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Technical Paper

Designing human-robot collaboration (HRC) workspaces in industrial settings: A systematic literature review

Ana Correia Simões [a,*], Ana Pinto [b,c], Joana Santos [d,e,f], Sofia Pinheiro [g], David Romero [h]

[a] INESC TEC, Centre for Enterprise Systems Engineering, Campus, FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] University of Coimbra, CeBER, Centre for Business and Economics Research, Economics Faculty, Av. Dias da Silva, 165, 3004-512 Coimbra, Portugal
[c] University of Coimbra, Faculty of Sciences and Technology, Pólo II da Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[d] Environmental Health Scientific Area, Health and Environment Research Center (CISA), School of Health of Polytechnic Institute of Porto (ESS|P.Porto), Rua Dr. António Bernardino de Almeida, 400, 4200-072 Porto, Portugal
[e] Center for Reahbilitation Research (CIR), School of Health of Polytechnic Institute of Porto (ESS|P.Porto), Rua Dr. António Bernardino de Almeida, 400, 4200-072 Porto, Portugal
[f] LAETA/INEGI, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias 4200-465 Porto, Portugal
[g] Master in Occupational Safety and Hygiene Engineering, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias 4200-465 Porto, Portugal
[h] Tecnológico de Monterrey, Monterrey, Mexico

A R T I C L E I N F O

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A B S T R A C T

In the pursuit of increasing efficiency, productivity and flexibility at production lines and their corresponding workstations, manufacturing companies have started to heavily invest in “collaborative workspaces” where close interaction between humans and robots promises to lead to these goals that neither can achieve on their own. Therefore, it is necessary to know the contributions, recommendations and guidelines that literature presents in terms of designing a manufacturing workplace where humans and cobots interact with each other to accomplish the defined objectives. These aspects need to be explored in an integrated and multidisciplinary way to maximize human involvement in the decision chain and to promote wellbeing and quality of work. This paper presents a systematic literature review on designing human-robot collaboration (HRC) workspaces for humans and robots in industrial settings. The study involved 252 articles in international journals and conferences proceedings published till 2019. A detailed selection process led to including 65 articles to further analysis. A framework that represents the complexity levels of the influencing factors presented in human-robot interaction (HRI) contexts was developed for the content analysis. Based on this framework the guidelines and recommendations of the analysed articles are presented in three categories: Category 1 – the first level of complexity, which considers only one specific influencing factor in the HRI. This category was split into two: human operator, and technology; Category 2 – the second level of complexity, includes recommendations and guidelines related to human-robot team’s performance, and thus several influencing factors are present in the HRI; and, finally, Category 3 – the third level of complexity, where recommendations and guidelines for more complex and holistic approaches in the HRI are presented. The literature offers contributions from several knowledge areas capable to design safe, ergonomic, sustainable, and healthy human-centred workplaces where not only technical but also social and psychophysical aspects of collaboration are considered.

1. Introduction

The recent progress in digital and industrial technologies, known as the Fourth Industrial Revolution or simply “Industry 4.0” (I4.0) [1], has been transforming the way the industry manufactures and offers its products and services. In addition to requiring production systems with “resiliency” and “flexibility” capabilities to cope with the volatility of global markets and increased demands for (mass-)customizable products and services, manufacturing companies have to address different environmental and social challenges such as minimizing waste and emissions and creating a more inclusive workforce [2,3].

Using industrial robots in production systems for increasing

* Corresponding author.
E-mail addresses: ana.c.simoes@inesctec.pt (A.C. Simões), ana.pinto@dem.uc.pt (A. Pinto), jds@ess.ipp.pt (J. Santos), sou.anasofia@gmail.com (S. Pinheiro), david.romero.diaz@gmail.com (D. Romero).

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productivity is not new. For many decades, industrial robots and humans have been kept working on production lines separately for safety reasons, but cooperatively with a proper division of labour to respond to high-volume demands of standardized products. However, customers' products demand in various global markets have been changing, facing manufacturing companies with the challenge of responding to high-mix, variable-volume demands of (mass-)customizable products, which requires more "flexible" production systems without sacrificing efficiency and productivity in the production lines to respond to such demands. Hence, the development of more "flexible" production systems will need to explore new forms of human-robot cooperation and collaboration to enable the efficient production of such a variety of (mass-)customized products, and the proper division of labour between these according to the characteristics of the work at hand and the workforce [4,5].

