

The concept of collaborative engineering: a systematic literature review

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ABSTRACT

Collaborative engineering is not a new subject but it assumes a new importance in the Industry 4.0 (I4.0). There are other concepts frequently mismatched with collaboration. Thus, the main objective of this paper is to put forward a collaborative engineering concept, along its sub concepts, supported by an extensive systematic literature review. A critical analysis and discussion about the fundamental importance of learning, and the central human role in collaboration, in the I4.0, is presented, based on the main insights brought through the literature review. This study also enables to realize about the importance of collaboration in the current digitalization era, along with the importance of recent approaches and technology for enabling or promoting collaboration. Main current practices of human centered and autonomous machine-machine approaches and applications of collaboration in engineering, namely in manufacturing and management, are presented, along with main difficulties and further open research opportunities on collaboration..

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1. Introduction

The understanding of collaboration and more specifically about collaborative engineering (CollEng) has been analyzed earlier (Putnik & Putnik, 2019). Although, it remains still difficult to establish a non-ambiguous or clear meaning to it, within the chaos of different terminologies, ideas and alternative meanings being associated under different application domains.

Therefore, the main purpose of this paper is twofold: (1) to put forward a conceptual model for the CollEng, with the clear identification and definition of its underlying main subconcepts or conditions, to enable its clear definition, and further an unambiguous use in the engineering context; and (2) to put forward a literature review for supporting the proposed CollEng concept, and its further deeper analysis and discussion, in the I4.0 context.

The objective (2) will be pursued through a systematic literature review (SLR) to generate further clarity and to consolidate the findings around CollEng for researchers as well as for practitioners, for instance, in the manufacturing and management (M&M)

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domain, because, as referred in Bechar et al., (2015), collaboration in M&M is not yet properly approached or developed. Thus, there are still some open space and opportunities for further consolidating this concept and apply it, through different kind of approaches, tools and platforms, for being successfully implemented in the Industrial context.

According to the authors in Denyer & Tranfield, (2009) Thomé et al., (2016) the SLR methodology consists of: planning and formulating the research question; localization and searching the literature; data gathering and quality evaluation; select and evaluate contributions; synthesis and analysis of data, with the presentation and interpretation of the results.

In order to accomplish the process underlying the SLR methodology, in this paper the following five step approach was used: (1) research scope definition, (2) topic conceptualization, (3) literature search, (4) literature synthesis, analysis and discussion, and (5) synthesis of future work and further research questions.

Following this main five-step approach, in this paper, after the introduction, [section 2](#) defines the scope of this research while presenting the main research questions focused. In the [section 3](#), the CollEng conceptual model is put forward, based on its main pillars or sub concepts, which are also briefly explored.

Next, in [section 4](#) the literature search process is described. After, [section 5](#) describes the publications categorization and presents a general data synthesis. [Section 6](#) presents a detailed literature analysis and discussion in the scope of the proposed collaboration concept and the I4.0. Finally, in [section 7](#), the main conclusions are drawn, and a synthesis of further work and research questions is also encompassed.

2. Research scope definition

In our opinion there is no true or full collaboration if there is no human participation, thus in this paper this is a central issue or research focus, as we are also convinced that there is no real or true learning without the human intervention, being learning considered a key issue in the proposed CollEng-M&M context. Thus, learning will be of prime importance, for enabling or reaching a real, true, complete or higher level of collaboration. Therefore, in order to contribute to the clarification and further consolidation of this aspect, namely regarding the importance of collaboration in the current I4.0, these aspects are further deeply analyzed and discussed in this paper, supported by existing literature.

Therefore, this paper is aimed at clarifying that there is no true, real or complete collaboration without a human intervention, according to a proposed collaboration concept, as it does further imply a learning process, which is just fully tangible or reachable when human participation does exist. Thus, there will be analyzed sources that do just accomplish a lower level of the proposed CollEng-M&M concept, for instance, regarding collaboration under the scope of pure automation or not human-centered approaches, which will be defined as Machine-Machine or M-M collaboration, and other that support a higher of full level of collaboration, based on human intervention, of Human-Human, H-H or Human-Machine, H-M collaboration types.

Therefore, through the collaboration concept put forward in this paper it is aimed a further explanation of its inherent hierarchy by considering key elements or sub concepts, in order to permit a clear, non-ambiguous, collaboration conceptualization, that highlights:

- (1) The importance of learning in collaboration;
- (2) The importance of the human role in collaboration;
- (3) The importance of CollEng-M&M in the I4.0.
- (4) The importance of I4.0 for enabling, leveraging or reinforcing CollEng-M&M.

In order to fulfil the main objective of this work, to bring together main insights regarding CollEng theory and practice, with a main focus on the M&M domain, next, the research scope of this theme is defined, with the underlying main research questions.

2.1. Planning and formulating the research questions

As mentioned in Denyer & Tranfield, (2009) Thomé et al., (2016) the primary phase of the SLR methodology consists of planning and formulating the research question of fundamental importance to properly focus and direct the literature search process to the intended subject to be studied. Thus, in this work, different alternative perspectives of analysis are explored, about two main subjects regarding the following main research questions, and sub questions posed, as follows:

RQ1) What are the main issues underlying collaborative engineering in the manufacturing and management domain (CollEng-M&M)?

Sub-questions:

- Is it possible to have true or full CollEng-M&M without learning?
- How important is the human role in CollEng-M&M, in the current I4.0?

RQ2) Is CollEng-M&M important in the I4.0?

RQ3) Does the I4.0 support, foster or promote CollEng-M&M?

RQ4) Are there any difficulties or major obstacles or concerns related to the implementation of collaborative approaches or practices in the current I4.0?

3. Collaborative engineering conceptualization

In this section, a CollEng-M&M conceptual model, along with its main underlying components or sub concepts will be put forward, based on the authors' own knowledge and experience, underlying main research activity, about core findings related to collaboration, along with some main findings from the literature, that were further deeply analyzed, through the results of the SLR conducted, to properly support the proposed model, and by briefly describing the main outcomes reached.

The proposed CollEng-M&M conceptual model consists of six main pillars that address some considered main conditions, structured as shown in [Figure 1](#).

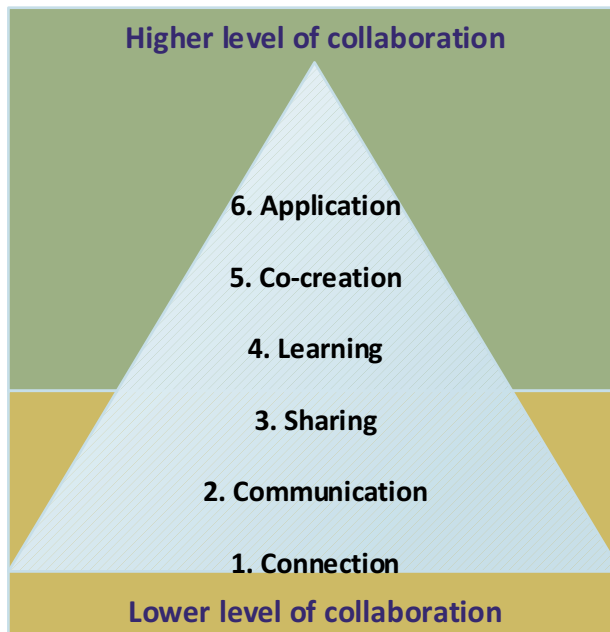


Figure 1. Proposed collaborative engineering conceptual model.

In this proposed CollEng-M&M conceptual model the ‘Learning’ element or sub concept is considered to be a fundamental one, or a core element that enables to truly distinguish a full or higher level collaboration concept from a partial or lower level one. Therefore, to further explore this condition posed, the literature contributions analyzed are, primarily, divided in two main groups, as follows:

- (1) Lower level of collaboration – without learning-based collaboration methodologies, and tools, requiring just connection, communication and sharing activities, based on distinct kind of approaches, models, methods, technology, and tools or platforms, for some kind of coordination or co-operation practice regarding partial Coll-M&M scenarios.
- (2) Higher or full level of collaboration – with learning-based collaboration methodologies, models, tools, and technology, envisioning some kind of co-creation, centered or not in a human intervention about M&M applications.

Besides, these two major categories of contributions considered in this study, the research analysis is thus further divided in human-centered and not human-centered subsets, for subsequent deeper details extraction regarding other main aspects, as the human role is considered a central issue, of utmost importance to be further explored in this work about CollEng-M&M.

4. Description of the proposed collaborative engineering conceptual model and its main sub concepts

In this section the main concepts and sub concepts to some extent related to the proposed CollEng-M&M model are briefly described.

Connection consists of some kind of physical or logical link between two or more things or entities. In case of more than two entities being connected, it is also usually referred as an 'Interconnection' [<https://en.wikipedia.org/wiki/Connection>].

Communication is the imparting or exchanging or transmission of information. Thus, the concept or state of exchanging data or information between entities.

For instance, a message is an example of data or information transferred in an act of communication [<https://en.wikipedia.org/wiki/Communication>].

Thus, communication is an instance of information transfer, and a required element for enabling a conversation or discourse.

Another example from the educational context can be referred as being the professors' communications of lively discussion or via email. So a communication is carried out through a passageway or opening between two or more locations, the connections.

Connection and communication together enable to establish networks and underlying interactions, usually called as network communications, through which can occur information transmission or sharing.

Network communications based on wireless and internet technologies (Internet of Things, IoT), along with the use of widened set of communication technology, tools, devices, and means, e.g. sensors, actuators, Radio Frequency Identification (RFID), along with smart objects, among other technology, serves to link machines, work products, systems and people, within a manufacturing plant, intra company or inter companies, through a more or less extended network of stakeholders, which may include, e.g. suppliers, distributors, business partners, and customers communicating worldwide.

Sharing is the joint use of a resource or space. It is also the process of dividing and distributing. In its narrow sense, it refers to joint or alternating use of inherently finite goods, 'sharing' can actually mean giving something as an outright gift: for example, to 'share' one's food really means to give some of it as a gift. Sharing is a basic component of human interaction, and is responsible for strengthening social ties and ensuring a person's well-being [<https://en.wikipedia.org/wiki/Sharing>].

So, in general, sharing consists of partaking or contributing with some kind of tangible or intangible asset, for instance:

- Sharing files, links, videos, data, and its processing, analysis and exploitation, either immediately on the factory floor, or in a broader sense, through the web or cloud.
- Sharing knowledge, competences, know-how, and skills.
- Sharing different kind of resources, e.g. manufacturing resources, processors, machines, tools, etc.
- Sharing tasks, problems, costs, challenges, dependencies, risks, concerns or difficulties.
- Sharing technology, techniques, software, benefits, innovations, time, and thinking.
- Sharing suppliers, business partners, products, materials, production systems, warehouses, transportation means and logistic systems, companies, and customers.

Learning consists of the acquisition of knowledge or skills through study, experience, or being taught [<https://en.wikipedia.org/wiki/Learning>], and an important requisite for this knowledge or skills acquisition is the existence of feedback among entities.

Eijnatten & Putnik, (2004) distinguish between different kind of learning sub concepts, further based on other existing sources, as follows (Eijnatten & Putnik, 2004):

Collective learning: “The ability of the collective to learn from experiences drawn by individuals while working. It is one single phenomenon that constitute of four abilities: relationics, correlation, internal model, and praxis (Backström, 2004).”

Collaborative learning or co-learning: “Learning that occurs as a result of interaction between peers in the completion of a common task (Noble, 2004).”

In [<https://en.wikipedia.org/wiki/Learning>] is also described the “Organizational learning” concept, as follows:

Organizational learning (OL): “is defined as the way people jointly construct maps (Argyris & Schön, 1997) or exercise competence and enact qualifications in a network of interacting people (Jensen & Rasmussen, 2004). OL is about the learning process, and more specifically about the co-operative learning process (McHugh et al., 1998) in a specific socio-cultural context (Cullen, 1999). Moreover, in OL introduces hierarchical levels of learning, i.e. single loop (correction of errors by using feedback), double loop (changing underlying norms and mechanisms), and triple loop (questioning essential principles, learning about learning), and includes organizational processes as well. In a critical review Tsang (1997) states that in OL change cognition is a necessary condition (Tsang, 1997): ‘The cognitive aspect is generally concerned with knowledge, understanding, and insights.’ But according to Eijnatten & Putnik, (2004) there is a split among definitions on whether a change in actual or potential behavior is required, and by potential behavioral change, these authors assume that the lessons learnt by an organization would have impact upon its future behavior.” In Eijnatten & Putnik, (2004) is also further explored the concept of Learning Organization, as follows:

Learning organization (LO): “An organization, structure, process or network ‘where people continually expand their capacity to create the results they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspirations are set free, and where people are continually learning to see the whole together’ (Senge, 1990). The five required disciplines or ‘component technologies’ are: (1) Team learning, (2) Building shared vision, (3) Mental models, (4) Personal mastery, and (5) Systems thinking (Senge, 1990).”

Additionally, the LO concepts is also seen or defined in Eijnatten & Putnik, (2004) as: “An organization, structure, process or network ‘which is capable of thriving in a world of interdependency and change’ (Kofman and Senge (1993).”

Further described in Eijnatten & Putnik, (2004) as being: “A social system whose members have learned conscious communal processes for continually generating, retaining and leveraging individual and collective learning to improve performance of the organizational system in ways important to all stakeholders; and monitoring and improving performance (Drew & Smith, 1995).”

Besides in Eijnatten & Putnik, (2004) the LO is also described as a: “Sum total of accumulated individual and collective learning (Hyland & Matlay, 1997).”

Moreover, in Eijnatten & Putnik, (2004) is also mentioned the LO as: “An organization, structure, process or network ‘exhibiting directed changes at the macro level’ (Jensen & Rasmussen, 2004).”

Further, in Eijnatten & Putnik, (2004) is also mentioned that “according to Huysman (2000), an LO is ‘a form of organization that enables the learning of its members in such a way, that it creates positively valued outcomes, such as innovation, efficiency, better alignment with the environment and competitive advantage’. Also that: “According to Huysman (2000), an LO is an organization capable of adapting, changing, developing and transforming itself in response to needs, wishes, and aspirations of people both inside and out.” And that: “Both structural and cultural organization learning mechanisms are important to create and maintain a LO (Pedler et al., 1991)”.

Besides Eijnatten & Putnik, (2004) do also state that: “Learning must transfer from individual(s) to collective(s) to organizational to inter-organizational, and vice-versa, and ‘must’ result in changes in behavior (Sun & Scott, 2003)”.

Further, as a concluding remark about the learning process in Eijnatten & Putnik, (2004) is referred that:

“In the most general sense, learning may be described as an iterative process of activities, whereby new knowledge is produced through transformation of experience. Whenever knowledge is created as a result of individual experiences – i.e. walking through the cycle of planning, decision-making (DM), action, experience and reflection – we speak of ‘individual learning’ (IL; Kolb, 1984). When it results from interaction between peers, we speak of ‘collective learning’ (CL; Backström, 2004) or ‘collaborative learning’ (Noble, 2004). The outcomes of IL and CL may be used for either personal or communal purposes, such as the further development of the own company.”

