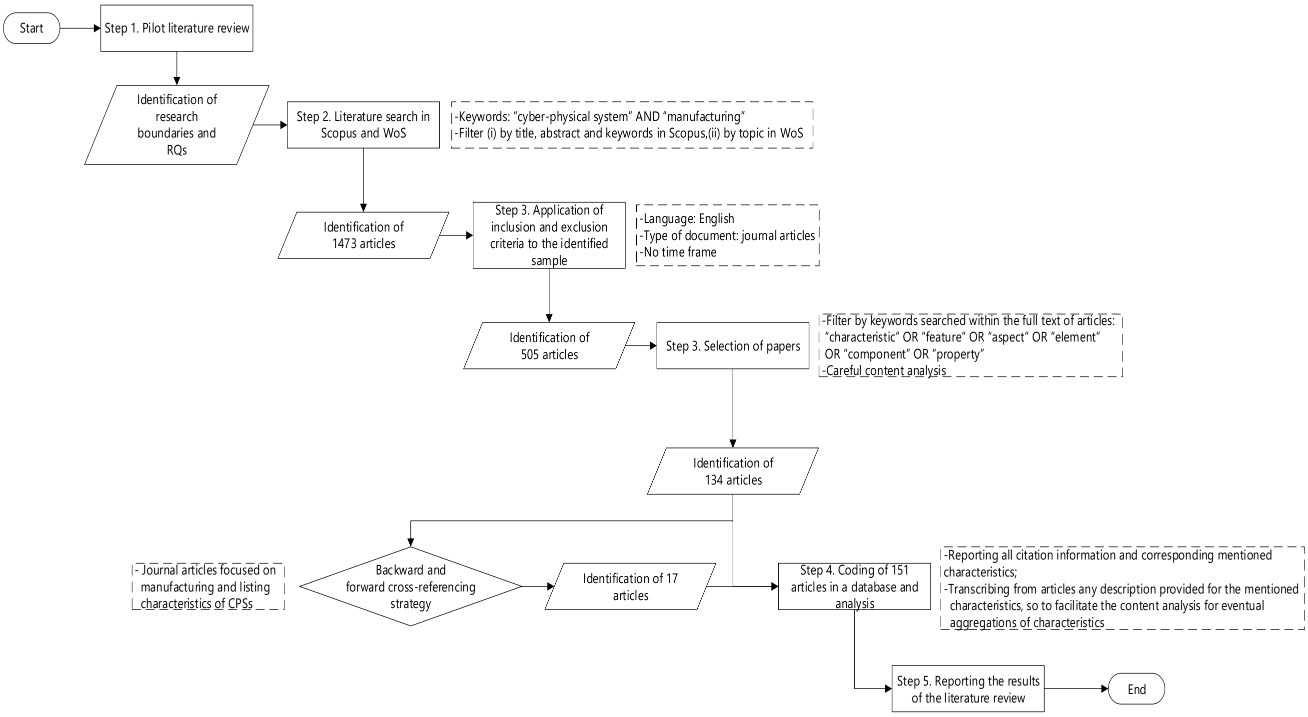

Figure 1 Adopted methodology

In a first step, the two relevant research questions were identified through a pilot literature review; the participation of the present authors in research and development projects in industrial settings had been influent to drive the pilot review. Consequently, the boundaries of the review were defined as argued in section 1.

In a second step, the sample of potentially relevant literature was identified. In order to find relevant papers from the academic point of view, the search databases used for the investigation are Scopus and WoS. To ensure the coverage of the research questions, the keywords "cyber-physical system" and "manufacturing" were combined through an AND Boolean operator. To remain in the research boundaries, articles identified through the Scopus database were filtered by article title, abstract and keywords; those identified through the WoS database were filtered by topic. Overall, 1473 works were identified (1466 on Scopus, 286 on WoS and 279 on both the search engines).

In a third step, the pertinent literature was selected by applying appropriate inclusion and exclusion criteria to the identified sample, as detailed below.

- To ensure the high impact of the selected articles in terms of readership, only articles written in English language were reviewed.

- To ensure the quality of reached primary studies, only journal articles were considered.
- To ensure the reliability and validity of the findings, theoretical, empirical and review papers were considered.
- Finally, no time frame was set as literature on the application of CPSs in manufacturing is relatively recent.

By applying the aforementioned criteria, a set of 505 articles was identified (491 in Scopus, 127 in WoS and 113 on both the search engines). In order to further select literature, the so identified set of articles was analysed in different ways. Firstly, to identify the characteristics of CPSs, the keyword “characteristic” (or “feature”, “aspect”, “element”, “component” and “property”) was searched within the full text of the identified 505 articles, so to ensure the identification of any article relevant to the purpose of the present paper. Once the keywords had been detected, corresponding text was examined in order to verify if such words were used in association to CPSs and, if so, to select those articles listing specific sets of characteristics. Following this procedure, a total of 134 articles listing characteristics of CPSs was selected. Furthermore, through a backward and forward cross-referencing strategy, other 17 journal articles were added within the scope of the investigation as they were focused on manufacturing and listing characteristics of CPSs.

In a fourth step, the 151 relevant articles were carefully analysed and coded in a database, reporting all citation information and corresponding mentioned characteristics. Whenever articles provided descriptions for the mentioned characteristics, these were reported in the Excel database so to facilitate the content analysis for eventual aggregations of characteristics. The overall set of 151 relevant articles is authored by 427 researchers and, as shown in the following chart (Figure 2), some of the researchers authored more than one work (for example Xu X. contributed to 10 of the 151 articles). This aspect was taken into account during the analysis and consequently to draw the results of the review as explained below.

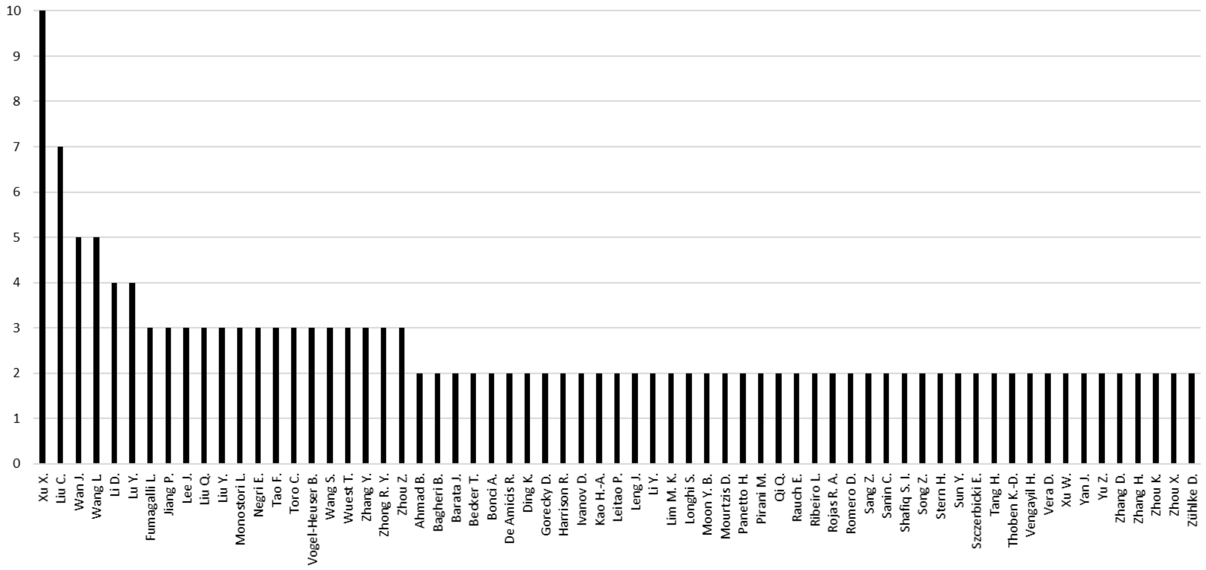

Figure 2 Researchers with multiple authorship within the sample

In a final step (as specified in the methodology suggested by Durach, Kembro and Wieland [21]), the results of the review were reported as detailed in the two results sections (i.e. sections 3 and 4).

The following flow chart (Figure 3) synthesizes the results of the literature review.