In the pursuit of such flexibility at production lines and their corresponding workstations, manufacturing companies have started to heavily invest in "collaborative workspaces", and as consequence, in the close interaction between humans and robots for higher levels of efficiency, productivity, and flexibility that neither can achieve on their own. Therefore, the adoption of collaborative robots, shortly known as "cobots", is growing in the manufacturing sector since they offer an opportunity for humans and robots to exchange information and share tasks for increasing labour efficiency and productivity [6]. Moreover, to improve this "interactive" experience with benefits for both, robots must understand humans, and humans must understand robots [7].

The recent development of collaborative robots, where robots work near humans by sharing a common workspace and tasks is relatively new [8]. The main aspects that distinguish a "collaborative robot" from a "traditional robot", which operates within fences are: (i) they do not need to work at the high speeds of the traditional robots, therefore the payloads are comparable to the ones a human can carry, (ii) they are used to cooperate with humans not to replace them, (iii) they are required to improve flexibility in short production series, therefore they require to be simple to command and program, and (iv) they need to be safe to work with when sharing common spaces and tasks with humans [4].

In addition, the above-mentioned advantages of using cobots for improving efficiency, productivity, and flexibility at the production lines, ergonomics benefits are also referred to by some authors such as Morioka and [9] and [10] since they can remove the workforce from dangerous or repetitive, tedious tasks. Furthermore, cobots may also have an inclusive role in manufacturing workplaces by helping workers with physical disabilities or ageing workers to stay productive [11].

Moreover, the fast development of collaborative industrial technologies as well as their innumerable advantages of using these at manufacturing workplaces, such as the case of cobots, are leaving decision-makers in manufacturing companies be no longer responsible for the choice between human-centric work and productivity, since collaborative industrial technologies are quickly leading to more human-centric production systems [12]. Additionally, regarding technological developments, there is a need to follow a proactive design approach, instead of a reactive design approach, when it comes to designing ergonomic manufacturing workplaces [13].

Furthermore, in a manufacturing workplace where "humans" and "cobots" interact with each other to accomplish defined objectives, the many aspects that influence this interaction need to be explored in an integrated and multidisciplinary way to maximize human involvement in the decision chain and to promote wellbeing and quality of work.

Considering the several aspects that arise from the diversity of knowledge fields, the design of human-robot interaction environments becomes a major challenge when robots and humans coexist in the same working environment and cooperate to complete defined tasks and achieve objectives together.

Having this challenge in mind and the literature gap, this paper aims to present a set of guidelines and recommendations for designing collaborative workplaces where humans and cobots successfully interact with each other to achieve higher levels of efficiency, productivity, and flexibility that neither can achieve on their own. Using a human-centred approach to design work systems, this study presented a set of guidelines and recommendations in physical, cognitive, social, organizational, environmental and other relevant knowledge areas that are critical in the manufacturing systems. For this purpose, a systematic literature review was conducted on the topics related to this objective.

Besides this introductory section, this paper is structured as follows: Section 2 defines the base concepts related to human-robot interaction. Section 3 describes the systematic literature review method used for conducting this research work. Section 4 presents the systemic literature review results and details the set of guidelines and suggestions identified from the literature for designing collaborative workplaces where "humans" and "cobots" can successfully interact. In this section, emergent future research topics are also presented. Finally, Section 5 addresses the conclusions of this research.

2. Basic concepts

This section intends to introduce and define the basic concepts that are directly related to the topic of this research. In this section, the concepts are defined in the context and scope they are used in this research. The following topics are approached in this section: (i) human-robot interaction definitions, (ii) collaborative robots, (iii) Individual Work Performance, (iv) trust, and (v) safety.

2.1. Human-robot interaction

With the elimination of physical barriers between humans and robots, the need to define concepts for their interaction arose, and many perspectives have been discussed. For a comprehensive classification, it is necessary to understand which and how humans are involved, what type of robots are being used, and how these agents interact with each other [14].

Human-Robot Interaction (HRI) can be defined as the actions and information exchanges between a human and a robot while performing any given task through an interface that includes all matters and procedures available in the system for interaction with its users (ISO 8373:2012, ISO 11064-5:2008). In this context, it is important to assure that the robot provides feedback about its understanding of actions and information being transmitted to him. Moreover, the HRI system must help with mechanisms that make human-robot communications as successful as possible [15]. To improve robot performance, these agents need to be able to use humans' skills and experience successfully, working not as a passive tool but as an active partner. For that, they need to have more freedom in their actions and be capable of guiding the HRI, instead of depending only on human commands [16].

Zacharaki [17] describe human-robot interaction in four categories: (i) *coexistence* – the human and robot work side to side but do not share a working space, (ii) *synchronized* – the human and robot share a working space, but only one of the agents are present at any time, (iii) *cooperation* – the human and robot share a working space at the same time, but never work simultaneously on the same component, and (iv) *collaboration* – the human and robot share a working space at the same time and work simultaneously on the same component.