Based on these main ideas and definitions it is possible to draw a set of learning means and outcomes as follows:

- Learning through shared experiences, and goals, regarding individual and collective learning approaches and practices;
- Learning manufacturing processes, and operations, in the context of H-H, H-M, and M-M collaboration;
- Learning M&M, and underlying DM processes, methods, and tools;
- Learning improved ways of interactions with worldwide companies’ stakeholders, e.g. suppliers, business partners, and clients;
- Learning innovations and education methodologies, etc.;
- Learning everything needed or wanted by interacting with someone and/or through something (organization, social network, etc.).
- Summarizing, the previously expressed main ideas inherent to the learning concept, and summarizing, as stated in Eijnatten & Putnik,(2004): ‘learning may be described as an iterative process of activities, whereby new knowledge is produced ...’. Moreover, as a ‘... LO is ‘a form of organization that enables the learning of its members in such a way, that it creates positively valued outcomes, ...’, and this leads to a kind of ‘natural linkage’ of the learning concept to the next one defined in the proposed CollEng-M&M conceptual model, the co-creation.

Co-creation is a general concept that can be used to define a widened set of ‘things’ that can be created, which may be intangible, such as more or less simple thoughts, or idea or some more complex piece of information or knowledge, by a set of two or more members or entities interacting through some means and kind of learning process. On the other side, in the tangible case, co-creation can further arise through diverse kind or

interactions, based on the underlying learning process, depending on the concrete type of means and materials used among the two or more interacting entities.

In the Wikipedia, in the context of a business, referring to ‘a product or service design process in which input from consumers plays a central role from beginning to end’. Less specifically, the term is also used for ‘any way in which a business allows consumers to submit ideas, designs or content’. This way, a firm will not run out of ideas regarding the design to be created and at the same time, it will further strengthen the business relationship between the firm and its customers. Another meaning is ‘the creation of value by ordinary people, whether for a company or not [<https://en.wikipedia.org/wiki/Co-creation>]’.

Co-creation was defined by Jansen and Pieters, in 2017, as ‘a transparent process of value creation in ongoing, productive collaboration with, and supported by all relevant parties, with end-users playing a central role’.

The co-creation term is already a concept relatively in regular use, especially in marketing and some design practices (e.g. open design), and in these disciplines it refers to a joint design of a product by designer and customer and further extensible to a more or less enlarged set of participating product development members, working together as a collaborative team.

This frequently mentioned co-creation concept is thus relatively close to the ‘traditional’ Concurrent Engineering (CE) concept that does also require some close relation and practices between a set of members in a team, working to usually reach some common or concurrent goal or objective, and which typically implies some kind of negotiation process (Putnik & Putnik, 2019).

However, the semantics is quite different from theory to theory, from author to author, from ‘user’-group to ‘user’-group, from community to community, and frequently CE and CollEng are mixed up or undistinguished, being thus frequently used as similar concepts (Putnik & Putnik, 2019; Putnik et al., 2021b, 2021c).

Therefore, in this paper, the objective is to clarify the CollEng concept, as being different from the CE one, as in fact we consider that in CollEng there is no need to have a common goal, but, instead, a common learning, between the collaborating members.

Besides the co-design or open design, it is also possible to consider other kind of co-creation, for instance, co-operation through human-robot collaboration, and further, based on any other possible co-creation type, such as: co-learning, co-decision, co-management, co-maintenance, co-transportation, and co or open innovation, among others.

One such specific term arising from the general co-creation one, which is frequently used is co-work or co-working, mentioned in Petrillo et al., (2018), and considered to be crucial up from the I4.0 and abroad to the next, the fifth industrial revolution (Industry 5.0 or I5.0, for short; Nahavandi, 2019).

Another closely related term to co-working is cooperating or cooperation. As stated in Bechtold & Lauenstein, (2014), Japan begins to talk about this fifth industrial revolution, which will be marked by the cooperation between man and machine.

The authors in Petrillo et al., (2018) claim about this importance of co-working in the context of an expected significant increase in the complexity of production environments, and corresponding problems to be solved, leading to a growing need for further

interactions, for instance, between humans and machines, which is the so-called H-M collaboration (Manupati et al., 2022; L. Varela et al., 2022).

Finally, in the Engineering field, the application or practical implementation of the ‘co-creation’ in some specific domain is also of utmost importance.

Application is defined in [<https://en.wiktionary.org/wiki/application>] as being the act of applying as a means; the employment of means to accomplish an end; a specific use. Also, the act of directing or referring something to a particular case, e.g. the application of a theory to a set of data, etc.

The application level is thus considered a key issue in the proposed CollEng-M&M concept, as in the engineering context it is naturally assumed and required to exist some kind of application or implementation.

According to the kind of co-creation underlying the earlier stage or level in our proposed CollEng model, the application can thus vary in a corresponding widened range of alternative scenarios, deriving from the underlying specific co-creation type.

For example:

- Through co-learning or co-innovation some new co-created concept or knowledge can be synthesized or formalized and further applied in some specific application domain.
- In the case of some kind of co-working, such as in a team of two or more people working together in some shared document, e.g. by using google docs, a final document will be jointly produced.
- Also, in the co-design or open design application scenario, as a result or application will derive some new product design, through a so-called H-H and/ or H-M collaboration.
- In a similar way, through co-management or co-decision some important conclusion or decision can be taken to be implemented.
- Also through co-maintenance or co-transportation, some kind of task can be carried out by a group of collaborating people and/ or jointly through some kind of means, tools, machines or transportation device.
- Further, in the case of some kind of co-operation, or for instance, in some H-M collaboration scenario, for instance, through human-robot collaboration, some kind of task will be accomplished jointly by a human and a robot, and in some context of M-M collaboration, two or more machines or robots can also cooperate to reach some specific objective or accomplish some kind of task together. Therefore, cooperation or mere coordination between two or more entities, namely between two or more machines, e.g. robots, is in fact just a lower-level of collaboration, as not implying co-learning and/or true co-creation, which is clearly the case in the M-M collaboration context, without human intervention.

Collaboration can thus be applied in different forms for reaching diverse kind of collaboration:

- H-H collaboration (ex: co-work based on shared resources, e.g. google drive and docs, etc.)

- H-M collaboration: for instance, based on the use of group DM approaches and methods, among other methodologies and approaches, e.g. based on AI approaches and methods, along with a varying kind of meta-heuristics, etc. for supporting joint decision making processes; human-robot work or cooperation; other kind of H-M collaboration, for example, for machine training, e.g. in supervised machine learning (ML) context, though the use of ‘the oracle’, or based on other approaches, such as, based on Game Theory, among others; or through some kind of H-M co-work, e.g. co-design, co-maintain, co-transportation, etc.
- M-M collaboration, e.g. through integrated automatic or autonomous processes (ex: use of multi-agents, blockchain and smart contracts, big data (BD) processing, chaos and complexity analysis, etc.)

Therefore, we may conclude that collaboration does, in fact, further imply some kind of application for reaching the proposed full CollEng-M&M concept, for instance, through: co-design (open design), co-work, co-operation, co-maintaining, co-monitoring, co-visualizing, co-learning, co-thinking, co-data handling, co-analyzing, co-interpretation, co-deciding, co-sensing, co-reasoning, etc., resulting in some kind of output, which, in the concrete engineering scope, will be referred as being some kind of application or implementation, either through a more tangible or intangible asset.

In [Table 1](#) are summarized a set of main contributions regarding each sub concept underlying the proposed CollEng-M&M concept.

This data was obtained by conducting an SLR process, as described in the following section.

5. Literature search

5.1. Methodology

The literature search process performed in this work was conducted primarily based on the proposed CollEng-M&M conceptual model, through which the main sub concepts specified act as fundamental keywords for carrying out a preliminary literature search process or phase to provide background for supporting the incorporation of these sub concepts into the proposed CollEng framework. This main conceptual basis, supported by corresponding literature, was previously summarized in the [section 3](#) of this paper. Subsequently, for accomplishing the next step or phase of the SLR methodology underlying this work, as defined in the introductory section (planning and formulating the research question; localization and searching the literature; data gathering and quality evaluation; select and evaluate contributions; and synthesis and analysis of data, with the presentation and interpretation of the results), the main research questions intended to be approached in this work were defined ([section 2](#)). Next, the main activity consisted on conducting a complete or deep literature search process, based on the underlying main steps of the SLR that was conducted, following some main literature review recommendations (Brocke et al., 2009; Rowley & Slack, 2004).

The starting point consisted on a primary general search on relevant journals in the focused Engineering, and M&M domains, which were screened based on the diverse perspectives underlying the proposed CollEng model to be approached, by analyzing

Table 1. Main references supporting the proposed CollEng-M&M framework's sub concepts.

CollEng-M&M sub concepts	References
Application	Eijnatten & Putnik, 2004; Abreu & Camarinha-Matos, 2008; Lai, 2011; Pfaff & Hasan, 2011; Hancock et al., 2013; Brettel et al., 2014; Hummel et al., 2015; Lun & Zhao, 2015; Quint et al., 2015; Römer & Bruder, 2015; Khalid et al., 2016; Landherr et al., 2016; Nelles et al., 2016; Posselt et al., 2016; Romero et al., 2016, Romero et al., 2017; Syberfeldt et al., 2016; Bochmann et al., 2017; Longo et al., 2017; Peruzzini et al., 2017; Reuter et al., 2017; Sacha et al., 2017; Stern & Becker, 2017; Ustundag & Cevikcan, 2017; Büth et al., 2018; Darvish et al., 2018; Malik & Bilberg, 2018; Papazoglou et al., 2018; Petrillo et al., 2018; Posada et al., 2018; Tvenge & Martinsen, 2018; Bilberg & Malik, 2019; Cherubini et al., 2019; Demir et al., 2019; Emmanouilidis et al., 2019; Guerin et al., 2019; Ma et al., 2019; Nikolakis et al., 2019; Oyekan et al., 2019; Putnik & Putnik, 2019; Schuhmacher & Hummel, 2019; Ansari et al., 2020; Bousdekis et al., 2020; Birch-Jensen et al., 2020; Çil et al., 2020; Cimini et al., 2020; Fantini et al., 2020; Fletcher et al., 2020; Kaasinen et al., 2020; Liu & Wang, 2020; Pace et al., 2020; Rauch et al., 2020; Putnik et al., 2020, Putnik et al., 2021a,b,c; Manupati et al., 2022; L. Varela et al., 2022.
Co-creation	Lai, 2011; Pfaff & Hasan, 2011; Hancock et al., 2013; Brettel et al., 2014; Hummel et al., 2015; Romero et al., 2015, Romero et al., 2016, Romero et al., 2017; Syberfeldt et al., 2016; Bochmann et al., 2017; Longo et al., 2017; Peruzzini et al., 2017; Sacha et al., 2017; Van Laar et al., 2017; Ansari et al., 2018; Büth et al., 2018; Darvish et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Petrillo et al., 2018; Posada et al., 2018; Cherubini et al., 2019; Demir et al., 2019; Emmanouilidis et al., 2019; Guerin et al., 2019; Nikolakis et al., 2019; Oyekan et al., 2019; Birch-Jensen et al., 2020; Bousdekis et al., 2020; Cimini et al., 2020; Çil et al., 2020; Fletcher et al., 2020; Kaasinen et al., 2020; Liu & Wang, 2020; Putnik et al., 2020; Rauch et al., 2020; Zolotová et al., 2020; Putnik et al., 2021a,b,c; Manupati et al., 2022; L. Varela et al., 2022.
Learning	Eijnatten & Putnik, 2004; Hummel et al., 2015; Quint et al., 2015; Kafle et al., 2016; Posselt et al., 2016; Peruzzini et al., 2017; Reuter et al., 2017; Sacha et al., 2017; Trstenjak & Cosic, 2017; Van Laar et al., 2017; Ansari et al., 2018; Büth et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Juraschek et al., 2018; Petrillo et al., 2018; Posada et al., 2018; Tvenge & Martinsen, 2018; Ottogalli et al., 2019; Putnik & Putnik, 2019; Schuhmacher & Hummel, 2019; Arias et al., 2000; Birch-Jensen et al., 2020; Rauch et al., 2020; Zolotová et al., 2020. Putnik et al., 2020, Putnik et al., 2021a, Putnik et al., 2021b, Putnik et al., 2021c; Manupati et al., 2022; L. Varela et al., 2022.
Sharing	Abreu & Camarinha-Matos, 2008; Lai, 2011; Hancock et al., 2013; Brettel et al., 2014; Landherr et al., 2016; Longo et al., 2017; Zhao et al., 2017; Ansari et al., 2018; Darvish et al., 2018; Malik & Bilberg, 2018; Bilberg & Malik, 2019; Ma et al., 2019; Nikolakis et al., 2019; Oyekan et al., 2019; Arias et al., 2000; Bousdekis et al., 2020; Liu & Wang, 2020; Rauch et al., 2020; Putnik et al., 2021a,b; Manupati et al., 2022.
Communication	Eijnatten & Putnik, 2004; Abreu & Camarinha-Matos, 2008; Pfaff & Hasan, 2011; Hancock et al., 2013; Brettel et al., 2014; Haddara & Elragal, 2015; Quint et al., 2015; Römer & Bruder, 2015; Romero et al., 2015, Romero et al., 2016, Romero et al., 2017; Kafle et al., 2016; Khalid et al., 2016; Landherr et al., 2016; Posselt et al., 2016; Longo et al., 2017; Stern & Becker, 2017; Peruzzini et al., 2017; Van Laar et al., 2017; Zhao et al., 2017; Darvish et al., 2018; Malik & Bilberg, 2018; Papazoglou et al., 2018; Posada et al., 2018; Varela et al., 2018; Bilberg & Malik, 2019; Tvenge & Martinsen, 2018; Nikolakis et al., 2018; Petrillo et al., 2018; Guerin et al., 2019; Ma et al., 2019; Oyekan et al., 2019; Ansari et al., 2018, Ansari et al., 2020; Arias et al., 2000; Cimini et al., 2020; Fantini et al., 2020; Fletcher et al., 2020; Liu & Wang, 2020; Pace et al., 2020; Rauch et al., 2020; Zolotová et al., 2020; Putnik et al., 2021a,b,c; Manupati et al., 2022.
Connection	Pfaff & Hasan, 2011; Hancock et al., 2013; Haddara & Elragal, 2015; Chen et al., 2016; Kafle et al., 2016; Landherr et al., 2016; Posselt et al., 2016; Ustundag & Cevikcan, 2017; Ansari et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Papazoglou et al., 2018; Emmanouilidis et al., 2019; Ma et al., 2019; Arias et al., 2000; Birch-Jensen et al., 2020; Çil et al., 2020; Cimini et al., 2020; Fantini et al., 2020; Kaasinen et al., 2020; Pace et al., 2020; Rauch et al., 2020.

some main publications from those journals, about Production Engineering and Management, Industrial and Manufacturing Engineering, and in Information Systems and Technology sub areas, for extracting other important key words, besides the ones directly underlying the proposed collaboration concept, to serve as additional key words in the further literature search process, based on the SLR methodology. Therefore, we analyzed sources through the SLR process, out of lists from considered main scientific domains more or less closely related to our focused collaboration concept, and did

progressively constrain the sample with regard to their quality. The basic quality criteria were for peer-reviewed articles, published in scientific journals and other relevant international scientific conferences materials in the focused research domain (Rowley & Slack, 2004). In addition, we assessed their ranking according to the ISI Web of Science ranking and the SCimago impact factor. This procedure led to a list of 291 papers, reflecting the exhaustive and selective character of the SLR carried out. After listing this initially valid set of publications, we did proceed with the remaining literature search and analysis process, in order to fulfil the complete process subjacent to the SLR methodology considered (Brocke et al., 2009; Rowley & Slack, 2004), in a structured and transparent manner, as described next.