(Figure 3 here)

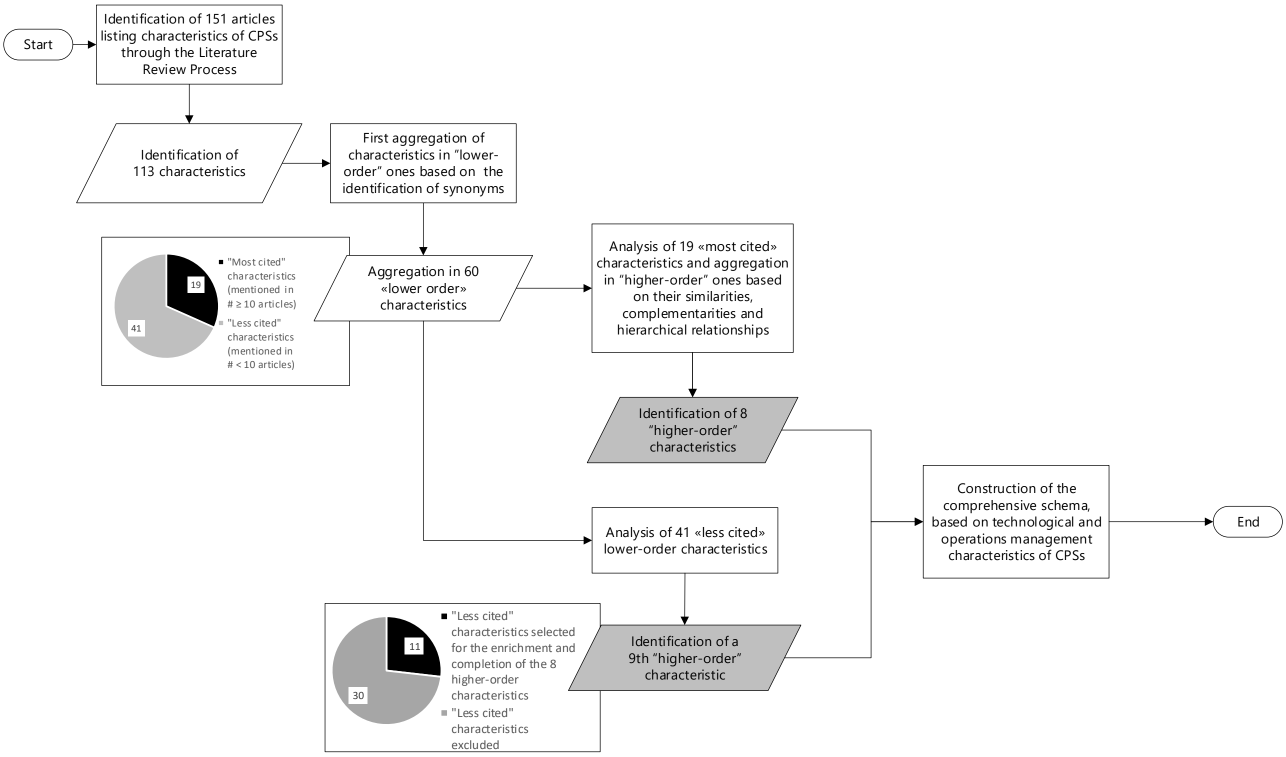

Figure 3 A summary of the results of the literature review

Based on the selected 151 articles, an extended list of 113 characteristics was identified. In this list, based on literature-based definitions, many of these characteristics were considered as synonyms and were grouped together as they can be intuitively overlapped (see for example connectivity and connectedness); therefore, the 113 characteristics were led back to a set of 60 "lower-order" characteristics. In the appendix, Tables A.1 and A.2 detail the results of this analysis: they specify articles mentioning specific characteristics (or their reported synonyms) and, in their last row, they provide the total number of articles mentioning such characteristics as indicator proxy for their current recognition in literature. Overall, 19 lower-order characteristics (i.e. those reported in the columns of appended Table A.1) were "most cited" ones as mentioned by at least 10 references.

As detailed in section 3, the literature-based definitions of the 19 most cited lower-order characteristics were analysed. Based on their definitions, these characteristics were further grouped together, based on their: (i) similarities, (ii) complementarities and (iii) hierarchical relationships. As a result, they were led back to a total of eight "higher-order" characteristics.

As detailed in section 4, in order to enrich and complete the eight higher-order characteristics, the literature-based definitions of the 41 “less cited” lower-order characteristics (those reported in the appended Table A.2) were also analysed and, based on their semantic meaning, some of them – i.e. a total of 11 lower-order characteristics – were selected. This further analysis led to the addition of a ninth higher-order characteristic to the set of eight characteristics previously identified. The remaining 30 “less cited” lower-order characteristics were excluded by the present authors because either: (i) their semantic meanings do not provide a particular enrichment or completion to the most cited characteristics; or (ii) are outside the scope of this paper since they refer to business performances while the paper is focused on technological and operations management characteristics.

To avoid any bias due to the presence of researchers with multiple authorship, the two results sections (i.e. sections 3 and 4) – which actually describe the characteristics exploiting concepts developed in the available literature – were built using the observations of as many authors as possible. For this reason, other articles outside the sample of 151 articles and reached by searching on Scopus and WoS the combination of the keywords “cyber-physical system”, “manufacturing” with any of the characteristics reported in Tables A.1 and A.2, contributed to build the results sections (i.e. sections 3 and 4).

Lastly, the nine higher-order characteristics were classified in technological (thus, associable to CPSs) and operations management ones (thus, associable to the entire CPS-based smart factory). The overall representation of groups of characteristics and relationships were synthesized in a comprehensive schema.

3 Characteristics of CPSs according to literature

This section focuses on the 19 most cited lower-order characteristics, providing their literature-based descriptions and explaining the reasoning behind their aggregation in eight higher-order characteristics, identified by the abbreviations C1, C2, C3, C4, C5, C6, C7 and C8. A list of abbreviations is provided in the appendix.

The remainder of this section – organized in correspondent sub-sections – illustrates how the analysis led to such aggregation. As for narration, the following logic is adopted for each of the eight higher-order characteristics:

- Firstly, a brief analysis of literature leading to the identification and justification of similarities (if any) between characteristics is presented. When present, such similar characteristics are stylistically described within the same bullet point.
- Secondly, a brief analysis of literature leading to the identification and justification of relationships (if any) between characteristics is provided (both their complementarities and hierarchical relationships were considered). When present, relationships are stylistically described within dedicated final bullet points.

3.1 Complexity/heterogeneity encapsulation (C1)

- **Complexity/heterogeneity encapsulation**. In manufacturing, the complexity of CPSs is due to the different nature of their elements. CPSs are often equipped with embedded systems (software and hardware) able to generate, communicate, and evaluate huge amounts of data about the ongoing production processes [24]. Indeed, CPSs are made of elements having heterogeneous nature [5,25,26]. According to Yuan, Anumba and Parfitt [27], CPSs are heterogeneous because they integrate several different systems together with standard communication and information exchange. They integrate various devices, including sensors, mobile devices, workstations and servers. Many authors remarked that CPSs' complexity/heterogeneity should be properly encapsulated and managed [15,28,29]. Even when referring to the "management" or "handling" of complexity/heterogeneity [29,30], the characteristic has typically been interpreted as a design requirement [8,31]. Indeed, the complexity has to be "encapsulated" during the engineering process (see [32,33]). Moreover, dynamic processes of heterogeneous systems included in CPSs should be properly designed, characterized and controlled [10,25,34]. All in all, handling the complexity and the heterogeneity is an issue related to the integration problem: it should be solved through proper solutions of encapsulation of systems and devices [7,31,33,35–37]; indeed, encapsulation can be considered a general design principle inherent to CPSs.

3.2 Interoperability, connectivity, communication, networking capability (C2)

- **Interoperability**. Interoperability is the capability of system components to connect, communicate, and operate with each other [9,38]. In other words, interoperability allows CPSs to exchange mutually intelligible information [39]. A critical factor for interoperability is standardization because components have to understand with each other [5,40,41]. Ghobakhloo [38] emphasized that interoperability differs from data standardization, as it is concerned with the meaning of the contents of the data and how different components of a system can communicate and understand the meaning of the data, and make a decision based on it. On the other hand, interoperability is enabled by standardization [42]: according to Leitao et al. [5], within heterogeneous CPS systems, the interoperability and the understanding of shared knowledge is an important aspect; to this end, standards addressing interoperability, information exchange and interfaces to legacy systems must be considered. Having similar concerns, the interoperability of CPSs allows reducing some relevant costs of manufacturing systems by avoiding the effort of building customized integration of their components [43].
- **Similarity of communication and connectivity**. The communication or, equivalently, connectivity characteristic of CPSs ensures real-time data acquisition from the physical world and information feedback from the cyber space [44–46]. Indeed, CPSs consist of entities that are connected, based on the context, within and across all levels of production activities, from machine operation, process control, up to entire production and logistics networks [32,47,48]. According to Wang, Torngiren and Onori [49], communication between CPSs may rely on the Internet. To them, when involving the Internet, CPSs are Internet of Things (IoT) Systems (systems in which components provide data over the Internet). Thus, the IoT is an important enabler of CPSs [50–52]. For example, Tedeschi et al. [52] remarked that Internet of Things (IoT) is an important and innovative technology used to defining internet protocols to allow

communication between machines, devices, objects and sensors. According to Isaksson, Harjunkoski and Sand [50], IoT means that any device can be connected to the internet allowing two-way communications across or between production systems: this makes new data available also across operations and supports more horizontal applications with decentralized decision making. As stated by Laird [51], relying on the infrastructure provided by the IoT, CPSs can share and analyse data and, based on what they learn, they can send out control commands to physical resources: by doing so they monitor and control the physical processes.