In the collaboration category, the working space shared by the human and robot while carrying out their operations is defined as the "collaborative workspace", and includes the area in which the agents perform their tasks (ISO 10218/ANSI RIA 15.06, TS 15066).

2.2. Collaborative robots

The way factory workers work with robots in production lines is now changing. Robots are no longer exclusively machines that are encaged or otherwise separated from the workforce. They now enter workers' workspace, and they are becoming co-workers which are meant to collaborate with humans [18]. This type of robot is called a “cobot”, short for a collaborative robot. A human-robot collaborative manufacturing system is more customised and flexible than a conventional manufacturing system [19]. According to the definition of ISO 10218-2, Point 3.2, a *Collaborative Robot* – is a robot designed for direct collaboration with a human in the middle of a defined workspace and without barriers. Unlike a classic industrial robot, cobots have been built in a way that is necessary to significantly limit the power and strength of their movements.

2.3. Individual work performance

Work Performance is defined as “scalable actions, behaviour, and outcomes that employees engage in or bring about that is linked with and contribute to organizational goals” [20]. According to a systematic review developed by [21], *individual work performance* comprises four broad dimensions: task performance, contextual performance, adaptive performance, and counterproductive work behaviour. The authors also refer that work performance is not the same as work productivity (input divided by output).

2.4. Trust

Trust is not limited to just interpersonal interactions. Therefore, it can be said that “trust” can affect human-robot interaction as it can affect a human user’s willingness to assign tasks, share information, cooperate, provide support, accept results, and interact with a robot. Trust is one of the requisites for building a successful human-robot interaction [22,23]. It is “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability” [24]. Research on trusting robots shows that humans should be able to trust that a collaborative robot does not harm their interests and welfare. The factors to build trust are mostly related to performance factors of the robot (cognitive trust), such as the behaviour cognitive trust, reliability, and predictability of the robot, and robot attributes (affective trust) such as proximity and (assumed) personality [22,25].

2.5. Safety

Safety can be defined as “a state in which hazards and conditions leading to physical, psychological, or material harm are controlled to preserve the health and wellbeing of individuals and the community” [26]. The introduction of industrial robots has always been connected to the operators’ safety concerns. Initially, the idea to achieve “safety” was to separate or create physical barriers between humans and robots [17,27]. This assumption influenced the initial safety studies and regulatory standards developed for HRI. However, the scenarios changed with the introduction of mobile and collaborative robots [28]. In the complexity of HRI, the physical viewpoint is mainly focused on the risks of collisions occurring between the robot and its user: too high energy/power may be transferred by the robot, resulting in serious human damages [29]. However, it has been shown that safety in the avoidance of collisions is not sufficient to ensure the comfort of the worker [30]. Collaborative robots have inherent safety mechanisms and no external safety devices are required. Mechanisms that have been developed, can act on the restriction of speed and range of motion of the robot [31]. It is essential to design robots compact, lightweight and useful. Design-level safety measures should be implemented, like: light connections and actuators, rounded edges, compatible joints, and coverage of robot connections with soft materials [32].

3. Systematic literature review method

A *Systematic Literature Review (SLR)* was conducted to identify, evaluate, and interpret all available research related to a specific topic of interest (research question), or phenomenon of interest [33]. In this study, an SLR was applied since it is a rigorous method to review the research results and also a replicable and transparent process approach [34]. With this method, unbiased results are achieved that can be audited and repeated [35].

In this study the sequential stapes was followed:

- Step 1: Establishing the research objectives of the SLR,
- Step 2: Define key terms (inclusion) and the studies that were not included and the search expression,
- Step 3: Screen titles and abstracts, and
- Step 4: Reduce data, generate categories, summary, and report of the results.

3.1. Search strategy

The systematic search was focused on the scientific literature on how to design a collaborative workspace for “human” and “robot” in an industrial context. The search strategy consisted of a comprehensive search that could locate the widest spectrum of articles for consideration and was performed in two electronic databases, namely: Scopus and ISI Web of Science (WoS), from the earliest date available in the database to December 2019.

A compound search expression was developed and applied in both databases. The search expression was composed of a set of six terms (see Table 1) related to the review objective: Robot/Cobot; industry, task, allocation, criteria, design. Only English papers were considered in the search.

Additionally, in the search expression, the articles in press, literature reviews, editorial, and undefined were excluded.