5.2. Detailed description of the search process conducted

The databases selected for conducting the publications search process, as previously referred, were mainly papers included in the Web of Science (WoS) and Scopus databases, which were chosen attending to their general publications quality, popularity, and availability of a large number of scientific publications to assure a representative set of sources for carrying out the SLR, regarding the set of keywords, exclusion and inclusion criteria considered in this work, as described next.

The WoS and Scopus databases are two of the most widely multidisciplinary databases used and available online about academic research, containing publications from selected peer-reviewed international journals, books, and conference proceedings, among others.

Additionally, some best known editors were also considered for reaching diverse kind of high quality publications, such as: Taylor & Francis, Science Direct, Elsevier, [John] Willey & Sons, IEEE, and MDPI, which did enable access to widely used and high-quality journals, including open access ones, being world's leading publishers of journals, books, and databases, namely in the focused scientific domain.

For searching for scientific peer-reviewed publication at an international scale were considered: journals, international conferences' publications (proceedings and papers), books, book chapters, and editorial material. Publications in the period from 2010 to 2021 were considered, since it was up from 2010 that the term I4.0 started to be fostered and spread through the worldwide scientific community (Ustundag & Cevikcan, 2017).

5.2.1. Definition of keywords' groups and search strings

The main keywords were identified and clustered in three main groups of the considered main search terms (KWG1, KWG2, and KWG3), as summarized in Table 2:

KWG1: Includes the keywords related to collaboration, by considering the most frequent or well-known keywords usually associated to collaboration (M&M), thus in the engineering context (KWG1).

KWG2: Includes a set of most frequently used terms about engineering or industrial contextualization of the scope of the intended search focus regarding M&M.

KWG3: Includes a set of the most relevant I4.0 pillars or principles, and underlying paradigms, approaches and technologies considered relevant ones under the collaboration scope.

The operator 'and' was used between the three keyword groups, combining, each time, two keywords' groups (KWG1 with KWG2, KWG1 with KWG3, and KWG2 with

Table 2. Groups of keywords.

KWG1 (How?)	KWG2 (Who?, Where?, What?)	KWG3 (Through which/ what I4.0 pillar?)
Collaboration	Manufacturing	Industry 4.0
Collaborative	Management	Industrie 4.0
Collective	Organization	I4.0
Collaborating	Enterprise	Digital
Co-creation	Factory	Integration
Co-work	Production	Servitization
Co-design	System	Service
Co-learn	Cyber physical	Share
Open design	Process	Connect
Open	Method	Communicate
Innovation	Model	Integrate
Interoperation	Resource	Distribute
Interoperability	Robot	Smart
Interaction	Machine,	Intelligent
Cognition	Human	Learning
Connection	Person	Cognitive
Communication	User	Autonomous
Sharing		Automatic
Dialogue		Self
Networking		P2P
Group decision		B2B
Emergence		X2X
Socializing		Point-to-point
Mindful		End-to-end
Mindedness		Real time
Total = 648 publications		

KWG3), in order to force a focus on the intended analysis about the relation between some kind of collaboration applied in engineering or industry, regarding manufacturing and/or management purpose, and further its contextualization in the current I4.0 scenario.

Summarizing the description of the search process used through the considered WoS and Scopus databases:

The search procedure has been done individually, i.e. term (keyword, KW) by term, and it was conducted in two parts, where the keywords from the first column KWG1 (Table 2) were maintained, and used in the two steps. In the first search step, each keyword from the KWG1 was associated with the terms/keywords from the KWG2, using an 'and' operator (KW11-KW21, ...).

In a second step, the search process was conducted through the combination of the keywords from KWG1 with the ones from KWG3, about I4.0, also by using the operator 'and'.

Finally, in the third step of the search process, keywords from the KWG2 and KWG3 were combined, by using the 'and' operator. The total number of sources obtained through the application of this search mechanism was of 648 publications.

5.3. Screening: data gathering and quality evaluation

A general publications screening and analysis process was carried out in this work based on a first general quality evaluation over the total list of **648** publications obtained through the WOS and Scopus databases searching process. Next, four sub analysis

were carried out, based on the definition of exclusion criteria, followed by the definition of inclusion criteria, the identification of the subset of the most important publications and, finally, the identification of the subset of the top upmost relevant publications for further deeper analysis and discussion, according to the corresponding relevance of their content to the focused research scope.

5.3.1. Definition of exclusion criteria

After the specification of the three groups of main keywords for obtaining relevant publications for analysis, in order to reach insights for further synthesizing main conclusions about this study, some further main publications' exclusion criteria have been defined, as presented next, and through this exclusion process a subset of 424 publications for further analysis was reached.

Exclusion criteria used: repeated publication, not peer reviewed, not in English, no full text available, not in WoS or Scopus, not published in journals, books or international conference proceedings, not related to production, manufacturing or management (ex: applications in training or services, e.g. medical, etc. were not considered), not related to some kind of collaboration or cooperation (of H-H, H-M or M-M type) or focusing some collaboration level (1. Connection, 2. Communication, 3. Sharing, 4. Learning, 5. Co-creation, 6. Application or implementation), and not published in some well-known editor/ journal, conference proceedings, books or editorial material (e.g. from Elsevier, Springer, Emerald, IEEE, Wiley & Sons, Taylor & Francis, Science Direct, MDPI).

5.3.2. Definition of inclusion criteria and publications organization

Regarding the definition of the criteria for selecting the subset of the publications to be included in the list of the most important publications to be further categorized and analyzed, the following procedure was defined:

At least two keywords out from each of the 3 KW groups (KWG1, KWG2, and KWG3) were satisfied, about: 1) Collaboration, 2) Manufacturing/ management, and 3) Industry 4.0, correspondingly.

Some level of collaboration is considered and, further, possibly, some kind of collaboration approaches and practice to be identified (H-H, H-M or M-M) is referred, and further correlated with some I4.0 issue in M&M domain, in order to satisfy the requisite underlying the specification of the main research questions defined in the [section 2](#) (RQ1, RQ2 and/or RQ3).

Moreover, some kind of difficulty or obstacle regarding the implementation of some type of collaborative practice (e.g. H-H, H-M or M-M), regarding M&M in the context of I4.0, was searched in the list of the publications, for being categorized and analyzed, as this is also an import aspect to be focused, as mentioned in the [section 6.5.2](#) (RQ4).

Thus, a total of 291 publications was obtained for further analysis. To this end, and according to the subset of 291 publications, out of the 424 valid publications previously reached, satisfying not just the exclusion criteria but also the inclusion ones, these 291 publications were further subject to a deeper analysis, after the application of the inclusion criteria, in order to further filter this set of publications to a subset of **127** main valid publications, considered most important ones, once accomplishing more strictly to the focused collaboration domain (Coll-M&M), by satisfying the inclusion of at least one keyword from each of the three groups of keywords established.

Table 3. Publications selection and evaluation process.

Publications analysis process	Number of publications analysis task performed	Number of publications removed	Number of publications considered
Identification	648 publications were identified through the WoS and Scopus databases searching and three groups of keywords, (Editors: Taylor & Francis, Science Direct, Elsevier, MDPI, IEEE, others).	–	–
Screened/ Exclusion	648 publications screened, and exclusion criteria defined applied	180 publications excluded, based on the exclusion criteria considered	424 publications reached, after the application of the exclusion criteria
Analyzed/ Inclusion	424 publications analyzed, to verify its accomplishment of the main inclusion criteria defined, for further general bibliographic analysis and classification (clustered)	177 publications not fully complying to the main inclusion criteria defined (not related to Industry – Manufacturing/ Production or Management)	291 publications reached, after the application of the inclusion criteria
Deeply analyzed	291 records identified as relevant publications, after a refined analysis, according to the defined inclusion criteria	164 publications (not really considering some level of the proposed Coll-M&M concept)	127 publications considered for a deeper analysis (more or less close or to some extend related with the proposed collaboration concept)
Deeper analysis of top most relevant publications for refined analysis and discussion	127 publications considered most important ones in the focused research domain	59 publications (not most impacting publications)	68 top most relevant publications for further deeper analysis and discussion

according to the process for refined publications screening and analysis referred in section 4.3.

This set of **127** publications was subject to a further refined selection for reaching a subset of the top most relevant publications, through a deeper analysis, based on impact criterion defined regarding the quality of the editor, the journal, and of the publication itself (e.g. the number of citations), further based on the primer importance of the underlying contribution to the focused scientific domain, as synthesized in the [Table 3](#).

According to the application of the full screening process, based on the exclusion and inclusion criteria, and the further refined analysis to reach the set of top most relevant publications, a final list of **68** publications was reached, which was further subject to a deeper analysis about CollEng-M&M practice or applications and its importance in the I4.0.

6. Publications categorization and general data synthesis

In line with the previously defined intention, in the introductory section, one of the key academic and practical contribution of this work relies on the categorization of the selected and analyzed publications from the literature, in a set of main thematic categories, classes or clusters, regarding the distinct perspectives within the sphere of collaborative engineering (CollEng-M&M), according to the conceptual model proposed, which considers two main issues, about the human role and the learning paradigm, which will, thus, be considered for establishing the main clusters of publications for further analysis.

6.1. Definition of main clusters of publications

According to the proposed collaboration, conceptual model put forward, and previously described, in the [section 3](#), in this work the main categories of publications were organized considering a partial or incomplete use of the collaboration concept (without 'learning'), e.g. through IoT, cloud computing or manufacturing, augmented reality, mixed reality or digital twins (DT) based approaches, purely based on technology, and without explicit learning (co-learning) practices, even based on some other collaborative tools, such as, serious games, Google docs, etc.). Although, in this cluster of publications there is, at least subjacent some: connection, communication, resources sharing or common data handling, based on some kind of Information and Communication Technology (ICT) infrastructure and/ or cyber-physical system (CPS; Baheti & Gill, 2011; Bousdekis et al., 2020; Emmanouilidis et al., 2019; Fantini et al., 2020; Romero et al., 2016; Shi et al., 2011; Stern & Becker, 2017), for reaching some kind of cooperation or joint/shared decision making process, in some kind of practical application domain, in the industrial (manufacturing and/or management) context. Thus, it continues to be considered some kind of collaboration, of H-H, H-M or M-M type.

In the presence of 'learning', a more significant, higher, full or complete accomplishment of the proposed collaboration concept (with 'learning' or 'co-learning') is present, and which may be either 'Not human centered' or 'Human centered'). In the case of being 'Not human centered', examples such as pure M-M learning approaches, based on ML or on other kind of procedures, for instance, based on Multi-agents' interactions, through Multi-Agent Systems (MAS) may occur. In the case of the human presence being a key factor, this category is considered most relevant one, in the scope of the proposed CollEng concept, being H-H: B2.1), and H-M: B2.2) collaboration types considered, and which are marked by some kind of co-learning practice, and further applied in some kind of industrial (M&M) context, thus reaching the higher or complete level of collaboration.

The [Table 4](#) synthesis the main clusters of publications and underlying principal characteristics regarding cooperation and collaboration issues, in order to properly and clearly state the collaboration concept and subjacent contributions from the literature.

6.2. Literature data synthesis and general analysis

The main data about the four main clusters of publications ('Human-Learning', 'Human-NotLearning', 'NotHuman-Learning', and 'NotHuman-NotLearning') between 2010 and 2021 was synthetized, based on the obtained set of 424 valid publications, as shown in [Figures 2 and 3](#).

According to the data in [Figure 2](#), it can be seen that the cluster 'Human-Learning' includes 128 publications (30%), the cluster 'Human-NotLearning' 163 publications (39%), the cluster 'NotHuman-Learning', 94 publications (22%), and the cluster 'NotHuman-NotLearning' has 39 publications (9%).

Thus, the total number of publications about 'Human' intervention are 291 publications (69%), and the total number of publications regarding 'Not human' intervention are 133 publications (31%), in CollEng-M&M.



Table 4. Principal characteristics regarding cooperation and collaboration issues in the main publications' clusters.

Collaboration Type Level	Not human based (M-M)	Human-based (H-H; H-M)	Main skills focus
2nd level (higher level): with learning, and/or co-creation	Machine/ deep learning; automation; self-organization; neural networks; intelligent systems, exponential technology, collaborative robots, AI, CPS, ...	Learning organization; semiotics; pragmatics; emergence; innovation; through co-x (co-design (open design), co-conceptualize, co-learn, co-decide, co-evolve, co-innovate, co-analyze, co-do or co-think), ...	Hard + Soft skills -> business/ organizational oriented: paradigms, models, methodologies, methods, systems, and platforms (based on feedback, dialogue, and, higher level approaches, through learning paradigms, means, and software, besides other kind of technological support)
1st level (lower level): connection, communication, and sharing	Digitalization; integration, smart systems; smart objects, automatization, self-parametrization, semantic web; servitization, point-to-point, end-to-end communication, ...	Recommendation models and systems, DSS, supervised machine learning, human-machine interactions, human-robot, co-x: co-work, co-act, co-produce, co-operate, co-maintain, co-transport ...	Mainly hard skills oriented -> models, architectures, methods, algorithms, tools, devices, systems, and platforms (based on data, knowledge, mainly transactional processes, means, and tools)
Main paradigm focus	cooperation	collaboration	

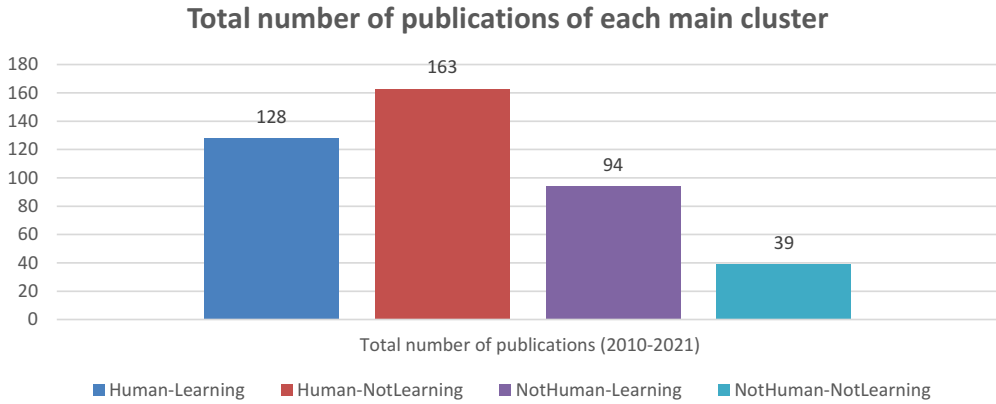


Figure 2. Number of publications from 2010 to 2021 in each cluster.

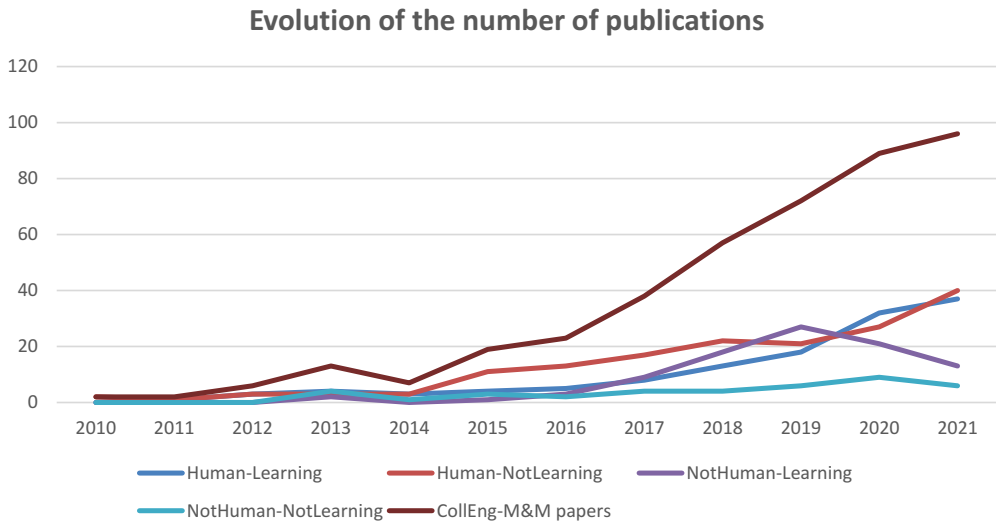


Figure 3. Evolution of the number of publications from 2010 to 2021 in each cluster.