- **Networking capability**. The networking capability can be described using the words of many authors [53–55]: CPSs should be composed of interconnected clusters of processing elements and physical elements in large-scale wired and wireless networks through a variety of sensors and actuators, aiming at constructing intelligence across different fields. Connecting these fields usually relies on the Internet; dynamic participation in the network is herein possible.
- **Hierarchical relationships between the characteristics in C2**. Building CPSs in manufacturing requires achieving interoperability, as base requirement for information exchanges amongst CPSs. In other words, interoperability allows developing the communication and connectivity of CPSs, indeed such systems connect with each other and with humans communicating via standard interfaces [56]. To some authors, connectivity allows manufacturing objects to set-up and use connections to other objects of a system [57,58]. Overall, the networking capability is enabled by the characteristics of interoperability, communication and connectivity [39,59,60]. To this end, many authors also referred to the “network connectivity” characteristic [25,61–64], which ensures that the sensing data can be successfully delivered from each sensor to specific network nodes.

3.3 Service orientation (C3)

- **Service orientation**. Through interconnection and communication, complex manufacturing tasks can be accomplished collaboratively by several manufacturing “services” [38]. Indeed, Yuan, Anumba and Parfitt [27] referred to the ability of CPSs to provide timely service in order to deal with real-time constraints. In CPSs, cyber aspects also include digital services encapsulated in service-oriented architectures [65]. The design of such architectures promises rapid integration of data and business processes [66,67]. In a service-oriented structure, the functionality implemented by each entity – in the CPSs' environment – is easily accessible to the others [42,68]. Moreover, following service-oriented constraints when developing the control logic of a system is a way to handle the complexity of integration [35].

From a different perspective, another footprint of service orientation is the growth expected for service/app marketplaces applied to smart manufacturing [15]. App/service marketplaces had gained significant attention in recent years as they offer flexibility, while the advances in cloud computing and cloud manufacturing support this claim [69]. Therefore, flexible app/service marketplaces that offer a set of core apps and allow users, or independent third parties, to develop customized apps focusing on certain issues in smart manufacturing realm, are desired by industries and researchers [4].

3.4 Modularity, autonomy, self-capabilities, decentralization (C4)

- **Modularity**. Modularity is the capability of a CPS to be modularized, flexibly changed, and reconfigured in response to rapidly changing customer needs and product changes [1,9,70]. Thus, modularity allows system independence, making it capable to adapt more flexibility [29]. Therefore, modularity is another important enabler of CPSs; indeed, according to Lins et al. [71], to enable their adaptability, CPSs are supposed to be developed in a plug-and-work manner, e.g., by aggregating predefined system modules and machine components (such as robots, conveyors and CNC machines).
- **Similarity of Autonomy and Self-capabilities**. Fettermann et al. [72] associated autonomy to the capacity of CPSs to independently learn and adapt to the environment. According to Ribeiro and Bjorkman [73], CPS are complex and evolving entities with a high degree of autonomy. Such autonomy should be appropriately designed so to ensure the adaptive response to disturbances of

components, enabling them to recover from localized changes. Rosenberg et al. [9] and Pirvu, Zamifirescu and Gorecky [74] described the autonomy of CPSs as their capability to close the control loop over their life-cycle, also assimilating the human factor, thus regardless of their automation degree.

Autonomy brings to the self-capabilities of CPSs. Self-capabilities can in fact be seen as exemplifications of autonomy [10,53]. Instances of self-capabilities are self-adaptivity [75], self-reconfiguration, self-organization [24], self-awareness [18], self-learning [76], self-diagnosis [5], self-healing [77], self-optimization [11], self-protection, and self-explaining [29].

- **Decentralization**. Decentralization means having CPSs working independently and making decisions autonomously in a way they remain aligned with the path toward the single ultimate organizational goal [38]. Distribution, as synonym of decentralization, has often been referred to the control/decision-making system of CPSs [47,78,79]. The components of a distributed system are located on networked computers, communicating and coordinating their actions by exchanging information to meet common goals [34].
- **Hierarchical relationships between the characteristics in C4**. Modularity enables autonomy of CPSs, i.e. the capability to perceive and interact autonomously with their physical environment over their lifecycle [80]. An overall effect of the autonomy/self-capabilities of CPSs, is the change from centrally-structured to decentrally-structured control [36]: thus, decentralization is the ability of CPSs within smart factories to make decisions on their own [1,9,81].

3.5 Integration

- **Integration**. Integration is a necessary and challenging issue for CPSs: CPSs are, indeed, integration of computation and physical processes [49,82,83]. Penas et al. [12] remarked that CPSs integration is a design concern (concerning physical systems, software and platform engineering) allowing future faster design of existing process networks between production resources.

- **Hierarchical relationships of Integration with C1, C2, C3 and C4**. Integration can be seen, and is interpreted as such in this paper, as a more comprehensive characteristic: it can be associated to multiple higher-order characteristics, C1, C2, C3 and C4, as detailed below.

  Firstly, integration is enabled by the complexity/heterogeneity encapsulation (C1) and the networking capability (C2). Indeed, the complexity/heterogeneity encapsulation (C1) is a general design principle inherent to CPSs that looks for solutions of integration of several different systems, also thanks to standard communication and information exchange (C2) [5,8]. Another characteristic enabling the integration of complex/heterogeneous systems is the service-orientation (C3): following service-oriented constraints when developing the control logic of a system is a way to handle its integration [35]. Furthermore, the growth of attention over App/service marketplaces, with the advances in cloud computing, offers flexibility in integrating even customized functionality [69]. The characteristic of decentralization (C4) also enables the integration characteristic: in fact, the decentralization of CPSs has the operational effect of their capability to work independently and make autonomous decisions while being aligned toward a systemic goal [38].

3.6 Virtualization, real-time capability (C5)

- **Virtualization**. Many authors [1,9,70,81] described virtualization as the ability to link sensor data to virtual factory models and simulation models; in other words, virtualization consists in creating a virtual copy of the real physical world and remaining connected to it over time. It allows CPSs both to remotely analyse and track physical processes [27], to simulate behaviours [84] and, in some cases, to allow a communication feedback from the digital world to the field [85]. Ghobakhloo [38] observed that virtualization enables the replication of a “digital twin” of the entire value chain (smart warehouse, smart factory, all related equipment and machinery, and even smart products). Sanderson, Chaplin and Ratchev [86] described the “digital twin” as a digital replica of the real system; such digital twin, supported by context-awareness, allows all elements in the factory to be fully traceable [86] for all their lifecycles granting the so-called digital continuity of the data about the systems, accompanying them from the design to operational and dismissal phases [87]. More comprehensively, Cimino, Negri e Fumagalli [88] defined digital twins as simulation environments which are hosted by, or connected to, the cyber part of CPSs. To them, such environments not only should allow CPSs monitoring physical resources, but also acting on such resources based on simulations results. Indeed, as remarked in some works [23,89], simulation comprises an indispensable set of IT tools and methods for the successful implementation of digital manufacturing. It allows quick and cost-effective experimentation and validation of product, process, and system design and configuration.

- **Real-time capability**. Real-time capability is the ability of CPSs to acquire and analyse real-time data on equipment, quality and raw materials and provide the derived insights immediately [1,9,90]. It is a key characteristic as it allows CPSs to detect any change in the physical processes and react in real-time to ensure the functional and safety requirements of the system [91]. Thus, real-time capability might also imply physical actions to prevent failures [8].
- **Complementarity relationships between the characteristics in C5**. Virtualization and real-time capability are complementary characteristics. Indeed, the “digital twin” is a digital replica of the real system, it should allow the real-time visualization of and feedback on the current status of manufacturing components, so to instantaneously provide the derived insights [1,86,92].

3.7 Computational capability (C6)

- **Computational capability**. Many authors (see, for example [38] and [9]) referred to the computational capability of CPSs. The provided definitions for such characteristic are all referred to data management and analytics carried out with methods/techniques from different domains (such as computer science and statistics). Therefore, the cyber parts of CPSs should be able to perform a significant amount of computation and control work previously performed by human, and today also strengthened by the possibility to share data and interact with each other [34,93].

Moreover, CPSs should be able to perform computing at any location, hence the concept of ubiquitous computing [94]. An enabler of such computational capability of CPSs is cloud computing [95,96]. In fact, cloud technologies provide an environment to connect and share distributed manufacturing resources including knowledge, computing and software tools, as well as physical resources via the Internet networking infrastructure [97].