Regarding the amount of publications explicitly focusing on learning, this subset includes a total of 222 publications (52%), and the subset not focusing on learning includes 202 publications (48%).

Figure 3 expresses a general increase on the number of the publications in each cluster, which is clearer up from 2016, showing an exponential upward trend for CollEng-M&M, with research works published between 2016 and 2021 accounting for **88.4%** of the total works published on this domain from 2010 to 2021, by presenting a noticeable growing tendency, over the last six years. Besides, as realized earlier, it is also visible a main focus, on one side, on the human role, and on the other one, on learning paradigm.

7. Detailed literature analysis and discussion about collaboration in the industry 4.0

The set of 127 considered important publications were further deeper analyzed in order to enable to reach main conclusions regarding the four main research questions posed in this paper. In order to accomplish this, the remaining content of this paper will focus on the exploration of the collaboration concept through the lenses of existing literature, along with the importance of the human role in collaboration, and the importance of learning. The importance of communication and middleware support, and technology (ICT) for supporting and promoting collaboration will also be further explored. A further deeper analysis about collaborative engineering practice or applications and its importance in the I4.0 will also be carried out, based on a subset of the considered top 68 top most relevant publications extracted from the literature. This analysis is focused on human centered collaboration, namely H-M collaboration based on learning factory, H-M collaboration in smart factories (SF) or CP[P]S, and H-M collaboration through collaborative robots (CR). Also not-human centered collaboration is further analyzed. Finally, the importance of I4.0 and CPS to foster or promote CollEng-M&M is analyzed, along with some main difficulties or concerns about the implementation of collaboration in the I4.0.

7.1. Collaboration concept under different literature perspectives

In this section, the collaboration concept will be analyzed through the lenses of existing literature, in order to properly support the main ideas underlying the proposed CollEng-M&M concept.

Collaboration is a word that comes from the word ‘colaborare’, and from its origin, it meant to express the action of working or operating with some other entity (e.g. someone) or anything, to produce or create something [<https://en.wikipedia.org/wiki/Collaboration>].

In the literature can be identified two distinct philosophical currents about the term collaboration, starting from the goal issue. One that defends the existence of a common goal or objective, and another one for which this does, in fact, not have to be verified.

In [http://mikeg.typepad.com/perceptions/2004/05/defining_collab.html] collaboration is defined as: “social skills, relationships, practices and technology services that improve how people work jointly and substantially together (sharing responsibility and risk), to communicate needs, coordinate activities, share information, exchange know-how, build community or achieve a common (team) objective (typically related to a process or project) within or across organizational boundaries.

In Abreu & Camarinha-Matos, (2008) Camarinha-Matos & Afsarmanesh, (2006) the authors do further state that collaboration is, in fact, not just related to sharing or distributing data, and information, but further with sharing knowledge, benefit, profit, skills, competences, along with costs, dependencies, difficulties, and even risks, between two or more entities.

In Lai, (2011) collaboration is defined as being a ‘mutual engagement of participants in a coordinated effort to solve a problem together.’ Moreover, the authors refer that

‘collaborative interactions are characterized by shared goals, symmetry of structure, and a high degree of negotiation, interactivity, and interdependence . . .’.

These considerations are in fact subjacent to the very closely related concept of concurrent engineering (CE), which is already very well established in the literature (Putnik & Putnik, 2019).

Different methodologies and technologies are mentioned to support geographically dispersed teams or entities within or across collaborating organizations that intend to share tasks, namely for facilitating product realization processes (Knoben & Oerlemans, 2006; Li & Qiu, 2006).

As stated by Knoben & Oerlemans, (2006), investments on time and resources, and even on several failures, or at least disappointing results, in the beginning of the establishment of an inter-organizational collaboration should be seen as learning and not as failure, as companies can indeed ‘learn’ to collaborate (Anand & Khanna, 2000; Knoben & Oerlemans, 2006; Lambe et al., 2002).

Moreover, given the fact that building organizational proximity asks for investments, organizations should focus on a relatively small number of collaborations. Empirical research has shown that organizations can manage at most six collaborations simultaneously (Draulans et al., 2003). Furthermore, research has also shown that it is more sensible for organizations to implement similar types of collaborations. Different types of collaborations have different requirements. Consequently, the building of organizational proximity takes place faster when similar types of collaborations are set up (Draulans et al., 2003).

In Li & Qiu, (2006) the authors do also refer to research works and commercial systems that have been put forward to provide solutions for what they mention to be collaborative and distributed product development processes, by further referring that these kind of practical applications are getting more pervasive and mature.

These authors do also refer that important existing work has been focusing on three main types of systems, concerning visualization-based systems, co-design systems and CE (concurrent engineering)- based systems. To this end, the authors refer to collaboration as being driven by the development of logical and intelligent co-ordination mechanisms to facilitate human-human and human-computer relationships.

Although, the main ideas expressed through these works do also fit the very well established definition of the CE concept (Putnik & Putnik, 2019), which it is quite different from the collaboration one (Putnik & Putnik, 2019; Putnik et al., 2021b, 2021c). In fact, besides the common importance of communication, alongside with the sharing issues, interaction, and interdependence or interplay, either in CE and CollEng, the existence of a common goal, along with, coordination, consensus and negotiation issues, are all well-known key aspects underlying CE (Putnik & Putnik, 2019) but do not have to comply with collaboration. Thus, the main existing contributions do not fully comply with the proposed CollEng concept, but just with its lower or basic level, which, in fact, does correspond, mainly, to the basic or lower level issues underlying the proposed CollEng concept, and the CE one.

This is because, in collaboration the existence of a common goal is not a requisite or even important, but, instead, the existence of a ‘common understanding’, in a broader sense, in order to enable and promote different points of view, and a constructive dialogue or discussion about some subject, which is enriched by diverse kind of feedback

and opinions that can even be opposite ones, with the main aim of reaching a common learning or co-learning stage – thus being important the existence of multi-disciplinarily interplaying teams, for promoting further discussion and an enriched or true co-creation and thus, innovation, which is considered a key issue in collaboration, and in the current digitalization era.

In this regard, an important contribution for the collaboration concept is put forward by Schrage (1990) in his book ‘Shared minds’, in which he refers that collaboration is not about agreement but about joint creation, and which thus does support the proposed CollEng concept. Although, co-learning being for us considered the real key issue in or for enabling such co-creation, thus reaching a higher or full level of collaboration.

Putnik et al., (2021b,c) further clarified the existence of an important difference between the CE and collaboration, which are frequently mismatched terms or taken as synonyms. Therefore, there is a need for distinguishing the semantic contents of these two concepts, besides the necessity to distinguish these two from others, also more or less closely related ones, for instance, about simultaneous or parallel engineering (Putnik & Putnik, 2019). Therefore, it is of utmost importance to notice and understand that in the M&M context, collaboration is mainly driven by new, emergent, organizational and management concepts that refer, for instance, to new features required for the engineering design, and regarding organizational and management issues and approaches.

According to Putnik et al., (2021b), the two new emerging theories, paradigms, and approaches that inform engineering design and practice, and on which base the definition of our CollEng is proposed, are the complexity theory and semiotics, in particular the complexity management in organizations and organizational semiotics (Putnik et al., 2021b). Thus, in a broader sense, the CollEng can also be seen as a new engineering design approach (Abbass et al., 2018; Putnik et al., 2021b).

7.2. The importance of the human role in collaboration

A widened set of works do mention the importance of the human role in collaboration, particularly nowadays, in the I4.0.

One frequently mentioned key aspect underlying collaboration, for instance, in Li & Qiu, (2006) Wang et al., (2002), is related to the possibility of augmenting the capabilities of individual specialists, along with the enhancement of their ability to interact with each other and with computational resources.

The authors in Li & Qiu, (2006) state that a collaborative mechanism of a system is needed for a specific design along a distributed architecture to meet the functional and performance requirements imposed, through sharing diverse and complex forms of information, further supported by a multi-disciplinary design team and integrating heterogeneous application services.

The frequently mentioned parallel and synchronous characteristics, alongside with the importance of interaction and multi-disciplinarily issues, regarding the joint working teams, which are, in fact, fundamental ones, also in CE besides its importance in the collaboration scope.

Although, besides the enrichment that arises from the interaction underpinned by a multi-disciplinary team in or for promoting interplay and constructive and diversified

discussion between entities or stakeholders, there is no real need to force the existence of big or complex multi-disciplinary teams in collaboration, because although this being important in CE, it is not a must or even important for enabling co-learning or co-creation, in CollEng. In fact, quite heterogeneous and/or complex teams can even be a problem in or for promoting collaboration, which are usually better suited or established when occurring in more contained, simpler or in lower dimension groups of interacting people.

In Haddara & Elragal, (2015) the authors refer that there are speculations that the I4.0 and the Factory of the Future (FoF) both carry bad news to people and employment. Although, they strongly advocate the counter argument. That is, people will continue to exist and play major roles in the FoF, but it is a different role with different skillsets. They mention that even the sensory subsystem, a major FoF component, needs people from sales, marketing, production, etc. to keep analyze and understand data and reflect on its implications. Moreover, they state that people are the supervisors of the robots, the architects of the control subsystems of the FoF. They do further mention that one key, new role that people play at the FoF is monitoring technology. They refer that failure of technology in the FoF could cause dramatic impact and therefore monitoring and actions are of paramount importance. Thus, they argue that in the future, people will have to change in content but will still remain irreplaceable. Particularly in view of customization, resulting in an increasing need for coordination. Therefore, they concluded that, more and more, workers will be required to be skilled in decision making in order to do their job in the FoF (Brettel et al., 2014).

The authors in Van Laar et al., (2017) identify seven human-centered issues that they consider to be fundamental for what they call the 21st century skills, currently needed to reach their so-called 'knowledge worker'.

In this regard, the authors mention that innovation starts with people, making the human capital within the workforce decisive. In their work, the authors conclude that the 21st-century skills are not necessarily underpinned by ICT. Furthermore, they did identify seven core skills: technical, information management, communication, collaboration, creativity, critical thinking and problem solving. Moreover, five contextual skills were also identified by the authors: ethical awareness, cultural awareness, flexibility, self-direction and lifelong learning. Therefore, it can be realized that the authors in their work put a high importance not just to the human role in the current I4.0, but also to the importance of communication, learning, and collaboration, besides more technical skills.

As stated in Riordan et al., (2019), the development of smart sensing technologies has allowed for modularity and versatility to become familiar terms on a manufacturing floor, notwithstanding, it is still widely recognized that a human employee is the most valuable and flexible asset a company may have. According to the authors, automation falls short in terms of flexibility due to its lack of independence during operations with high levels of variance, such as varying target position from cycle to cycle. Moreover, the authors state that processes with high levels of variance disallow employment at a satisfactory level of standard or more traditional automation methods due to the lack of ability of current systems to deal with the unexpected.

As stated in Vocke et al., (2020), the digital transformation of entire economic sectors and occupational profiles as well as the introduction of new forms of human-machine collaboration through the increased use of BD and cognitive systems requires completely

new approaches. Thus, in addition to the establishment of flexible working models and agile processes, the increased generation and integration of knowledge into and around technical systems in the course of targeted competence development of employees is indispensable. Therefore, the introduction and use of technical systems must go hand in hand with the flexibilization of innovation and collaboration processes as well as the development of employee skills in order to generate the currently missing socio-technological link – for companies' added value and for the benefit of people. In their paper, the authors present an overview of creativity techniques and innovation methods along with restrictions of tools for enabling human-machine collaboration.

In Abreu & Camarinha-Matos, (2008) the authors mention that in collaborative networks (CNs) the continuous and repetitive interactions among partners make that the value benefits generated by a collaboration process is not just determined by its tangible assets, for instance, products, and services, but also by its intangible assets, that enable the creation of relationship value, so-called social capital.

Moreover, Arrais-Castro et al., (2018) and Vafaei et al., (2019) further enhanced the importance of the human role in collaboration, namely through the use of collaborative platforms. Also in Birch-Jensen et al., (2020) the authors mention that a systematic use of customer-initiated feedback being fundamental for improving digitally connected services (DCS) that require three distinct efforts. Firstly, aims to capture customers feedback through various entries into the organization. Second, processing refers to utilizing this feedback within the organization for service improvements. Third, seeking for knowledge conversion to turn learning from feedback into knowledge that is dealt effectively across various functions such as quality management and customer services.

7.3. The importance of learning in collaboration

Learning is thus another key issue considered among a widened set of researchers.

As stated in Trstenjak & Cosic, (2017), one of the most important factors in the I4.0 is BD management. It is done with use of CPS, IoT and cloud computing. Human professions are obligated to adapt and change so the roles that are known are suggested to get a different structure in the future. In these new context, workers have to learn to deal with new situations and accept the term of life-learning process, constantly improving their performance. In the end, by using both, technological and human improvements, higher productivity, product quality and income with lower product delivery (manufacturing) time and product price are expected. Apart from that, the term of mass customization has become very important and does also demand very flexible manufacturing, along with enriched human skills, to enable proper production and process planning (PP) and manufacturing data analysis.

The authors in Q. Liu et al., (2019) present a systematic implementation of a framework about human-robot collaborative disassembly (HRCd), which combines a set of advanced technologies such as cyber-physical production system (CPPS), and AI, by further involving a set of considered by the authors five main aspects about perception, cognition, decision, execution and evolution aiming at the dynamics, uncertainties and complexities in disassembly processes. To this end, the authors propose the use of deep reinforcement learning, incremental learning and transfer learning that they investigate in the systematic approaches for HRCd.

As mentioned in (rana-Arexolaleiba et al., (2019), nowadays in the context of the I4.0, manufacturing companies are faced by increased necessity to enable self-learning capabilities to accommodate the natural variation exhibited in real-world tasks. In their paper, the authors propose a Reinforcement Learning (RL) enabled robot system, which learns task trajectories from human workers. Furthermore, according to them, their robot is able to build upon the learned concepts from the human expert and improve its performance over time.

Posselt et al., (2016) also mentioned that new manufacturing paradigms such as the I4.0, based on CPS and ubiquitous manufacturing along with rapid development of underlying technologies, increases with the importance of integrated lifelong learning processes, as part of the overall activities within manufacturing companies.

7.4. Collaborative engineering practices or applications and its importance in the Industry 4.0

In this section a deep analysis about CollEng-M&M practices is provided, based on the previously identified set of 68 publications that were considered most relevant ones, in order to further uncover the main research results and corresponding conclusions, one step forward from the previously exposed more general analysis and description, along with the global data analysis, presented in the [section 5](#).

According to the compilation and analysis carried out so far, the next deeper literature analysis will thus follow the same general structure, regarding human centered and not human centered approaches and applications. One important analysis that comes out from this research is related to the interpretation and understanding about the interrelation[ship] between CollEng-M&M and I4.0 principles, issues or technologies, based on the secondary research sources, in order to answer other important research questions raised in this work, about the relation between CollEng and I4.0, which will be also explored next.

7.4.1. Human centered collaboration

In this section human-based collaboration practices will be synthetized. In this context, collaboration examples will be briefly presented, focusing on different kind of co-creation examples or applications, for instance, related to co-design, co-work, or co-learn, among others.

In (Louw & Walker, 2018), is referred that the FoF will make use of actuators, sensors and CPS to provide an environment in which humans, machines, and resources will communicate as in a social network. The authors consider information flow a key enabler of such FoF. Further they state that industrial engineers, as designers and improvement agents of such FoF, will need to develop better skills in various aspects of data analytics and information communication technologies.

As referred in (Chen et al., 2016), intelligent industrial ecosystems enable the collection of massive data from various devices (e.g. sensor-embedded wireless devices) dynamically collaborating with humans (Varela et al., 2018). According to the authors this is essential to improve the efficiency of industrial production/service. In this paper, the authors propose a collaborative sensing intelligence framework, combining collaborative intelligence and industrial sensing intelligence, which they state does facilitate

the cooperativity of analytics by integrating massive spatio-temporal data from different sources and time points.

In (Bechtold & Lauenstein, 2014) is referred that the current industrial revolution is characterized by the cooperation or collaboration of intelligent machines, storage systems, production systems and people into intelligent networks, merging the real and virtual worlds through CPS. The authors do further state that these CPS integrate IT systems with mechanical and electronic components connected to online networks that allow the communication between machines in a similar way to social networks, and these innovative technologies enable factories to become 'smart,' resulting in productions of customized products on an industrial scale while providing many opportunities for improvements in operational flexibility and efficiency, including with human work, as further mentioned in (Kaasinen et al., 2020; Putnik et al., 2021a; Varela et al., 2021).

Moreover, the authors in (Bechtold & Lauenstein, 2014) mention that CPS' influence on the human factor is linked through four elements: (1) tools and technologies, (2) organization and structure, (3) working environment, and (4) organizational cooperation. They consider that the FoF will increase the need for skilled digital work, that there will be a decrease in the need for manual work, and that the workers will be provided with the exact information needed, in real time (RT), to perform properly and efficiently execute tasks. Thus, that intelligent systems will further make it possible for the worker to make qualified decisions in a shorter time. Also that CR will share a workstation with humans, and that these robots will support the them, for example, in situations that are critical regarding ergonomic conditions. Besides, that intelligent tools and technologies will become more autonomous and automated, but the supervision and efficient application of machines by humans will become more important than ever before.

In (Petrillo et al., 2018) the authors refer believing that a significant change in the used technologies should and will proceed jointly with a significant change in organization and structure of companies. In this regard, the authors mention that workers will be capable of working in accordance to dynamically available and updated information through more or less complex data flows that will no longer be necessarily bound or restricted to a certain production area. Thus the new operator skills will be of primer importance to improve job management by making it more qualified, responsive, and a more or better informed DM process, taken remotely. According to the authors, the future working environment will be an open and creative space. Work will be more flexible and transparent, more planned, and balanced. The authors believe that the homework will increase. Although, that modern assistant systems will provide the workers with the ability for quick DM despite the increased complexity of their job contents. Moreover, the authors do further state that the work will be improved with respect to ergonomics. More precisely, that those non-ergonomic processes are likely to become automated, to improve the workers' conditions. In the FoF, intra-organizational cooperation and communication will be fundamental. Networking and interconnectedness are focal components of the I4.0. Workers will collaborate and communicate in real time without borders using smart devices. The Internet provides the possibilities to meet globally in virtual rooms at almost any time and to reach out for required information as needed. All kinds of information and data will be ubiquitous and at the fingertips of the workers leading to a whole new level of knowledge management. Humans will

communicate with each other and with intelligent machines, and intelligent machines will also communicate with each other.

In (Knoben and Oerlemans (2006); Wang et al., 2002), is enhanced the importance of information sharing and communication for facilitating, for instance, audio/video conferencing, on-line chatting, instant messaging, whiteboard and application sharing, for performing more advanced collaborative activities.

The communication, and underlying facilities and means, as expressed through the proposed CollEng concept, does, in fact, represent a key issue, along with the sharing ones, functioning as basic conditions, for CE but also for collaboration (CollEng). Although, just accomplishing communication requisites is not enough for fulfilling real or full collaboration, as referred before. This, in one side, is justified by the fact that two or more entities may be communicating but, for example, just in one direction through information transmission or discourse, based on a more or less pure transactional process, thus, without the existence of a real interaction, interplay or dialogue, thus, not configuring real or full collaboration.

Moreover, although many different kind of metrics do exist, for measuring levels of communication, and which have been put forward and used over the last decades to evaluate them, these are, in fact, just ways for measuring CE implementation degrees, not being really able to measure interactions and/or dialogue levels, considered of utmost importance in collaboration (Coccoli et al., 2014; Putnik & Putnik, 2019; Putnik et al., 2021b, 2021c).

In (Coccoli et al., 2014) the authors state that recent evolutions, such as pervasive networking and other enabling technologies, have been dramatically changing human life, knowledge acquisition, and the way works are performed and people learn. Also in (Shamszaman & I, 2019) is referred that IoT has initiated a few interesting research directions such as Social Internet of Things (SIoT), Cloud of Things (CoT), and Edge of Things (EoT). The authors state that nowadays, a large number of IoT nodes are available and there is a need to ensure automated access and communication among these IoT nodes. According to the authors, an emerging area of study is to make a social platform for IoT nodes so that devices can communicate with each other and create automated and on-demand services. The authors foresee that, as these IoT nodes and services along with human skills will be crucial to collectively form a cognitive society to share resources, information and skills.

The authors in (Bechar et al., 2015) refer that communication is what enables cooperation. They refer that the main novelty is to enable innovation through collaboration. Also, that communication is a two-way process of reaching mutual understanding, in which participants not only exchange (encode-decode) information, new ideas and feelings but also create and share meaning. According to them collaboration has been gaining increased importance, and visibility. New technologies are emerging to enable and support physical, implicit and explicit collaborations, which they considered essential for dealing with increasingly complex systems in unstructured, dynamic environments. Moreover, they refer that research activities concerning new ways of using lasers as a collaboration supporting technology has been recognized as vital for activities that demand increasingly more coordinated effort among interacting agents (e.g. humans, machines, particles) and digital, possibly photonic agents, but that its practical application is still on its infancy.

Different kinds of CollEng-M&M approaches and platforms have been put forward, during the last decade, and with a refreshed and reinforced importance nowadays, in the I4.0, for enabling human centered collaboration. In this context, Computer Supported Cooperative or collaborative work (CSCW) is gaining a new importance and expression (G.D. Putnik et al., 2021d; Putnik et al., 2020).

(Li & Qiu, 2006) referred that collaboration is to establish an effective communication channel between the upstream design and downstream manufacturing to enrich the principles and methodologies to link diversified engineering tools dynamically. Thus, according to the authors, the future trends for the collaborative systems include, although not being limited to, the integration of various collaborative manners and systems.

Their proposed integral system can support interrelated activities and share domain knowledge between designers and systems to improve design quality and efficiency. It integrates modules for hierarchical collaboration that can be wrapped as services for remote revoking. The authors state that their system enables scheduling and coordination, which they consider becoming more crucial and challenging, and to be enhanced through the use of distributed intelligent algorithms and technologies such as MASs or Web services for increasing the potential of collaboration.

The authors do further mention that research and development have been actively carried out to develop technologies and methodologies to support collaborative design (CD) and development systems, and that software vendors have quickly realized the huge business opportunities in this area, having been launching to the market a variety of commercial systems to promote collaboration (Li & Qiu, 2006).

Schrage (1990) mentions that it is noticeable a lack of structures that allow people to express their competences creatively. Moreover, he refers that merely teamwork does not mean authentic collaborative work, and that 'shared spaces' like blackboards or brainstorming sessions enable to pass from mere communication to true collaboration.

The authors in (Haddara & Elragal, 2015) do refer that the I4.0 is based on the technological concepts of CPS, and IoT, enabling the FoF, and that CPS enable to monitor physical processes, create a virtual copy of the physical world and decentralized decisions. Moreover, in such kind of environment, through the IoT, CPS are able to communicate and cooperate with each other and with humans in RT. Further, that Enterprise Resource Planning (ERP) systems are considered the backbone for the I4.0, being currently ready for the FoF.

Moreover, in (Lee et al., 2014) the authors mention that today, in the I4.0 factory, machines are connected as a collaborative community. They state the current evolution requires the utilization of advanced prediction tools, so that data can be systematically processed into information to explain uncertainties, and thereby make more 'informed' decisions.

According to (Arias et al., 2000), new media allows framing and resolving complex design problems by extending the power of the individual human mind. Thus, approaches, systems, and collaborative and participatory processes, are key enablers for future collaborative human-computer systems. Moreover, the authors mention that human-computer interaction (HCI) research is being referred over the last decades as collaboration key-enablers, while contributing to the creation of new paradigms and new forms of working, learning, and collaborating in the information age.

It has further been referred that major emphasis has been put to develop new technologies (e.g. at the hardware, basic software, and application levels), new interaction techniques (e.g. graphical user interfaces), and new design approaches (e.g. user centered, human-centered, work-oriented, and learner-centered design). Also that much of this research has emphasized and pioneered socio-technical approaches. Further, that HCI work has progressed from early concerns with low-level computer issues to a focus on people's tasks (Myers, 1998; Newell & Card, 1985; Norman & Thomas, 1990). Besides, other relevant theory has been mentioned being primarily grounded in social and organization themes in the new millennium (Hutchins, 1995; Thomas & Kellogg, 1989).

(Nadin, 2001) mentioned that as the digital world becomes part of the underlying structure of human existence and activity, human interaction will be less and less direct. Mediated through various interfaces, human interaction via all kinds of networks becomes increasingly an expression of the semiotic condition of the human being in the post-industrial age. Also, that professionals dedicated to human-computer interaction, and semioticians must realize that they would benefit mutually if they would collaborate better than they have until now.

In (Obieke et al., 2020) the authors highlight the value of using emergent technologies to support human effort in identifying creative design problems." They show the importance and benefits of problem exploring in design and why it deserves attention. Consequently, they illustrate the use of emergent technologies to support problem-exploring in design and give reasons why this is possible in the I4.0." Their proposed technologies include data mining, natural language processing, ML, and duplication recognition, among others.

In (Kubicki et al., 2019) the authors mention the enhancement of team collaboration through a strong reflexivity analysis in the scope of a follow-up project (4DCollab, www.4dcollabproject.eu) by the use of horizontal touch-based tabletops for synchronous collaboration of the research team. They highlight the importance of these technologies in the BIM projects, as they imply collaborative working amongst geographically distant teams, and these devices and technologies enable 'synchronous distant' coordination meetings.

Papazoglou et al., (2018) referred that Product-Service Systems (PSS) are being revolutionized into smart, connected products, which changes the industrial and technological landscape and unlocks unprecedented opportunities. The intelligence that smart, connected products embed paves the way for more sophisticated data gathering and analytics capabilities leading to a new era of smarter supply and production chains, smarter production processes, and even end-to-end connected manufacturing ecosystems. According to the authors, this imposes a new technology stack and lifecycle models to support and capacitate smart, connected products and services.

The main contribution put forward in (Papazoglou et al., 2018) is a PSS customization lifecycle methodology with underpinning technological solutions that enable collaborative on-demand PSS customization by supporting companies to evolve their product-service offerings by transforming them into smart, connected products. According to the authors, this is facilitated by their proposed lifecycle formalized knowledge-intensive structures and associated IT tools that provide the basis for actionable PSS and production 'intelligence' and a move toward more fact-based manufacturing decisions. Moreover, the authors state that their PSS customization lifecycle methodology enables

a way for a new direction in highly-connected, knowledge-enabled smart factories (SF), where devices, production equipment, production processes, and human-operators are connected, offering DM support on the basis of production knowledge and data.

In (Garcia et al., 2020) the authors mention the importance that CPPS and the IIoT will have in improving the flexibility of the future production systems in the newest SF. Particularly they refer to the new trend in robotic cells based in the Human-Robot Collaboration (HRC) through which robots and humans work together.

In (Soatti et al., 2019), the authors mention that distributed signal processing methodologies are highlighted as enablers for next generation cloud-assisted IoT systems. The authors refer to their proposed distributed algorithms that run inside a wireless cloud network (WCN) platform and are exploited for WCN self-organization, distributed synchronization, networking and sensing. Further, they refer that the WCN platform can lease augmented communication and sensing services to off-the-shelf industrial wireless devices via a dense, self-organizing ‘cloud’ of wireless nodes, with application in practical IoT scenarios. In particular, cooperative communication algorithms adopted to support reliable communication services. Besides, their localization and vision applications based on distributed processing of wireless signals are intended to support contact-free human-machine interfaces.

The authors in (Dombrowski et al., 2018) show the importance of digital factory tools for the planning of human-robot collaboration (HRC), the associated risk assessment and the safety certification of the entire HRC-application.

(Ooi & Shirmohammadi, 2020) mentioned that IoT has been disrupting many industries by providing an unprecedented approach for a (potentially large) number of distributed components connected over a network to collect data, collaborate, and perform tasks with almost no human intervention. They also state that the deep understanding of IoT and therefore its definition are still evolving. Meanwhile, IEEE defines an IoT system as ‘a system of entities (including cyber-physical devices, information resources, and people) that exchange information and interact with the physical world by sensing, processing information, and actuating’.

Further, they refer that in an industrial setting, IoT can enable the integration of manufacturing machines or robots equipped with instrumentation, sensing, processing, communication, and collaboration, leading to more efficiency and profitability in the management of equipment, assets, processes, and produced goods.

The authors in (Cao et al., 2018) examine the new challenges posed by human-driven edge computing. They state that massive proliferation of personal computing devices is opening new human-centered designs that blur the boundaries between man and machine. The authors state that now, the frontier for the research on the data management is related to the so-called edge computation and communication, consisting of an architecture of one or more collaborative multitude(s) of computing nodes that are placed between the sensor networks and the cloud-based services.

The authors in (Syberfeldt et al., 2016) mention that with augmented reality (AR), virtual information can be overlaid on the real world in order to enhance a human’s perception of reality. In their study, the authors aim to deepen the knowledge of augmented reality in a shop-floor context and analyze its role within smart FoF. Their study evaluates a number of approaches for realizing AR and discusses advantages and disadvantages of different solutions from a shop-floor operator’s perspective.

In (Kafle et al., 2016) the authors mention that the IoT is envisioned to connect things of the physical world and of the cyber world to make human life more productive, safe, healthy, and comfortable by solving numerous challenges related to the environment, energy, urbanization, industry, logistics, and transportation, among others. It presents several key networking concepts, such as software-defined networking, information-centric networking, and ID-based communication.