3.8 Intelligence/smartness

- **Intelligence/smartness**. CPSs are supposed to have intelligence, *alias* smartness, as they are capable of being identified, sensing events, interacting with others, and making decisions by themselves [98]. Monostori [99] referred to the intelligent capabilities of CPSSs regarding data management, analytics and computation. CPSs bring computation and communication capabilities to physical components to create intelligence [100]. Such intelligence is distributed among entities [56,101]. More specifically, a CPS can use sensors and actuators to collect information about the physical operations in real-time and conduct intelligent control over physical systems to adapt to changing conditions and environment [48].
- **Hierarchical relationships of intelligence/smartness with C5 and C6**. Intelligence/smartness can be seen, and is interpreted as such in this paper, as more comprehensive characteristic because it can be associated to two higher-order characteristics, the virtualization and real time capability (C5) and the computational capability (C6). Indeed, CPSs exploit digitalization and real-time capability to collect and monitor information about the physical process in real-time [48], thus they bring the computation capabilities to process information and create intelligence [99,100].

3.9 Cooperation, collaboration (C7)

- **Similarity of cooperation and collaboration**. In this work, cooperation and collaboration are considered equivalent characteristics, even if collaboration is generally a stronger concept entailing resource sharing and joint goals [102]. There is in fact a kind of continuum emerging in the current discussion, from cooperation to collaboration of CPSs. CPSs cooperate within the shop floor for carrying out tasks: they can control themselves for adapting to changes as well as cooperate with other CPSs to accomplish specific activities [103]. According to Etxeberria-Agiriano [8], cooperation is the capability of a distributed system with autonomous subsystems to dynamically decide which components will carry out a certain task in order to optimize performances such as the response time. Indeed, a good combination of autonomy and cooperation of CPSs confers smart factories specific characteristics such as self-organization and self-maintenance [103,104]. It is also worth remarking that many authors specified the inclusion of humans in such process of cooperation/collaboration between entities of the factory [48,49,105]. For example, Wang, Torngren and Onori [49] referred to the symbiotic human-robot collaboration, which combines the flexibility of humans and the accuracy of machines; they referred to the possibility for humans to instruct robots by speech, signs and gestures and the possibility for robots to assist humans in the implementation of tasks. Eventually, collaboration relies on the ability to share manufacturing information between different stakeholders at different locations [49]. Overall, in case of collaboration, involved parties share information, resources and responsibilities to jointly plan, implement and assess the set of activities required to achieve a common goal [102].

3.10 Dynamic reconfigurability, adaptability (C8)

- **Similarity of dynamic reconfigurability and adaptability.** Generally speaking, dynamic reconfigurability refers to the characteristic that enables quick responsiveness to market changes and disturbances [7]. In this perspective, CPSs allow achieving reconfigurable manufacturing [5,12,106]. Specifically, CPSs can evolve over time through dynamic reconfiguration of their structures, they can also reorganize their functionalities, change behaviour and modify their boundaries [12,107].

  Similarly, adaptability is the ability of CPSs to adapt to quickly changing situations and new requirements (such as new products or product variants) through dynamic reorganization/reconfiguration [27,108]. To this end, some authors remarked that adaptability relies on self-organization, learning and evolving capabilities of CPSs [74,104]. Adaptability is especially needed in case of dynamic and turbulent environments [35,109]. Rosenberg et al. [9] referred to the flexible adaptation of smart factories to changing requirements by replacing or expanding individual modules. Also to Panetto et al. [104], systems need to be modular to support modification and (self-)adaptation. To this end, Ribeiro and Bjorkman [73] remarked that the most important design feature to attain adaptability is to endow components at each level with enough autonomy to enact an adaptive response to disturbances, enabling them to deal with localized changes without having to rely on components at a higher level.

3.11 Concluding remarks

The following figure (Figure 4) synthesizes the aggregation of characteristics in the eight higher-order ones.

(Figure 4 here)

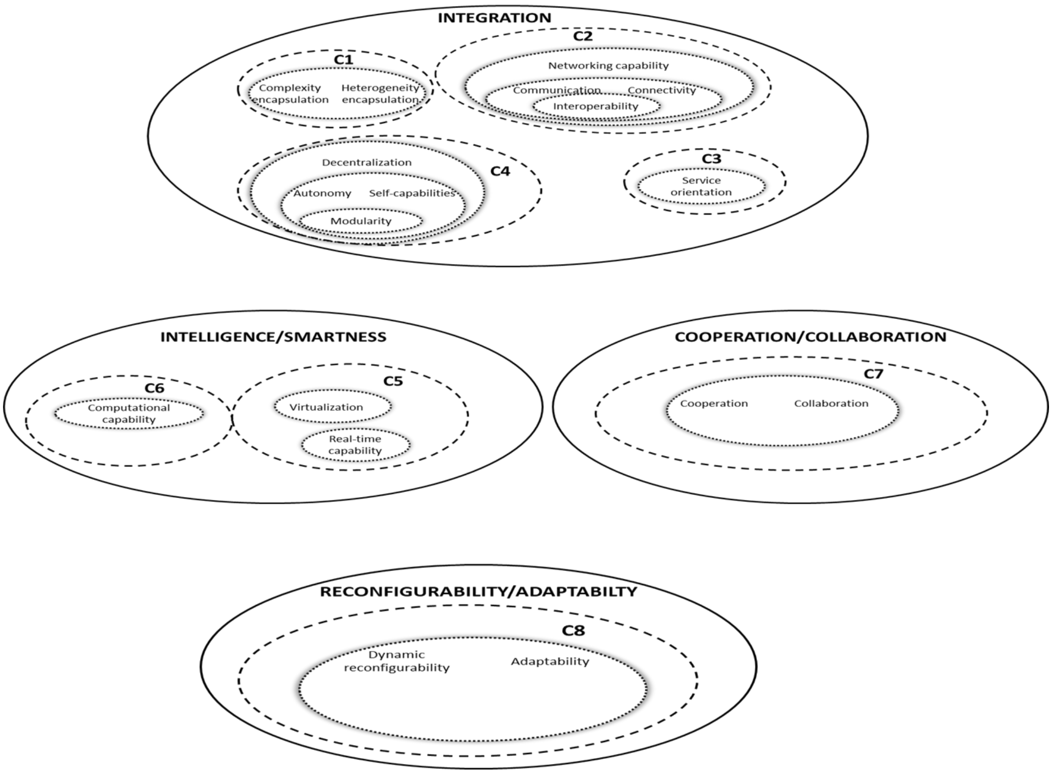

Figure 4 Aggregation of the most cited lower-order characteristics in eight higher-order characteristics

Similarities, complementarities or hierarchical relationships, used to aggregate lower-order in higher-order characteristics, are graphically represented as herein illustrated:

- in case of similarities (e.g. communication and connectivity in Figure 4), lower-order characteristics are represented in the same circles;
- in case of complementarities (e.g. virtualization and real-time capability in Figure 4), lower-order characteristics are represented in juxtaposed circles;
- in case of hierarchical relationships (e.g. decentralization enabled by autonomy/ self-capabilities in Figure 4), lower-order characteristics are represented in hierarchically contained circles (i.e., in the hierarchical relationship, contained circles are enablers of containing circles).

The lower-order characteristics shown in Figure 4, as most cited ones, were considered in this paper as “basic” characteristics. Indeed, these are the basis for the results of this paper.

4 Characteristics to build CPS-based smart factories

This section, enriches the characteristics shown in Figure 4 by adding therein selected less cited lower-order characteristics. As less cited ones, these 11 characteristics were considered in this paper as the ones whether “enriching” or “completing” the “basic” characteristics (i.e. the most cited ones). Finally, in order to address the RQ1 and RQ2, this section further aggregates the characteristics in technological and operations management ones. As anticipated in Section 1, the “technological” characteristics (in a broad sense, also involving specific competences, skills and functionalities offered by technology providers and production resources) should be the base (like bricks to build constructions) to create a smart factory, different from a traditional factory because capable to promptly evolve over time thanks to its “operations management” characteristics.

4.1 Enrichment and completion of characteristics

Definitions of the less cited characteristics (i.e. those reported in the appended Table A.2) were analysed and some of them were appropriately selected based on the knowledge of the present authors, as members of the scientific community and participants in industrial projects. According to their semantic meaning, the selected characteristics were associated to the “basic” characteristics shown in Figure 4. Some of them are described in the remainder as “enriching” the “basic” characteristics, as they can be interpreted as instances of those discussed in section 3. Some others are described as “completing” the “basic” characteristics as they provide additional insights to the characteristics discussed in section 3. The completing characteristics are also represented in the following figure (Figure 5). As shown in Figure 5, this phase of investigation led to the addition of a new higher-order characteristic (C9) to the eight characteristics identified in section 3.