As mentioned in (Emmanouilidis et al., 2019), the Industrial CPS have benefitted substantially from the introduction of a range of technology enablers. These include web-based and semantic computing, ubiquitous sensing, and IoT with multi-connectivity, advanced computing architectures and digital platforms, coupled with edge or cloud side data management and analytics, and have contributed to shaping up enhanced or new data value chains in manufacturing. While parts of such data flows are increasingly automated, there is now a greater demand for more effectively integrating, rather than eliminating, human cognitive capabilities in the loop of production related processes. Human integration in Cyber-Physical environments can already be digitally supported in various ways. However, incorporating human skills and tangible knowledge requires approaches and technological solutions that facilitate the engagement of personnel within technical systems in ways that take advantage or amplify their cognitive capabilities to achieve more effective sociotechnical systems. After analyzing related research, this paper introduces a viewpoint for enabling human in the loop engagement linked to cognitive capabilities and highlighting the role of context information management in industrial systems. Furthermore, it presents examples of technology enablers for placing the human in the loop at selected application cases relevant to production environments. Such placement benefits from the joint management of linked maintenance data and knowledge, expands the power of ML for asset awareness with embedded event detection, and facilitates IoT-driven analytics for product lifecycle management.

In (Birch-Jensen et al., 2020) the authors refer that a growing number of manufacturers advance their offerings by providing digitally connected services (DCS) that require companies to revisit quality improvements based on customer feedback. In their paper the authors explore how firms use customer-initiated feedback for quality improvement of DCS. DCS entail a human-to-digital interface for enabling ongoing provider-customer interaction.

(Oestreich et al., 2019) referred that due to an increasing demand for individualized products and the resulting high variability in manufacturing processes, flexibility and cognitive skills of human workers are highly important for manual assembly processes. Hence, the focus of their contribution is an interactive learning procedure of the assembly of a new and complex products, based on digital assistance systems.

(Pilati et al., 2020) presented a hardware/software architecture to assist, in RT, operators involved in manual assembly processes during the training phase to support their learning process, both in terms of rate and quality. A marker-less depth camera captures human motions in relation with the workstation environment whereas an AR application based on visual feedback guides the operator through consecutive assembly tasks during the training phase, based on a Learning factory (LF) environment, which the authors mention did increase learning rate of 22%, along with a reduction in manual process duration up to -51% in assembly cycles.

7.4.2. *Human-machine collaboration based on learning factory*

As mentioned in (Büth et al., 2018) the I4.0 is posing huge challenges to industry in terms of technology implementation as well as human resources development. In particular, theoretical knowledge and practical skills regarding data acquisition, processing, visualization and interpretation are needed to exploit the full potential of digitalization, being the learning factory a well-suited paradigm for this purpose.

According to (Hummel et al., 2015), planners have to find the ideal solution for functional as well as social interaction between humans and machines in a CPS. According to the authors, such collaborative work systems consider the individual capabilities and potentials of humans and machines to combine them in a manner that assists the operator during his/her daily work routine towards more productive, less burdening work. The authors state that group-based, activity-oriented scenarios enable the participants to put the learnings into practice within their professional environments. By this, LF have an indirect impact on the transfer of proven best practices to the industry and thereby on the diffusion of the idea of a human-centric working environment.

(Schuhmacher & Hummel, 2019) mentioned that conventional planning and control systems, which rely on predefined processes and central DM, are not capable to deal with the arising system's complexity along the dimensions of changing goods, layouts and throughput requirements. The authors mention that the concepts of 'self-organization' in combination with 'autonomous control' provide promising solutions to solve these new requirements by using, among other things, the potential of autonomous, decentralized and target-optimized DM. The authors refer to intelligent logistical objects (e.g. smart products, bins and conveyor systems) which are able to communicate and interact with each other as well as with human workers. To investigate the potential of automation and human-robot collaboration for intralogistics, the authors propose a research project for the development what they call a collaborative tugger train based on LF principles.

(Juraschek et al., 2018) put forward an overview of applications of mixed reality (MR) based on LF paradigm. The authors state that MR can be utilized for information visualization, remote collaboration, human-machine-interfaces, design tools and education and training. According to the authors, this kind of development makes new demands on LF in two major fields: one regarding the empowerment of users to work with MR in industrial applications. The second one is about the utilization of the potential of MR for teaching and learning in LF. The authors state that a great potential lies in the new possibilities of connecting digital content with the physical world.

In (Quint et al., 2015) the authors propose a system architecture for an MR-based learning environment, which combines physical objects and visualization of its digital content via AR. According to the authors, reducing the gap between the real and digital world makes the factory environment more flexible, more adaptive, but also demand broader skill of human workers. Interdisciplinary competencies from engineering, information technology, and computer science being required in order to understand and manage the diverse interrelations between physical objects and their digital counterpart.

In (Reuter et al., 2017) the authors refer to LF trainings as an enabler of proactive workers' participation regarding I4.0. Further, in (Oberc et al., 2018) an LF concept to train participants regarding digital and human centered decision support is put forward. The authors refer to changes of work caused by decision support systems (DSS) as well as

the functionalities of assistance systems. Further, CPS are mentioned to lead to an emerging quantity and quality of data that can be collected and processed within the whole production process (Abbass et al., 2018; Oberc et al., 2018). This data helps to rationalize and optimize the production planning as well as the operative level. In order to handle this amount of complex information, digital support systems are required. Besides assistant systems, crosslinking of data and machines within a company is one of the central aspects of the I4.0.

In (Daniyan et al., 2020) the authors mention that the LF are platform created to provide an effective learning environment that will bring about human capacity development in a bid to bridge the gap between learning and practice. In their study, the authors refer to training modules involving the AI system, which comprises of the Artificial Neural Network with dynamic time series model they did develop. The authors clarify that the aim is to train maintenance personnel on how to constantly monitor and analyze data from the IoT and other sources in order to predict the state and potential failure of a railcar wheel bearing.

7.4.3. Human-machine collaboration in smart or cyber physical manufacturing systems

According to the authors in (Osterrieder et al., 2020) 'human machine interaction encompass research activities creating solutions for the co-automation, physical and digital assistant systems. The authors state that beside technological developments, the human perspective and the role in autonomous SF is central ...'. Moreover, they do further mention that: 'This pillar is solidly connected to DM and CPS'.

In (Schuhmacher & Hummel, 2016) is further mentioned that the increasing emergence of CPS and a global crosslinking of these CPS to CPPS are leading to fundamental changes of future work and logistic systems requiring innovative methods to plan, control and monitor changeable production systems and new forms of human-machine-collaboration.

The authors in (Longo et al., 2017) refer that the I4.0 requires human operators with experience to face increased complexity of their daily tasks, requiring them to be highly flexible and to demonstrate adaptive capabilities in a very dynamic and smart working environments. Therefore, there is a necessity for tools that can be easily embedded into everyday practices of operators, to enable to combine complex methodologies with high usability requirements of the tasks.

As stated in (Fernández-Caramés & Fraga-Lamas, 2018) one of the challenges of the I4.0 is the creation of vertical networks that connect smart production systems with design teams, suppliers and the front office. According to the authors, to achieve this, information has to be collected from machines and products throughout a SF. Moreover, they mention that the IIoT paradigm once applied to smart labels attached to objects permits them to be identified remotely and discovered by other I4.0 systems, allowing such systems to react in the presence of the smart labels, thus triggering specific events or performing a number of actions on them. The authors do further refer that the amount of possible interactions is endless and creates unprecedented industrial scenarios where items can talk to each other and with tools, machines, remote computers or workers. In their paper, the authors provide main foundations for developing what they called the next generation of the I4.0 human-centered smart label applications.

Moreover, it also mentioned that Human-centered design (Abbass et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Hippertt et al., 2019) is an approach to system design and development that aims to make interactive systems more usable and useful by focusing on their use by operators and their requirements within a collaborative industrial environment. Thus, the authors argue that their proposed approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance.

Besides, it is also mentioned that human-centered smart systems (Lun & Zhao, 2015; Nelles et al., 2016; Reis et al., 2017; Sacha et al., 2017; Zhao et al., 2017) together with the design principles of the I4.0 paradigm (Fantini et al., 2020), require the connection among all actors of a manufacturing chain, from semi-finished products, to workstations, as well as machines and workers. Therefore, for a factory to become 'smart', and able to take the most out of data collected from operations and production systems, RT connectivity will be needed to the link information about products and items in a smart manufacturing (SM) environment.

According to (Thomas & Kellogg, 1989), human-machine symbiosis in the AI era, and especially in I4.0 environments, is at its early stages and there are still many unexplored opportunities. The I4.0 enables new types of interactions between operators and machines (Emmanouilidis et al., 2019; Rauch et al., 2020). This allows a paradigm shift from independent automated and human decisions towards a human-AI symbiosis, characterized by the collaboration of AI and human intelligence (Guerin et al., 2019; Romero et al., 2016, 2015, 2017).

The authors in (Bousdekis et al., 2020) put forward a Human Cyber Physical System (HCPS) framework for Operator 4.0 – AI Symbiosis and its main architectural building blocks. Operator 4.0 is defined as being an 'operator of the future', a smart and skilled operator who performs 'work aided' by machines if and as needed in an I4.0 oriented environment (Romero et al., 2016, 2015, 2017). The HCPS concept, building on top of human automation interaction (Hancock et al., 2013), aims at studying the symbiosis between humans and AI, in which the human is an integral part of the CPS.

Further, in (Zolotová et al., 2020) is also presented a HCPS, which the authors consider important for fulfilling the current new demands for productivity and effectiveness in production. The authors refer that a traditional operator is being transformed to the Operator 4.0, and in their paper, they describe evolving roles of the operators in the factories, by mentioning different ways to enhance the operators' physical, sensing, and cognitive capabilities that according to them can be used individually or in combination to put humans into the center of the current technological revolution.

The authors in (Bousdekis et al., 2020) do further refer that in recent years, human – machine symbiosis in the I4.0 era has started to emerge, however being still at a conceptual level. Therefore, the authors contribute with their proposed HCPS framework, which is based on three pillars: AI in manufacturing, DT in CPS and Operator 4.0-AI symbiosis. In their paper, they present a HCPS for Operator 4.0-AI symbiosis in I4.0 manufacturing systems (MS). It presents a conceptual architecture for making humans, cyber systems, and physical systems working together in optimal complementarity by taking advantage of the strengths of both human intelligence and machine

intelligence. According to the authors, their proposed framework will serve as a blueprint of our future work aiming at developing a HCPS for Operator 4.0-AI symbiosis in compliance with the I4.0 principles. The authors state that up to their knowledge, there are mainly conceptual approaches on H-M symbiosis, while others focus on specific manufacturing processes (Emmanouilidis et al., 2019; Fletcher et al., 2020; Guerin et al., 2019; Kaasinen et al., 2020; Rauch et al., 2020).

According to (Ansari et al., 2020) an increasing number of AI-enhanced approaches provide helpful 'know-how' for reproducing and imitating skills and finally substituting human jobs with algorithms and intelligent machines. However, complementarity of human and machine, especially in hybrid man-machine settings is still not sufficiently explored. Thus, in their paper the authors propose a twofold qualitative and quantitative methodology for optimal selection of a competent jobholder(s) to perform a certain task by semantic modelling and analysis of jobholder – humans and machines – profiles corresponding to the task characteristics and learning requirements including knowledge, skills and competences.

According the authors in (Ansari et al., 2018) Cyber Physical Social Systems (CPSS) tend to integrate computation with physical processes as well as human and social characteristics. The fusion of cyber, physical, and socio spaces through I4.0 emerges a new type of production systems known as CPPS. The CPPS enriches communications among cyber-physical-socio space in the production environment. The authors enhance that utilizing human-cantered CPPS in SF as being an ideal scenario resulting in a mutual transition from human-machine cooperation to active collaboration, characterized by cyber-physical-socio interactions, knowledge exchange and reciprocal learning.

According to (Giorgio et al., 2020) in the current digital manufacturing age there is a need to elicit and transfer procedural knowledge (PH) between humans and machines, being essential for having proper knowledge in DM processes. To capture experiences and turn them into knowledge is thus fundamental in learning processes and knowledge developments. The authors mention that in the I4.0 era, humans and machines must be able to collaborate in such a way that enables both to be able to exploit the best abilities of each other in a manufacturing process. In their paper, the authors introduce a PK approach to capture and define unexpected events, while a process step is intended to perform its required functions and transfer this information as machine-understandable knowledge about failure modes.

In (Arana-Arexolaleiba et al., 2019) the authors refer that holistic learning culture and modern learning environments are required. To allow the learner to independently acquire knowledge and skills in a LF an intelligent learning management system with extensive feedback information to the learner is required. Thus, the authors propose an approach to pursue interactive knowledge transfer through a multi-sensory approach combined with processes feedback that enables a learning process with full human senses.

7.4.4. Human-machine collaboration through collaborative robots

The authors in (Gualtieri et al., 2020) present design principles and design guidelines for products to enhance safety, ergonomics and efficiency in collaborative assembly, considering that in addition to MS design, a corresponding product design can also influence the feasibility of collaborative assembly and working cells. According to the authors, based on the generally so-called 'Design for X' assembly technologies have to be

substituted by more innovative approaches to assemble products using human-robot collaboration.

In (Pace et al., 2020) a systematic review of AR interfaces for collaborative industrial robots is proposed. According to the authors, their literature review aims at identifying the main strengths and weaknesses of AR with industrial robots in human-robot collaborative scenarios.

In (Dusadeerungsikul et al., 2019) is mentioned what is called a brain-inspired model for production systems, a virtual Hub for Collaborative Intelligence for receiving human instructions through a human-computer interface (HUB-CI) and command robots via ROS. They state that the purpose of their proposed HUB-CI is to manage diverse local information and RT signals obtained from system agents (robots, humans, and warehouse components, namely, carts, shelves, and racks), and globally update RT assignments and schedules for those agents.

As mentioned in (Bochmann et al., 2017), the development towards decentralized MS aims at increased flexibility and robustness by maintaining the level of productivity. According to the authors, in order to meet these requirements, human-robot collaboration is considered a basic framework within future intelligent manufacturing cells. Particularly, the relationships between factory layout planning, production scheduling, and human-robot work distribution are investigated by the authors.

The authors in (Çil et al., 2020) refer that the collaboration of human workers and robots draws increasing attention from the manufacturing enterprises to embrace the I4.0 paradigm. Therefore, motivated by the requirements of collaboration between human workers and robots in assembly lines, they studied a mixed-model assembly line balancing problem with the collaboration between human workers and robots.

The authors in (Cherubini et al., 2019) introduce BAZAR, a collaborative robot that they consider to be of utmost importance in the FoF, which are: mobility for navigating in dynamic environments, interaction for operating side-by-side with human workers, and dual-arm manipulation for transporting and assembling bulky objects.

In (Z. Liu et al., 2018) refer to human-robot collaborative manufacturing (HRC-Mfg) by considering the dynamics and uncertainties in manufacturing environments, which the authors consider crucial for tasks allocation and properly supporting DM. To this end, in the sight of CPPS, based on bilateral game and clan game, the authors present the characteristics of HRC-Mfg and show the applicability of cooperative game in such environment, in order to maximize production benefit.

The paper (Bilberg & Malik, 2019) discusses an object-oriented event-driven simulation as a DT of a flexible assembly cell coordinated with a robot to perform assembly tasks alongside humans. The authors mention that the DT extends the use of virtual simulation models developed in the design phase of a production system to operations for RT control, dynamic skill-based tasks allocation between human and robot, sequencing of tasks and developing robot program accordingly, allowing flexible human-robot working teams.

In the paper (Malik & Bilberg, 2018) is presented a DT framework to support the design, build and control of human-machine cooperation. In this study, the authors refer to computer simulations being used to develop a digital counterpart of a human-robot collaborative manufacturing environment for assembly work.

In (Demir et al., 2019) the authors state that there are a few visions for the I5.0, being one emerging theme human-robot co-working. In their paper, the authors discuss the possible issues related to human-robot co-working from the organizational and human employee's perspective, believing that these issues will be the focus of many upcoming organizational robotics research studies.