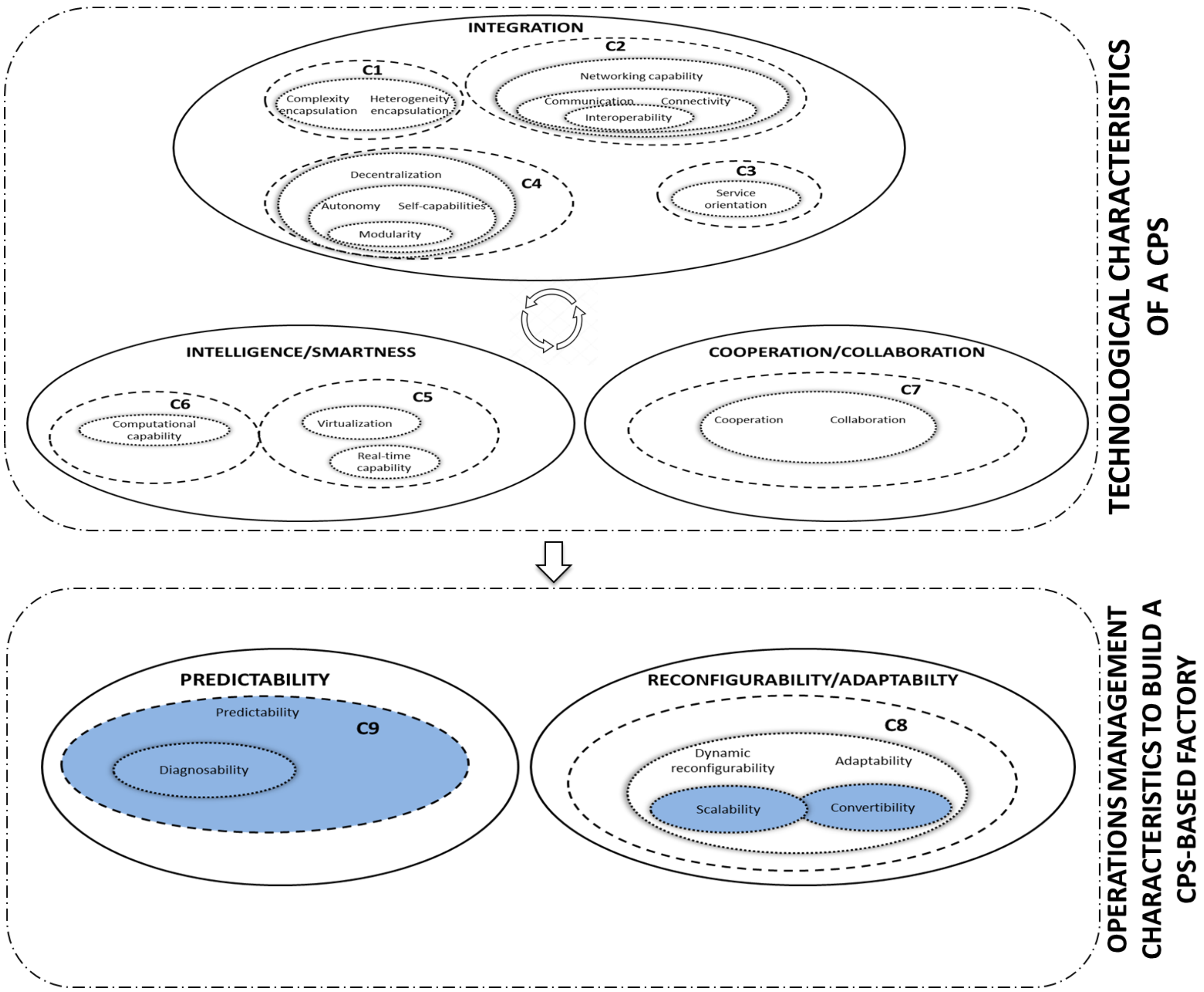

Figure 5 A comprehensive schema of characteristics of CPSs

4.1.1 Enrichment of characteristics

C2 is a characteristic given by the combination of a set of lower-order characteristics, whose overall effect is the networking capability (as discussed in section 3.2). According to literature, different kinds of interaction should be possible in CPSs: human-to-human, machine-to-machine and human to machine/robot/system [36,45,110]. As remarked by Emmanouilidis et al. [111], human integration in industrial environments is receiving increasing attention, with terms such as “Operator 4.0” used to denote the vision of human empowerment with Industry 4.0 technologies. For this reason, the human-machine interaction (which is a lower-order characteristic reported in Table A.2) is considered as a relevant example to be included in C2. Indeed, human presence is essential in CPSs.

C5 is a characteristic given by virtualization and real-time capability as complementary characteristics. It is worth stressing that the real-time capability also includes the real-time visibility (which is a lower-order characteristic reported in Table A.2). Indeed, in a CPS, the current status of manufacturing components can be determined and visualized in real time [92]. For example, Chen and Tsai [94] referred to the application of RFIDs and auto IDs to manufacturing to develop core characteristics such as real-time objects tracking and increased asset visibility.

C6 is a characteristic that, in section 3.7, is described as computational capability. The authors considered appropriate to consider four other characteristics whose combination allows the enrichment of the computational capability. Indeed, the following characteristics (which are lower-order characteristic reported in Table A.2) can be seen as complementary requirements for the intelligent behaviour of CPSs. These are: (i) the context awareness; (ii) the sensing (or perception) capability; (iii) the cognitive (or learning) capability and (iv) the actuation capability. Firstly, a context-aware CPS should assist people and machines in the execution of their tasks through the exploitation of sensors and actuators to trigger actions based on the environmental context [36]. Thus, systems should be self-aware of current state of the production process [112]. Secondly, in order to be able to perceive the context, the sensing capability, which relies on the presence of sensors, is required; according to Wu, Terpenny, and Schaefer [113], multiple types of sensors should be adopted in intelligent CPS applications; these cross-domain sensing data are exchanged over heterogeneous network. Thirdly, sensed data should be exchanged and processed, remarking the relevance of the cognitive capability supporting to this end. The cognitive capability is considered as the ability of CPSs of knowing, thinking, and information processing [114], typically in relationship to the assistance of humans in the decision-making loop [17,18]. Finally, the actuation capability adds the implementation of actions in response to manufacturing problems within the physical environment; to give an example, Chen et al. [75] referred to cognitive robots, which can perceive information uncertainty, change scheduling management and adjust manufacturing behaviour to independently cope with a complex manufacturing problem; another example is a robotic CPS in order to enable safe human-robot collaboration without any fencing [15] through characteristics of dynamic task planning, active collision avoidance, and adaptive control in presence of humans.

C7 is a characteristic that, in section 3.7, was exhaustively synthesized as cooperation/collaboration. However, the authors considered appropriate to further stress the relevance of human presence, by including in C7 a specific example of cooperation/collaboration: the one between humans and machines (which is a lower-order characteristic reported in Table A.2). Emblematically, some authors referred to the “symbiosis” between humans and machines/robots to remark that such collaboration is designed not to replace but to augment the skills and abilities of humans, so to improve productivity and resources effectiveness [14,32,49,115].

4.1.2 Completion of characteristics

C8 is a characteristic synthesized as dynamic reconfigurability/adaptability. The authors considered scalability and convertibility (which are lower-order characteristic reported in Table A.2) as characteristics enabling the dynamic reconfigurability/adaptability (see Figure 5). Scalability allows changing the production capacity of a system quickly and with a low effort. It refers to the ability of complex CPSs to change during their life cycle, due to either a growing or shrinking number of “nodes” (nodes could be either participating or managed physical systems, sub-systems or components of the CPSs) [29]. According to Garcia-Valls et al. [116] scalability means that CPSs should contain the needed logic to deal with aspects such as moving nodes and joining/removing them. Relying on the logical and physical modularity of system components and on the standardization of the interfaces between such modules, CPSs should be scalable and composable [67,73]. Convertibility can be described as the capability of CPSs to extend the overall system functionality by relatively easily adding new functions, supported by modular manufacturing execution systems capable to inform on the current state and support better decisions [35].

Finally, a new characteristic – C9 – was added to the set of eight ones identified in section 3 (see Figure 5). This new characteristic results in the predictability, which, in turn, is enabled by the diagnosability (both predictability and diagnosability are lower-order characteristics reported in Table A.2). C9 is an essential operations management characteristic as it improves the capability of the CPS-based smart factory to react quickly to changes. Indeed, according to literature, predictability strengthens (i) the adaptivity of production and logistics [117] and (ii) the implementation of predictive maintenance [70]. For example, according to Lee, Bagheri and Kao [17], CPSs' capability to predict the behaviour of machines relies on degradation monitoring and remaining useful life prediction of machine components as well as predictive health monitoring of machines.

Predictability is the ability to predict CPSs' behaviour, supporting the detection of unexpected events and the root cause analysis in case of a failure [29]. As shown in Figure 5, predictability is enabled by the diagnosability of CPS-based smart factories: such factories should autonomously detect and diagnose the root cause of product defects or otherwise actively support users in their identification; moreover, they should operate in a traceable way [67,73]. Sun et al. [118] stressed the need to ensure the timeliness of the characteristic of predictability. Such timeliness can be achieved recurring to the diagnosability. Indeed, in smart manufacturing diagnosis and prediction of equipment faults will become routine and, in some cases, autonomous repair may take place [119]. For instance, intelligent machines may trigger maintenance processes autonomously and may be capable of predicting failures [120].

4.2 Characteristics of CPSs and characteristics of CPSs-based smart factories

The aforementioned schema (Figure 5) is a construct based on literature findings; it answers to the RQ1 and RQ2 by aggregating the aforementioned nine higher-order characteristics in two macro-groups: the technological (in a broad sense) ones, describing the CPSs, and the operations management ones, to build the CPS-based factory.

This construct relies on a distinction between technological and operations management characteristics: to the aim of this paper, technological characteristics are intended as structural enablers of operations management characteristics; the latter, unlike technological ones, need to be dynamically exploitable to deal with operational aspects, leading to the operational practices implemented in a CPS-based smart factory.

Thus, in Figure 5, a first macro-group includes the technological characteristics that describe CPSs (intended as technological systems included within the factory). It contains three groups of higher-order characteristics that were synthesized in section 3 as: (i) "Integration", (ii) "Intelligence/smartness" and (iii) "Cooperation/collaboration". The second macro-group drawn in Figure 5 includes the operations management characteristics to build CPS-based smart factories (intended as comprehensive systems made of CPSs with the purpose to develop new manufacturing applications leading to new operations management practices). This group includes the remaining higher-order characteristics: "Reconfigurability/adaptability" and "Predictability". Such characteristics describe the systemic operational effect of the introduction of CPSs (thus, they are characteristics of the CPS-based smart factory).

4.3 Concluding remarks

In this section, literature is exploited to achieve the characterization of the CPS-based smart factory. The major characteristics are also synthesized in the schema of Figure 5, which actually synthesizes the answer to the two RQs.

The following table (Table 1) synthesizes and quantifies the results of the literature review. The first column lists the lower-order characteristics analysed in sections 3 and 4. Therefore, the second column specifies whether such characteristics are (i) the basic ones (i.e. those leading to the schema of Figure 4) or (ii) the completing ones (i.e. those enriching the Figure 4, leading to the schema of Figure 5). Moreover, from left to right, Table 1 shows the progressive aggregations of lower-order characteristics in higher-order ones and then in technological and operations management ones.

From the numerical point of view, Table 1 provides:

- indication of recognition for each lower-order characteristic, reporting in the third column the total number of times these were addressed as characteristics of CPSs (such figures are also reported in the last rows of the appended Tables A.1 and A.2 which, indeed, count the total times each characteristic were mentioned/recognised);
- indication of recognition for each higher-order characteristic (i.e. C1, C2, …, C9), reporting in the fifth column the total number of references addressing them as characteristics of CPSs (obtained by summing times in which references referred to any of their lower-order characteristics);
- indication of recognition for each group (i.e. integration, intelligence/smartness, cooperation/collaboration), reporting in the seventh and eighth columns the total number (obtained by summing times in which references referred to all their higher-order characteristics) and percentages of references addressing them as characteristics of CPS.

Overall, the last column of Table 1 finally results in an indication of recognition of the two macro-groups – i.e. the characteristics of a CPS (or technological characteristics) and the characteristics of a CPS-based smart factory (or operations management characteristics) – by summing percentages of times literature dealt with their corresponding higher-order characteristics. Such indication provides a measure of their relative weights, thus it is a proxy for their current recognition among researchers. For the sake of clarity, the percentage values reported in the eighth (and tenth) column were calculated diving the aggregated totals corresponding to specific groups (and macro groups) of characteristics by total number of references (e.g. 56,24% is obtained dividing 248 by 441).

(Table 1 here)

Table 1 Summary of characteristics of CPSs according to literature

Lower-order characteristics	Basic (B)/ Completing (C) characteristics	Total references	Higher-order characteristics	Aggregated totals for higher-order characteristics	Groups	Aggregated totals for groups	Relative weights of groups	Macro groups	Relative weights of macro groups
Integration	B	19	Integration	19	Integration	248	56,24%	Characteristics of CPSs (technological ones)	85,71%
Complexity and heterogeneity encapsulation	B	18	C1	18					

Interoperability	B	15	C2	96					
Connectivity	B	47							
Communication	B	14							
Networking capability	B	20							
Service orientation	B	12	C3	12					
Modularity	B	14	C4	103					
Autonomy	B	46							
Self-capabilities	B	19							
Decentralization	B	24							
Intelligence/ smartness	B	37	Intelligence/ Smartness	37	Intelligence/ Smartness	102	23,13%		
Virtualization	B	20	C5	40					
Real-time capability	B	20							
Computational capability	B	25	C6	25					
Cooperation	B	14	C7	28	Cooperation/ Collaboration	28	6,35%		
Collaboration	B	14							
Scalability	C	7	C8	49	Reconfigurability/ adaptability	49	11,11%	Characteristics of CPS-based smart factories (operations management ones)	14,29%
Convertibility	C	2							
Dynamic reconfigurability	B	11							
Adaptability	B	29							
Diagnosability	C	5	C9	14	Predictability	14	3,17%		
Predictability	C	9							
Total	B	441		441		441	100%		100%

As synthesized in Table 1, the great part of available contributions is on technological characteristics, especially on the integration characteristics (i.e. the aggregation of C1, C2. C3 and C4). So far, operations management characteristics have gained less attention from literature.

Some of the less cited characteristics, selected based on their semantic meaning, added interesting insights on the most cited ones (as reported in Sections 4.1.1 and 4.1.2). In particular, regarding technological characteristics, (i) the relevance of human presence was stressed and (ii) the computational capability was detailed with the complementary characteristics of sensing, actuation and cognitive capabilities. Moreover, as shown in Figure 5, the enrichment of the characteristics was especially insightful to gain further feedback on operations management characteristics. Above all, a new characteristic – C9, representing the predictability of the factory – was added. It adds to the other two characteristics of a CPS-based smart factory the inclusion of aspects allowing quick reactions to shop-floor contingencies.

5. Conclusions

In this paper, based on literature review, the characteristics of CPSs were investigated. As a result, nine characteristics were identified, by aggregating together – based on similarities, complementarities and hierarchical relationships – a high number of characteristics introduced by available literature. Thus, characteristics were classified and synthesized in a comprehensive schema to build future CPS-based smart factories: technological characteristics (i.e. those specifically describing CPSs as technological systems) are building bricks that should be properly combined together to allow practitioners to build CPS-based smart factories which are different from traditional thanks to their characteristics of reconfigurability/adaptability and predictability (referred as operations management characteristics in this article).

Therefore, the schema is a first step to envision how factories will be evolving in a next future, towards CPS-based operations. To move further in this direction, additional research is required.

- The relationships between such characteristics may be explored, so to achieve an understanding of "how" technological characteristics should be exploited by operations managers to benefit from the implementation of CPSs. Indeed, practitioners need to know how new technologies should be combined together and managed to successfully face the current and future scenarios.
- Moreover, the schema may be enriched by means of the reinforcement of extant characteristics as emerged in this work, and the introduction of new characteristics, upcoming in the next years; specifically, the schema may be valuably enriched focusing on the operations management characteristics, which, as shown in Table 1, do not boast a high number of contributions.

- Finally, an investigation on the effects of both technological and operations management characteristics on business competitiveness may allow glimpsing the benefits of operations management characteristics in terms of business performances. Indeed, the business management perspective is a relevant topic that is outside the scope of this paper, but deserves further research (to this regard, the appended Table A.2 shows that some authors identified characteristics related to business performances, specifically, eight papers referred to "responsiveness" which indeed represents a highly desired performance in the current unpredictable context).

The main limitation of this work is related to the relative novelty of the topic, leading to the rapid evolution of the topic itself and the correspondent development of new theory. For this reason, a future replication of this research may lead to slightly changed results; however, by comparing new results with current results, any replication may actually help framing the evolution of CPS-based smart factories over time.

Concerning future development of the theory, starting from the present paper, it is worth making some reflection.