7.4.5. Not-human centered collaboration

The authors in (Lee et al., 2014) put forward what they call a systematic framework for self-aware and self-maintained machines. Their framework includes concepts of CPS and DSS. The authors state that the I4.0 proposes the predictive manufacturing in the future industry, characterized by machines that are connected as a collaborative community.

In (Rathee et al., 2019) the authors refer that Communicating Things Network (CTN) is the latest paradigm in the development of smart technologies. CTN comprises a network of physical devices capable of extracting and sharing digital information. The aim of CTN is to develop smart appliances that boost productivity and provide RT data faster and more accurately than any structure or network that is dependent on human interference. The authors mention that interconnected physical objects in the network communicate with each other and facilitate intelligent DM by monitoring and analyzing their surroundings. The authors state that in today's I4.0 era, CTNs are playing a significant role in daily activities by providing a substantial reduction in costs with increased visibility and efficiency in all aspects of businesses and individuals. Having proposed what they call a secure Hybrid Industrial IoT framework using the blockchain technique. They have used a hybrid industrial architecture where different branches of a company are located in more than one country. According to the authors, although IoT devices are used in many organizations and assist in reducing their production costs along with improving quality, several threats can occur in IoT devices initiated by various intruders.

In (Bourellos et al., 2020) is proposed an approach for an operational software framework of modular components that can create intelligence in Housing Units. Their framework is based on the lightweight Case Based Reasoning approach and principles to extract knowledge from generic historical data. The authors mention that collaboration between houses is included through the sharing of anonymized high-level problem solution data, as an instantiation of the same social learning principles that govern human behavior and enable knowledge diffusion.

In (Hilal et al., 2018) is referred that in the recent times world events have underscored the need for large area surveillance systems. According to the authors, such systems require effective sensing and collaborative DM to operate in highly dynamic environments with demanding time constraints. They state that pervasive IoT is a novel paradigm that enables detailed characterization of the real physical applications. To this end, they propose a pervasive IoT surveillance applications that according to them can offer an effective framework to collect situation-aware knowledge being vital for planning effective security measures.

In (Orsino et al., 2018) is put forward a caching-aided collaborative device-to-device (D2D) operation for communicating, extracting and predictive data disseminated based on industrial IoT. In their work, the authors address contents dissemination process in factory automation scenarios by proposing to engage moving industrial machines as

D2D caching helpers. With the goal of improving the reliability of what they call high-rate mmWave data connections, by introducing alternative contents dissemination modes and then constructing a mobility-aware methodology to enable predictive mode selection strategies based on radio link conditions. The authors did mention that their proposed predictive solutions based on D2D-enabled collaborative caching at the wireless edge permits lower contents delivery latency and improve data acquisition reliability.

The work in (Trab et al., 2015) proposed a multi-agent architecture for product allocation planning with compatibility constraints, which uses a decision mechanism for product's placement, based on negotiations between agents associated to compatibility tests. The approach presented by the authors did consider issues that they consider important ones for carrying out decentralized management of warehouses in a dynamic and reactive environment. The negotiations mechanisms relying on an IoT infrastructure and MAS were defined to solve security problems of product allocation operations. According to the authors, industrial deployment of IoT platforms represent an ideal solution for decentralized management and to support collaboration between products and shelves.

In (Xenakis et al., 2019) the authors present their proposed distributed IoT/cloud based fault detection and maintenance framework, in the context of industrial automation, without a need for frequent human intervention, which they mention be based on collaboration and information sharing among IoT, across fog nodes, being decision rules set and controlled by cloud layers, called a global consensus cross layer optimization problem resolution process. The framework is based on automatic data acquisition by sensors distributed across machines, along with feature extraction for RT machine condition monitoring and fault prediction.

In (Bello et al., 2019) refers to contributions of a special section focusing on embedded and networked systems for intelligent vehicles and robots. In this work is mentioned that embedded and networked systems for intelligent vehicles and robots are expected to have a significant economic, societal, and technological impact on industrial and automotive applications. Further, it is referred that among the aspects that will benefit from these technologies the first one is safety, thanks to the reduction of accidents caused by human errors. Moreover, another issue considered is the positive effect expected on sustainability, due to the increase in transport systems efficiency. Also, comfort and inclusiveness is mentioned to be improved, ensuring users' freedom for other activities and 'mobility for all.' The authors enhance that logistics and factory automation are among the main areas that will take advantages from intelligent vehicles and robots that are expected to play a key role in the I4.0, where intelligent vehicles and industrial robots will move and operate autonomously and cooperatively. They refer that such a revolution includes many key enabling technologies, such as, networked sensors, actuators, and embedded computing and control platforms, that will be distributed on-board the vehicle/robot. They do also reinforce that contribution of AI and deep learning computing platforms is also emerging to achieve full intelligent autonomous mobility of vehicles and robots.

In (Besharati-Foumani et al., 2019) is focused intelligent process planning (PP), AI, and SM in the I4.0. The authors do emphasize the fundamental quality requirements of a process plan, while having a major impact on the efficiency and productivity of the whole production process in addition to the quality of the final product. The authors refer

several approaches such as search logic structure, variant or case-based, generative approach, hybrid, and knowledge-based or expert systems that have been employed to develop CAPP systems with the aim of reducing and finally removing the role of experienced process planners in providing a reliable and optimized process plan to achieve the automated and intelligent CAPP system. The authors refer that, however, despite these huge efforts, the PP task is not completely automated yet and still depends on human experiences and knowledge. They believe that AI, ML, and Data Analytics seem to be promising tools to achieve the total independence of CAPP systems on the experience of the process planners in the era of I4.0 and SM systems. They do further state that ideal intelligent CAPP systems will be able to collect the experience and knowledge of the technology experts in addition to being adaptive and self-learning according to the machining process RT data and work history.

The authors in (Schuhmacher et al., 2017) refer to a decentralized material supply control of production and logistics processes through the use of an intelligent bin system developed at the ESB Logistics LF, to be integrated into a self-developed, cloud-based and event oriented Self-Execution System, which they mention goes beyond the common functionalities and capabilities of traditional Manufacturing Execution Systems (MES).

7.5. The importance of I4.0 to foster or promote collaboration

In collaboration there are some main key words that are more or less closely implied, such as: interaction, interoperation, integration, distribution, decentralization, networking, which may further imply an increased complexity, arriving not just from the great amount and diversity of data/ information shared, but also by the unpredictable interrelations and interchanges of this data/information, through a more or less widened network of collaborating entities, for instance, machines, in an extended manufacturing environment context.

This complexity will, in the limit, conduct to the necessity of using approaches and tools for supporting decision support, namely based on chaos and complexity management, game theory, group decision making, organizational semiotics, and learning organization principles, along with machine/deep learning, among other intelligent management and DM paradigms and methods, including more autonomous or automatic ones, for instance, based on MAS, which is typically used in M-M collaboration.

Moreover, collaboration is also fostered or can be enhanced by the use of other recent technologies, for instance, for improving information and knowledge sharing capabilities, namely through the use of a widened set of AI-based approaches and platforms that enable 'servitization', emergence, social communities, and networks, along with varying kind of internet based paradigms, protocols and technologies, to be used among collaborating organizations. These organizations may collaborate through extended supply networks, for establishing interconnections between business partners, in virtual, agile and distributed enterprises, supported by entrepreneurship philosophies, along with advanced ICT, and exponential technologies, e.g. High Performance Computers (HPC), along with other technologies and principles underlying the I4.0, for instance, based on parallel tasks programming.

Therefore, the I4.0 and underlying technology can enhance or promote collaboration, by enabling full digitalization of everything, vertical and horizontal integration or

entities, and point-to-point or end-to-end access and communication, along with agile IT technologies, platforms, and services for improved interconnections and information, knowledge and resources sharing and co-working or co-creation [<https://twitter.com/mikequindazzi/status/829,993,822,008,532,992>].

Thus, the so called smart or intelligent industry will further be based on different collaboration levels, varying from process, and technology to the full organizational and inter-personal levels, not just in terms of intra but also inter organizations and among stakeholders worldwide. These will be spread through a widened range of globally distributed points, of not just physical but also virtually distributed and complex networks of entities, including not only factories but varying, heterogeneous and extended set of inter-players, including machines, and tools. Further these complex networks will include suppliers, and customers, through extended supply networks, as is also reinforced by the determination of the so-called 'Smart Industry 4.0 readiness index', through which it is considered that 'Inter- and Intra- Company Collaboration' is a fundamental condition in the scope of Organizations' structure and management (Pfaff & Hasan, 2011).

Moreover, also in (Ustundag & Cevikcan, 2017) the authors mention that the current digital era differs from the others by not just providing changes in main business processes but also by revealing concepts of smart and connected products, along with service-driven business models that enable to increase collaboration in the production network through consistent data availability, along with the use of exponential technologies for offering multiple benefits, being the enhanced productivity just a starting point.

In (Srivastava, 2008) is further explored the collective intelligence concept and its importance for the so-called new corporate governance. According to the authors, relevant new concepts, technological aids and events are a part or contribute in framing their proposed new corporate governance model based on Collective Intelligence and Knowledge Management. For instance, based on amplified intelligence technology, acquired information, information society, collective reflection, collective DM, and extended organization.

As stated in (Tvenge & Martinsen, 2018), the emerging advances in sensor systems, automation and ICT for manufacturing opens new possibilities for lifelong learning utilizing data from production. The data can be source for on-the-job practical learning as well as serve as cases for more formal learning situations. In their paper, the authors propose a model for company's implementation of learning, and discusses how this implies a closer integration with the learning activities to the cyber-physical MS as a seamless, integrated ICT learning and a hybrid human-machine intelligence model based on data analysis, simulations and communication as sources not only for supporting DM, but also to enable continuous learning and knowledge enhancement.

The authors in (Oyekan et al., 2019) mention that the use of a Virtual Reality digital twin (VRDT) of a physical layout can act as a mechanism to understand human reactions to both predictable and unpredictable robot motions. To this end, they put forward a set of metrics to analyze human reactions and validate the effectiveness of their proposed VRDT, to inform about the safe implementation of Human-Robot Collaborative strategies in factories of the future.

In (Gammieri et al., 2017) the authors refer that the current trend in manufacturing is to obtain a flexible work cell in which human and robot can safely interact and

collaborate. The authors mention that Virtual Reality (VR) represents an effective tool capable of simulating such complex systems with a high level of immersion, as well as to train operators. The authors refer that their approach allows simulating HRC in several scenarios, to reproduce the safe behavior on the real robot, as well as to train operators.

The authors in (Posada et al., 2018) refer to the importance that visual computing technologies have nowadays in manufacturing, regarding the current I4.0 scenarios, with intelligent machines, human-robot collaboration and LF. In their paper, the authors explore challenges and examples on how the fusion of graphics, vision and media technologies can enhance the role of operators in this new context.

In (Liu & Wang, 2020) the authors mention collaborative robot's lead-through as being a key feature towards human-robot collaborative manufacturing. The authors clarify that lead-through feature can release human operators from debugging complex robot control codes. Although, the authors state that in a hazard manufacturing environment, human operators are not allowed to enter, but the lead-through feature is still desired in many circumstances. To target the problem, the authors introduce a remote human-robot collaboration system that follows the concept of CPS.

The authors in (Nikolakis et al., 2018) discuss a software system for supervising the operation of a robotic station where humans coexist and collaborate for completing their assembly operations. According to the authors, to achieve effective collaboration, awareness on the operational status is necessary. Therefore, they mention that advances are needed regarding sensor data collection, integration and processing towards achieving context awareness on a shop floor. The authors do further present an implementation of a cyber-physical context-aware system to coordinate collaborative and individual assembly operations through an event-driven controller aiming to achieve flexible assembly operations.

The authors in (Osterrieder et al., 2020), present a literature review about the central role of the so-called smart factory (SF) as a key construct of the I4.0, by enhancing main issues related to the adaptability, predictability, decision-support, physical and digital assistants, co-automation and learning, referred as main pillars, defined together with specific research targets, along with other key concepts that are crucial ones in the context of collaboration, for instance, about cooperation.

The authors in (Cimini et al., 2020) claim that in recent years, the introduction of I4.0 technologies in the manufacturing landscape promotes the development of SF characterized by including relevant socio-technical interactions between humans and machines. In this context, the authors mention that understanding and modelling the role of humans turns out to be crucial to develop efficient MS of the future. Through their paper the authors put forward a deep reflection about human-machine interaction in the wider perspective of Social Human-in-the-Loop CPPS, in which sets of agents collaborate and are socially connected. Through their proposed architecture, the authors intend to represent the different human roles in the SF and the exploration of both hierarchical and so-called heterarchical data-driven DM processes in manufacturing.

In (Schlegel et al., 2017) the authors highlight the potential of SMEs for eco-efficient flexible production. The authors state that production-oriented ICT solutions enable intelligent networking of value adding systems, which are interconnected and able to communicate with each other and with the Internet, being able to be seen as key enablers for the next generation production systems in the I4.0. Moreover, the authors state that

these future MS will be able to adapt to new requirements and conditions, incorporating human flexibility, creativity and problem-solving capabilities. Thus, the authors highlight the importance of competent and qualified employees to interact with and to make use of technologies, and the currently underlying ready-to-use technical systems and adequate advanced organizational structures. The authors do further mention that the human capabilities will play an even higher importance in SMEs with limited R&D capabilities having to overcome significant obstacles in order to implement advanced technology underlying the I4.0.

In (Rychener et al., 2020) is mentioned that despite the considerable advances in extending the capabilities of the CAPP systems, there is still area to improve the accuracy, reliability, and efficiency of the systems for handling the complex task of PP in an automated and intelligent way. In addition, that future research efforts will focus on development of feature-based modelling and feature recognition methodologies to ease the data extraction of complicated 3D models and increase the accuracy of feature intersection detection and comprise more parameters related to materials, operation condition, tolerances, and so on into the feature data. Therefore, the authors state that knowledge-based expert systems can be improved by simplifying their database modification, providing more user-friendly interfaces, integrating self-adaptiveness and automated data acquisition capabilities to achieve RT control of the machining process, and incorporation of precision machining PP capability.

In (Zhang et al., 2018) is put forward an architecture for ML based industrial process monitoring. The authors mention that in the context of I4.0, an emerging trend is to increase the reliability of industrial process by using ML to detect anomalies of production machines. The main advantages of ML are in the ability to (1) capture non-linear phenomena, (2) adapt to many different processes without human intervention and (3) learn incrementally and improve over time. In this paper, the authors take the perspective of IT system architects and analyze the implications of the inclusion of ML components into a traditional anomaly detection systems. Fourth, they state that human crafted alarm rules can now also include a learning process to improve these rules, for example, by using active learning with a human-in-the-loop approach. Thus, the authors clarify that these reasons are the motivations behind their proposed micro service-based architecture for an alarm system in industrial machinery.

The authors in (Rojas et al., 2020) mention a revolution in geoscience that has resulted from the Geospatial Sensor Web (GSW), serving as a new cyber-physical spatio-temporal information infrastructure for geoscience on the web, based on a literature review. The authors state that in contrast to previous experiment-based and sensor-based paradigms, the GSW-based paradigm is able to accomplish the following: (1) achieve integrated and sharable management of diverse sensing resources, (2) obtain RT or near RT and spatiotemporal continuous data, (3) conduct interoperable and online geoscience data processing and analysis, and (4) provide focusing services with web-based geoscience information and knowledge. The authors refer to integrated management, collaborative observation, scalable processing and fusion, and focusing service web capacity. Furthermore, they mention four challenges to the future GSW in geoscience research for enabling the integration with humans for pervasive sensing, integration with IoT to achieve high-quality performance and data mining, and integration with AI to provide smart geoservices. They

have concluded that GSW has become an indispensable cyber-physical infrastructure, and will play a greater role in geoscience research and application.