- The analysis of the less cited characteristics was useful, in the present work, to shed light on the (currently less investigated) operations management characteristics. Looking at future development, such less investigated characteristics can be intended as symptom of newly emerging characteristics that could reinforce in future researches.
- Moreover, industrial practices are essential to provide insightful suggestions on how such evolution will take place: digitalization is an on-going phenomenon in current firms, thus empirical research may provide useful insights on how characteristics of CPSs should be actually concretized in manufacturing firms of different sectors.

Thus, for a complete understanding on how future CPS-based smart factories will develop, empirical research on field should be associated to the theoretical contribution. Indeed, field-based examples on how this digitalization is currently taking place may bring into light insights on managerial best practices and/or weaknesses, accelerating the knowledge generation process. Finally, empirical research is also strongly suggested to gain relevant insights on how CPS-based factories will be declined in different sectors: another limitation of this work is the lack of reference to any specific sector and, as this paper has the aim to spread awareness to practitioners, future research may valuably focus on the specification of the characteristics according to different sectors.

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Appendix

(Tables A.1 and A.2 here)

Table A.1 Characteristics of CPSs according to literature (most cited characteristics)

Authors	Integration	Complexity encapsulation/ Heterogeneity encapsulation/ Complexity/ Heterogeneity	Interoperability	Connectivity/ Connectedness/ Interconnection	Communication/ Data exchange characteristic	Networking capability /Network connectivity/ Network changeability	Service orientation/ Servitization	Modularity	Autonomy	Self-capabilities	Decentralization/Distribution	Intelligence/Smartness	Virtualization /Digitalization / Digital twin	Real-time capability	Computational capability /Analytical capability	Cooperation	Collaboration	Dynamic reconfigurability/ Reconfigurability/ Configurability	Adaptability / Adaptivness /Self-adaptation /Adaptivity /Automated adaption/ Adaptive response
Alexoupoulos et al. 2018 [121]	▨		▨		▨		▨		▨		▨		▨		▨		▨		▨

Allgöwer et al. 2019 [122]				X					X		X						X		X
Ang et al. 2017 [123]									X										
Beregi, Pedone and Mezgár 2019 [124]						X									X				
Bibby and Dehe 2018 [125]				X															
Bohacs and Rinkacs 2017 [126]									X		X								
Bonci, Pirani and Longhi 2017 [127]										X									
Brodner 2018 [128]									X			X							
Byrne et al. 2018 [30]		X																	
Cardin 2019 [56]				X	X							X			X				
Carreras Guzman et al. 2019 [91]														X					
Chang and Chen 2017 [129]			X	X													X		
Chen 2017 [130]	X			X								X			X		X		
Chen and Tsai 2017 [94]			X																
Chen et al. 2018 [75]	X	X		X				X	X		X	X					X	X	
Cheng et al. 2018 [131]	X			X									X						
Cimino, Negri and Fumagalli 2019 [88]													X						
Contreras, Garcia and Pastrana 2017 [42]												X							
Cozmiuc and Petrisor 2018 [132]		X																	
Cruz Salazar et al. 2019 [133]																		X	X
Culler and Long 2016 [134]					X				X	X					X		X		
Ding and Jiang 2017 [135]	X			X	X		X		X	X	X								
Dumitrache et al. 2019 [136]				X							X								
Facchinetti and Della Vedova 2011 [117]	X																		
Fettermann et al. 2018 [72]				X					X							X			
Fumagalli et al. 2018 [137]								X											
Gaham, Bouzouia and Achour 2015 [138]									X			X					X		
Garetti, Fumagalli and Negri 2015 [16]		X				X													
Ghadimi et al. 2019 [139]				X							X			X					
Ghobakhloo 2018 [38]	X			X			X	X			X	X	X		X				
Gladysz 2015 [46]					X										X				
Grundstein, Freitag and Scholz-Reiter 2017 [140]						X				X		X							
Harrison, Vera and Ahmad 2016a [31]		X						X											
Harrison, Vera and Ahmad 2016b [141]	X			X													X		
Hofmann and Rusch 2017 [90]				X						X			X						X
Hozdic 2015 [142]									X							X		X	
Hu and Zhou 2018 [143]									X										
Huang et al. 2019 [144]								X			X		X	X					
Hwang 2016 [120]																			
Iarovyi et al. 2016 [35]																			X
Ilsen, Meissner and Aurich 2017 [24]									X	X	X								
Ivanov, Sokolov and Ivanova 2016 [107]											X								
Jakovljevic, Mitrovic and Pajic 2017 [145]					X									X	X				
Jiang, Ding and Leng 2016 [146]							X												
Jiang et al. 2017 [147]		X							X		X	X							
Jones, Romero and Wuest 2018 [148]			X	X								X							X
Kang, Lee and Noh 2019 [149]												X		X					
Kao et al. 2015 [150]										X			X						
Khalid et al. 2016 [151]									X	X									X
Kolberg, Knobloch and Zuhlke 2017 [152]																			X
Krishnamurthy and Cecil 2018 [153]		X				X									X		X		
Krueger et al. 2016 [68]				X					X							X			
Kusiak 2018 [119]	X		X	X									X				X		
Latorre-Biel et al. 2018 [154]				X	X								X		X				
Lee, Bagheri and Kao 2015 [17]				X								X			X				
Lee and Kim 2016 [155]		X		X															
Lee, Bagheri and Jin 2016 [156]	X		X																
Lee, Ryu and Cho 2017 [1]			X				X	X			X		X	X					
Leitao et al. 2015b [157]															X				
Leng et al. 2019 [158]					X										X				
Li et al. 2017 [28]					X					X									
Lins, de Araujo and Corazzim 2019 [71]								X											
Liu and Jiang 2019 [159]									X			X							
Liu and Xu. 2017 [160]	X					X						X							
Liu et al. 2017 [44]				X		X						X			X				X
Liu et al. 2018 [161]				X		X			X			X	X	X	X				
Liu et al. 2019 [162]						X						X		X					X
Lu and Xu 2019 [58]				X								X							
Luo and Kuo 2016 [163]		X					X		X										
Miranda et al. 2017 [164]									X							X			
Moghaddam et al. 2018 [79]			X	X			X		X				X						
Monostori 2015 [99]				X					X							X			

Monostori et al. 2016 [32]				X								X			X				
Mora et al. 2017 [34]		X				X								X	X		X		
Morel, Pereira and Nof 2019 [165]							X		X										
Morozov, Lezoche and Panetto 2018 [166]					X				X										
Mourtzis and Vlachou 2018 [41]			X	X															
Neugebauer et al. 2019 [167]						X													
Oborski 2016 [168]															X				X
Ocker et a. 2019 [169]				X													X		
Otto, Vogel-Heuser and Niggemann 2018 [108]																			X
Panetto et al. 2019 [104]		X	X						X	X						X			X
Penas et al. 2017 [12]	X	X		X					X			X			X	X			
Pereira and Romero 2017 [80]				X					X				X			X			
Peres et al. 2018 [170]										X									
Peruzzini and Pellicciari 2017 [171]										X									X
Pirvu, Zamfirescu and Gorecky 2016 [74]	X								X										X
Posada et al. 2015 [105]				X					X			X							
Qu et al. 2019 [172]									X			X			X				
Rama et al. 2016 [110]				X															
Ribeiro and Bjorkman 2018 [73]								X										X	X
Ribeiro and Hochwallner 2018 [67]																			X
Rojas et al. 2017 [39]				X	X				X							X			
Rojas and Rauch 2019 [173]		X																	
Ruppert et al. 2018 [40]	X		X					X			X		X						X
Sanderson, Chaplin and Ratchev 2018 [86]				X				X	X	X			X						
Sanislav and Miclea 2012 [174]						X												X	
Schuhmacher, Baumung and Hummel 2017 [175]									X										
Shafiq et al. 2015 [176]																			X
Shafiq et al. 2016 [177]																			X
Shamim et al. 2017 [114]											X								
Song et al. 2017 [178]		X				X	X												
Song and Moon 2019 [179]						X	X						X	X					
Sun, Zhou and Yang 2018 [180]							X												
Tang et al. 2017 [101]									X	X		X							X
Tang et al. 2018 [181]									X	X		X							X
Tao and Qi 2019 [65]			X	X			X										X		
Tao et al. 2019 [182]					X														
Tarallo et al. 2018 [183]													X	X					
Tavcar and Horvath 2019 [184]										X				X					X
Terziyan, Gryshko and Golovianko 2018 [185]			X					X					X	X					
Thoben, Wiesner and Wuest 2017 [15]																	X		
Thramboulidis and Christoulakis 2016 [186]									X						X			X	X
Tran et al. 2019 [103]					X				X	X		X				X			X
Trappey et al. 2016 [78]									X		X								
Tsai and Lu 2018 [112]				X						X				X					
Tu, Lim and Yang 2018 [48]				X								X							X
Tuptuk and Hailes 2018 [187]			X					X											
Uhlmann, Hohwieler and Geisert 2017 [188]						X					X	X							
Upasani et al. 2017 [47]				X					X							X			
Wan et al. 2011 [10]	X	X				X					X							X	
Wan et al. 2013 [25]	X					X			X		X							X	
Wang et al. 2015 [189]			X			X									X				
Wang, Torngren and Onori 2015 [49]	X	X		X					X		X			X			X		X
Wang and Haghighi 2016 [55]						X					X	X		X	X				X
Wang et al. 2016 [190]				X					X		X								
Wang 2017 [191]				X			X							X					
Wang, Zhang and Zhong 2020 [192]												X							
Weyer et al. 2016 [106]				X		X		X			X		X						
Woo et al. 2018 [57]				X								X							
Wu, Kao and Tseng 2011 [54]					X	X						X							
Wu and Moon 2019 [193]				X								X							
Xu 2017 [194]	X																		
Xu and Hua 2017 [195]	X																	X	
Xu and Duan 2019 [196]				X								X							
Xu et al. 2018 [197]				X								X							
Yao et al. 2018 [198]															X				
Yu, Xu and Lu 2015 [199]													X						
Yu et al. 2017a [77]			X					X	X			X				X		X	X
Yu et al. 2017b [45]				X					X	X		X				X			X
Yuan, Anumba and Parfitt 2015 [27]	X	X							X		X		X	X		X			X
Zhang et al. 2017 [200]									X									X	
Zheng et al. 2018 [201]									X	X	X			X					