7.6. Synthesis of main literature contributions in collaborative engineering manufacturing and management

In this section a summarized overview about the main contributions in CollEng-M&M from the literature will be presented.

The [Table 5](#) resumes the main insights brought through the SLR carried out in this work that supports the main concepts underlying the proposed CollEng-M&M model, in order to reach a clear answer to the underlying research questions posed.

7.7. Difficulties or concerns in the implementation of collaboration

In (Oyekan et al., 2019) is referred that wherever humans and industrial robots share a common workplace, accidents are likely to happen and always unpredictable. The authors affirm that this has hindered the development of human robot collaborative strategies as well as the ability of authorities to pass regulations on how humans and robots should work together in close proximities. Thus, in their paper they present the use of a VRDT of a physical layout as a mechanism to understand human reactions to both predictable and unpredictable robot motions.

According to the authors in (Landherr et al., 2016), human-robot interaction is an important aspect of the I4.0, but the extended use of robotics in industrial environments will not be possible without enabling them to safely interact with humans. This imposes relevant constraints in the qualitative characterization of the motions of robots when sharing their workspace with humans. Thus, in their paper, the authors address the trade-off between two such constraints, namely the smoothness, which is related to the cognitive stress that a person undergoes when interacting with a robot, and the speed, which is related to normative safety requirements. According to the authors, their proposal allows the identification of preferable sets of the possible motions that satisfy an operator's psychological well-being, along with the assembly process performance, by complying this with safety requirements in terms of mechanical risk prevention.

In (Nikolakis et al., 2019) the authors do also mention that the main challenge currently is establishing human safety while performing near to robots. Towards enabling safe human-robot collaboration several physical and software systems should be combined. In their paper, the authors propose a CPS for enabling and controlling safe human-robot collaborative assembly operations. Their approach considers a shared fenceless working space where humans, industrial robots, or other moving objects, such as auto-guided vehicles, may co-operate. The authors propose monitoring the working space through optical sensors to ensure human safety, as a major challenge. Thus their paper focuses on a CPS for enabling human-robot collaboration based on RT evaluation of safety distance and a closed-loop control for triggering collision preventive actions.

In (Shamszaman & I, 2019) is referred that building intelligent societies automatically using SIIoT is a big challenge, mainly due to the complexity of the systems and availability of a large number of nodes. The authors mention that in such scenarios, it is not trivial to



Table 5. Main outcomes from the literature supporting the proposed CollEng-M&M model and research questions.

Research question	Concepts	Outcomes	References
RQ1. The importance of learning in collaboration	Learning/ co-learning; Learning organization; Organizational learning; Semiotics; Pragmatics; Emergence; Evolution; Innovation;	Learning, the learning organization, chaotic enterprise, chaos & complexity, and organizational learning The importance of lifelong learning/ co-learning	(Eijnatten & Putnik, 2004; Hummel et al., 2015; Quint et al., 2015; Reuter et al., 2017; Sacha et al., 2017; Trstenjak & Cosic, 2017; Büth et al., 2018; Juraschek et al., 2018; Posada et al., 2018; Ottogalli et al., 2019; Putnik & Putnik, 2019; Schuhmacher & Hummel, 2019; Putnik et al., 2021a, b,c).
RQ2. The importance of the human in collaboration	Human centered collaboration, interactions or interplay, human-robot operation, co-X (co-work, co-operate, co-produce, co-do, co-maintain, co-transport, co-act, co-conceptualize, co-learn, co-decide, co-evolve, co-innovate, co-analyze, co-think, ...) through: business/ organizational oriented paradigms, models, methodologies, methods, systems, and platforms, based on discussion, dialogue, and approaches, involving learning paradigms, means, devices, software, tools, and further technology	Central role of the human in collaboration Relevance of virtualization, networking, and dialogue for collaborating and building change in I4.0 manufacturing Creating shared understanding through collaborative design 21st century skills: the 'knowledge worker', and co-worker; request of the operators' competencies in the I4.0, the Operator 4.0 Importance of human-machine collaboration or cooperation or human-AI symbiosis	(Eijnatten & Putnik, 2004; Abreu & Camarinha-Matos, 2008; Hancock et al., 2013; Brettel et al., 2014; Quint et al., 2015; Khalid et al., 2016; Zolotová et al., 2020; Putnik et al., 2021a,b). (Arias et al., 2000; Abreu & Camarinha-Matos, 2008; Longo et al., 2017; Ma et al., 2019; Putnik et al., 2021a). (Hancock et al., 2013; Haddara & Elragal, 2015; Romero et al., 2016; Longo et al., 2017; Peruzzini et al., 2017; Van Laar et al., 2017; Fernández-Caramés & Fraga-Lamas, 2018; Petrillo et al., 2018; Bousdekis et al., 2020; Fletcher et al., 2020; Kaasinen et al., 2020; Zolotová et al., 2020; Putnik et al., 2021a). (Hancock et al., 2013; Lun & Zhao, 2015; Romero et al., 2015; Romero et al., 2016; Romero et al., 2017; Sacha et al., 2017; Malik & Bilberg, 2018; Tvenge & Martinsen, 2018; Bilberg & Malik, 2019; Demir et al., 2019; Emmanouilidis et al., 2019; Guerin et al., 2019; Nikolakis et al., 2019; Schuhmacher & Hummel, 2019; Ansari et al., 2020; Bousdekis et al., 2020; Fantini et al., 2020).

(Continued)

Table 5. (Continued).

Research question	Concepts	Outcomes	References
RQ3. The importance of the collaboration in the I4.0	Relevance of collaboration and/or of some main underlying issues in the I4.0: connection/ connectivity, communication, sharing, learning, co-creation: co-X (co or open design, co-working, cooperation, ...), and applications	Importance of collaboration, and/or of its main sub concepts Collaboration along with learning as important issues in the I4.0 General requisite on humans' skills and experience to collaborate in the I4.0	(Eijnatten & Putnik, 2004; Abreu & Camarinha-Matos, 2008; Lai, 2011; Römer & Bruder, 2015; Nelles et al., 2016; Posselt et al., 2016; Bochmann et al., 2017; Sacha et al., 2017; Papazoglou et al., 2018; Cherubini et al., 2019; Nikolakis et al., 2019; Putnik & Putnik, 2019; Birch-Jensen et al., 2020; Çil et al., 2020; Pace et al., 2020; Putnik et al., 2021a,b,c); Manupati et al., 2022; L. Varela et al., 2022; Hummel et al., 2015; Kafle et al., 2016; Peruzzini et al., 2017; Reuter et al., 2017; Van Laar et al., 2017; Ansari et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Petrillo et al., 2018; Zolotová et al., 2020; Putnik et al., 2021a). (Hancock et al., 2013; Haddara & Elragal, 2015; Römer & Bruder, 2015; Khalid et al., 2016; Stern & Becker, 2017; Longo et al., 2017; Ansari et al., 2018; Ansari et al., 2020; Putnik et al., 2021a).
RQ4. The importance of the I4.0 to reinforce or promote collaboration	I4.0 oriented models, architectures, methods, algorithms, approaches, methodologies, tools, devices, systems, and platforms, based on: machine/ deep learning; digital twin; augmented and mixed reality, self-organization; automation; neural networks; intelligent systems, exponential technology, collaborative robots, other AI, and CPS issues, devices and systems, DSS, H-H, H-M and M-M collaboration, digitalization; integration, smart systems; smart objects, self-parametrization, automatization, semantic web; servitization, point-to-point, end-to-end interactions, ...	I4.0 managing the digital transformation, organizational and management change, with the human in the loop Need for technological support for communication, co-working/ collaborating, and collaborative robots Real time connectivity, middleware support, digitalization, devices, systems, tools and platforms for collaborating in the I4.0 I4.0 enabling new types of interactions between operators and machines	(Pflaff & Hasan, 2011; Hancock et al., 2013; Ustundag & Cevikcan, 2017; Ansari et al., 2018; Emmanouilidis et al., 2019; Nikolakis et al., 2019; Cimini et al., 2020). (Haddara & Elragal, 2015; Longo et al., 2017; Peruzzini et al., 2017; Ansari et al., 2018; Darwish et al., 2018; Oyekan et al., 2019; Ma et al., 2019; Varela et al., 2018; Liu & Wang, 2020; Pace et al., 2020; Zolotová et al., 2020) (Hancock et al., 2013; Chen et al., 2016; Kafle et al., 2016; Landherr et al., 2016; Ansari et al., 2018; Birch-Jensen et al., 2020; Çil et al., 2020; Fantini et al., 2020; Kaasinen et al., 2020; Pace et al., 2020). (Hancock et al., 2013; Römer & Bruder, 2015; Romero et al., 2015; Romero et al., 2016; Romero et al., 2017; Zhao et al., 2017; Malik & Bilberg, 2018; Posada et al., 2018; Tvenge & Martinsen, 2018; Petrillo et al., 2018; Bilberg & Malik, 2019; Guerin et al., 2019; Ansari et al., 2020; Fantini et al., 2020; Rauch et al., 2020).

find a suitable SIoT service node correctly to avail a service in RT. Thus, the authors propose a common platform to virtualize the physical objects and make them available in the cyber-world and at the same time to ensure resource sharing. In their paper, the authors focus on virtual object management and selection process for SIoT platform.

The authors in (Landherr et al., 2016) mention that one main concern currently consists on enabling a strong connection of the physical, the service and the digital world to improve the quality of information required for planning, optimization and operation of MS.

The authors refer that their contribution intends to introduce the Application Center I4.0, which they consider to be an advanced platform for enabling cooperative research and development of innovative CPPS between the IFF at the University of Stuttgart, the Fraunhofer IPA and cutting-edge manufacturing companies. Their paper provides a detailed overview over the concept of the Application Center I4.0. The IT platform Virtual Fort Knox is further described as serving as a backbone to realize a safe, secure and flexible way to integrate all relevant data and information sources and sinks. This includes humans, IT-Systems and technical components. The authors state that this concept is substantiated by the introduction of selected, prototypically implemented demonstrators that offer new ways of understanding and operating MS.

The authors in (Schlegel et al., 2017), refer that the ongoing introduction of CPS in many areas of manufacturing will create profound changes in work design, for instance, regarding the allocation of work tasks between humans and machines, in the presence of new computerized tools, along with changes in tasks. Thus, the authors state that the possible utilization of the potential enabled by CPPS will highly depend on to what extent they will be designed for humans. Therefore, the authors mention that an integrated system design will be needed, by further including the human factors at an early design stage, and this is an idea underlying to the concurrent engineering paradigm or concept (Putnik et al., 2020, 2021a,b,c) as being a key enabler, of very first step for further reaching full collaboration.

As mentioned in (Li & Qiu, 2006), security and interoperability of collaborative systems is a fundamental concern. As customers, suppliers and designers from different places move to Internet-based collaboration, security must be considered carefully. The authors mention that enhanced interoperability between open design or CD systems, and CD and PDM systems, need to be achieved. Further, they refer that IGES and STEP are currently the fact standards for SMEs and suppliers. The author clarify that thus, at a minimum, CD solutions must be able to successfully handle IGES and STEP importing and exporting between the major collaborative applications to realize data-centric integration and interoperability. Moreover, they state that the goal for collaborative solutions must include the ability to access and manipulate legacy design and CAD data in their native file formats for various services and applications. Besides, they mention the need for more advanced feature- and assembly-based methodologies in collaborative systems for efficient sharing of information and multiple domain applications. They do also state that the current collaborative systems are not generally accepted in industry.

In (Li & Qiu, 2006), the authors refer that besides the reason that different cultures, educational backgrounds, or design habits of designers hinder an effective collaboration, another major problem for the systems, is due to weakness in interactive capabilities, RT

and convenient collaboration. Moreover, they refer that effective distribution, and collaboration algorithms are imperative to develop new feature – and assembly -based methodologies to improve the communication and cooperation efficiency.

According to the authors, some promising directions for developing the methodologies and algorithms include simplifying design models to eliminate some unnecessary exchanged information of the models when co-designing to reduce the width requirements of the Internet, and incrementally transmitting models for streaming (frame-by-frame) communication. Besides, the authors state that meanwhile, in order to support feature-based applications to cross-domains between design and manufacturing to support distributed hierarchical collaboration, algorithms need to be explored to realize bi-directional communications and information conversions between various application domains.

As referred in (Bechar et al., 2015) collaboration in M&M is not yet properly approached or developed. Thus, there is still some open space, opportunities and need for further development of these kind of approaches and platforms, for instance, for being implemented in the Industrial context.

8. Conclusion

Collaboration is a term that has been frequently used but many times it has been mismatched with other, more or less closely related ones, for instance, with concurrent engineering, which although having some similarities, is quite different in nature. This frequent misunderstanding about collaboration, namely about its application in engineering and industrial areas, has motivated this study, in order to contribute to the further clarification of the collaboration paradigm, based on a systematic literature review (SLR), along with the proposal of a collaboration conceptual model.

The collaboration concept proposed includes two main levels, the first one regarding the necessity to satisfy the underlying connection, communication and sharing sub concepts, and the second, higher level one, about the accomplishment of learning (co-learning), and co-creation, for enabling a full or complete level of the proposed collaboration concept, along with some kind of application or implementation, regarding its consideration in terms of collaborative engineering – manufacturing and management (CollEng-M&M).

Through the study carried out, based on the SLR methodology used, it was possible to realize about the importance of the human role, not just in the context of CollEng-M&M, but further in the Industry 4.0 (I4.0).

Learning was also shown to assume a fundamental importance in collaboration, namely in CollEng-M&M.

It was also possible to realize about the importance of collaboration (CollEng-M&M) in the I4.0, and of the digital and technological support arising from the I4.0 in promoting or enabling CollEng-M&M.

Summarizing, this study did enable to clarify about the importance of collaboration, for instance, CollEng-M&M, in the current digitalization era, in order to promote a sustainable development of companies, namely industrial ones, regarding not just economical, but also social and environmental issues. In the current I4.0 oriented CollEng-M&M context the essential importance of the human in the loop was clarified,

along with its learning capabilities, for which the ICT-oriented support, subjacent to the I4.0, was also visible for enabling and promoting collaboration.

Besides the awareness of the importance of collaboration (CollEng-M&M), some difficulties or concerns do persist nowadays, for its successful practical implementation in companies, namely in industrial ones, for instance, regarding human-machine or more specifically human-robot collaboration, mainly to ensure appropriate and secure working conditions, among other concerns and restrictions, which have to be further explored and focused, as this kind of collaboration has been gaining a primer importance in the current digitalization era, and has been already mentioned to be also a further main pillar in the I5.0.

Future research should, thus focus on the development of new approaches and technologies to enable human-machine collaboration, along with the exploration of further machine-machine collaboration, in order to evaluate its implementation in diverse organizations and industrial sectors, namely for supporting manufacturing and management practices.

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Data Availability Statement

The authors confirm that the main data supporting the findings of this study are available within the article, and that the full data can be retrieved according to the search process conducted and described in the article, through the open Web of Science and Scopus repositories, correspondingly, at <https://www.webofscience.com/wos/woscc/advanced-search>, and <https://www.scopus.com/search/form.uri?display=advanced>.

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