Zhou, Liu and Liang 2016 [2]		X												X					
Zhou et al. 2018 [202]					X										X				
Zhou et al. 2019 [93]	X											X			X				
Total	19	18	15	47	14	20	12	14	46	19	24	37	20	20	25	14	14	11	29

Table A.2 Characteristics of CPSs according to literature (less cited characteristics)

Authors	Closed-loop control and high degrees of automation/ Automation	Control /Self-control	Human in the (control) loop/ Human integration	Integrability	Interactivity/ Real-time communication	Human-machine interaction	Openness	Cyber capability	Integrality	Context awareness / Context sensitivity /Self-awareness	Sensing capability / Perception capability	Cognitive capability/ Learning capability/ Self-learning	Actuation capability	Human-machine cooperation/ Human-robot collaboration	Sociability/Socialization/Sociality/Benevolence(willingness to cooperate)	Timeliness	Real-time Visibility / Visibility-traceability	Predictability / Self-predictiveness / Prediction	Redundancy /Resources replication	Diagnosability /Maintenability / Self-diagnosis/ Self-healing	Locality	Mobility	Scalability	Convertibility	Usability/Composability/ Reusability/Commonality	Irreversibility /Evolvability	Personalization / Customization	Flexibility	Efficiency /Cost-effectiveness	Security/ Reliability/ Safety	Robustness/ Resiliency	Responsiveness / Proactiveness	Reactivity	Dependability	Discretization	Others mentioned only one time (specified in the corresponding row)
Alexoupoulos et al. 2018 [121]										X																										
Allgöwer et al. 2019 [122]	X																																			
Beregi, Pedone and Mezgár 2019 [124]											X		X																							
Bohacs and Rinkacs 2017 [126]							X												X													X				
Bonci, Pirani and Longhi 2017 [127]								X																												
Bonci, Pirani and Longhi 2019 [203]																																				Pervasiveness and Ubiquity
Brodner 2018 [128]												X		X																						
Cardin 2019 [56]		X																														X				
Carreras Guzman et al. 2019 [91]		X	X																											X			X			Concurrency
Chen and Tsai 2017 [94]																	X																			
Chen et al. 2018 [75]																												X								
Cruz Salazar et al. 2019 [133]																												X		X				X		
Culler and Long 2016 [134]		X																																		
Ding and Jiang 2017 [135]			X												X												X					X				
Dumitrache et al. 2019 [136]																															X	X				Coordination
Gaham, Bouzouia and Achour 2015 [138]			X																																	
Harrison, Vera and Ahmad 2016a [31]				X																					X											
Hozdic 2015 [142]																												X	X							
Hu and Zhou 2018 [143]															X																					
Hwang 2016 [120]																	X	X										X								
Ilsen, Meissner and Aurich 2017 [24]					X																															
Jones, Romero and Wuest 2018 [148]															X																					
Khalid et al. 2016 [151]			X		X				X						X						X															
Kolberg, Knobloch and Zuhlke 2017 [152]				X																																
Krishnamurthy and Cecil 2018 [153]											X																									
Latorre-Biel et al. 2018 [154]											X																									
Lee, Bagheri and Jin 2016 [156]											X																									
Leng et al. 2019 [158]		X																																		
Li et al. 2017 [28]		X																																		
Lins, de Araujo and Corazzim 2019 [71]																									X											
Liu et al. 2017 [44]			X															X																		
Liu et al. 2018 [161]											X																									

Liu and Jiang 2019 [159]																																	X			
Liu et al. 2019 [162]			X															X																		
Lu and Xu 2019 [58]										X																										
Mittal et al. 2019 [204]				X																																
Monostori et al. 2016 [32]																																X				
Mora et al. 2017 [34]											X		X																							
Morel, Pereira and Nof 2019 [165]															X																X	X				
Oborski 2016 [168]																							X								X					
Penas et al. 2017 [12]							X					X																								
Peres et al. 2018 [170]										X								X					X													
Peruzzini and Pellicciari 2017 [171]																									X											
Pirvu, Zamfirescu and Gorecky 2016 [74]									X						X						X					X										
Posada et al. 2015 [105]														X																						
Qu et al. 2019 [172]					X																															
Rama et al. 2016 [110]					X																															
Ribeiro and Bjorkman 2018 [73]				X																X			X	X			X									
Ribeiro and Hochwallner 2018 [67]				X														X		X				X	X					X						
Rojas et al. 2017 [39]				X							X	X	X																							
Rojas and Rauch 2019 [173]					X					X																							X			
Sanderson, Chaplin and Ratchev 2018 [86]										X																										
Sanislav and Miclea 2012 [174]	X							X																										X		
Scholze, Barata and Stokic 2017 [76]										X																										
Shafiq et al. 2015 [176]																													X							
Shafiq et al. 2016 [177]																													X							
Song and Moon 2019 [179]																		X																		
Stern and Becker 2019 [205]						X																														
Tang et al. 2017 [101]																																			X	
Tang et al. 2018 [181]																																			X	
Tao and Qi 2019 [65]															X																					
Tavcar and Horvath 2019 [184]												X																								
Thoben, Wiesner and Wuest 2017 [15]														X																						
Thramboulidis and Christoulakis 2016 [186]							X													X			X			X		X								
Tran et al. 2019 [103]											X	X								X																
Trappey et al. 2016 [78]																X							X							X						Fault tolerance
Tsai and Lu 2018 [112]										X																										
Tu, Lim and Yang 2018 [48]																																X				
Tuptuk and Hailes 2018 [187]										X															X					X						
Uhlmann, Hohwieler and Geisert 2017 [188]												X																								
Wan et al. 2011 [10]	X							X																												
Wan et al. 2013 [25]	X							X																												
Wang et al. 2015 [189]											X																									
Wang, Torngren and Onori 2015 [49]			X				X					X																								
Wang and Haghighi 2016 [55]																		X													X					
Wang et al. 2016 [190]																																				Negotiation
Wang, Zhang and Zhong 2020 [192]																		X														X				
Weyer et al. 2016 [106]																							X													
Wu, Kao and Tseng 2011 [54]																						X														
Xu and Duan 2019 [196]					X																										X					
Yao et al. 2018 [198]						X																														
Yu et al. 2017a [77]					X															X					X					X						
Yu et al. 2017b [45]												X																				X				
Yuan, Anumba and Parfitt 2015 [27]	X													X		X																				Uncertainty
Zhang et al. 2017 [200]																							X													
Zheng et al. 2018 [201]										X								X																		
Zhou, Liu and Liang 2016 [2]																												X								
Zhou et al. 2019 [93]			X									X																								
Total	5	5	8	6	7	3	4	4	2	9	9	9	3	4	6	2	2	9	1	5	2	1	7	2	6	2	2	6	3	6	4	9	4	2	2	-

List of abbreviations

C1. Complexity/heterogeneity encapsulation

C2. Interoperability, Connectivity, Communication, Networking capability

C3. Service orientation

C4. Modularity, Autonomy, Self-capabilities, Decentralization

C5. Virtualization, Real-time capability

C6. Computational capability

C7. Cooperation, Collaboration

C8. Scalability, Dynamic reconfigurability, Adaptability

C9. Predictability, Diagnosability