3.2. Screening criteria

The searching process is illustrated in Fig. 1. The search expression was applied in both databases resulting in 234 articles. Since the search was made in two databases, a first reduction was accomplished by searching for duplicates, and 48 articles were removed. The exclusion of irrelevant articles was performed using a three-step systematic approach: (i) titles were examined for relevance, (ii) abstracts were then considered (in particular, objectives and methods), and (iii) the full-text article was retrieved and considered. If there was any doubt regarding the content or if the title and the abstract did not provide sufficient

Table 1
Keywords in the Search Expression.

Keywords	Synonymous	
Cobot	human robot interact*	Collab* human-robot
	human-robot interac*	human-robot collab* workstation
	Human-interact* robot	Co-robotic
	Human-interact*	Cobot
	HRI	Cobotic
	Collab* robot	Light robot*
Industry	Manufactur*	Producti*
	Factor*	Industr*
		Lab*
Task	Activity	Assignment
	Work	Job
Allocation	Assign*	Allocat*
	Share	
Criteria	Criter*	determinant*
	indicat*	factor*
	dimension*	
Design	Design	Proposal
	map	Method
	representation	Framework
	model	

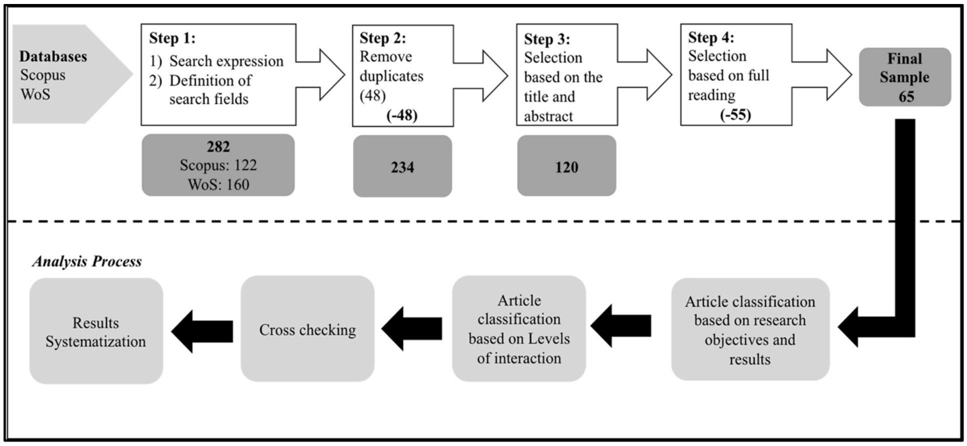

Fig. 1. Searching Process.

information to decide whether the inclusion/selection criteria were met, then the article proceeded to the next step. Based on the title and abstract reading, articles were automatically excluded for further analysis if one of the following conditions were met: (a) do not fit the research objective, (b) humans were not involved, (c) the focus was on a different context than the manufacturing, (d) no robots are involved in the interaction, (e) no level of interaction between human and robot was considered, and finally, (f) concerns about safety are not considered. The next step within the selection process was full reading of the remaining 120 articles. The full reading of these articles led to the exclusion of more than 55 articles mainly due to the context and the interaction nature presented in the article. Finally, 65 articles were considered for the analysis.

4. Results

In this section, the main results of this SLR are addressed. First, the descriptive results related to the articles selected for further analysis are presented. Formerly, the framework developed for the content analysis is described. Later, the results of the content analysis are presented based on the framework developed by the authors. Finally, the most emergent future research topics are presented in the area of the human-robot interaction in the industrial context.

4.1. Descriptive results

In this section, a brief presentation of the descriptive results regarding the articles selected for the full analysis is made (see Fig. 2), namely, the publication year (a); type of publication (b); type of result provided (c), and the research method that was applied (d). Then, the distribution of the articles by country (see Fig. 3) and category of analysis (see Fig. 4) are also presented.

For the final set of articles analysed (65 articles), it is possible to observe a concentration of articles after 2013 with the last three years of the analysis, 2017–2019, to gain more prominence (see Fig. 2a). Regarding the type of publication, an almost similar distribution between journal (29 articles) and conference (35 articles) was found (see Fig. 2b). More than fifty per cent of the articles analysed to propose a set of tools and techniques (37articles) and guidelines (25 articles) to manage the collaborative spaces (see Fig. 2c). Finally, conceptual model (with a case study and/or experimental study and/or simulated scenarios) (30 articles), as well as experimental studies (24 articles), are the research methods most used in the literature analysed (see Fig. 2d).

The research topic approached in this study is more represented in the United States of America and Europe since the first authors of the analysed articles come mainly from the USA, Germany, Italy, the UK and Canada (see Fig. 3). As explained before, the recommendations and

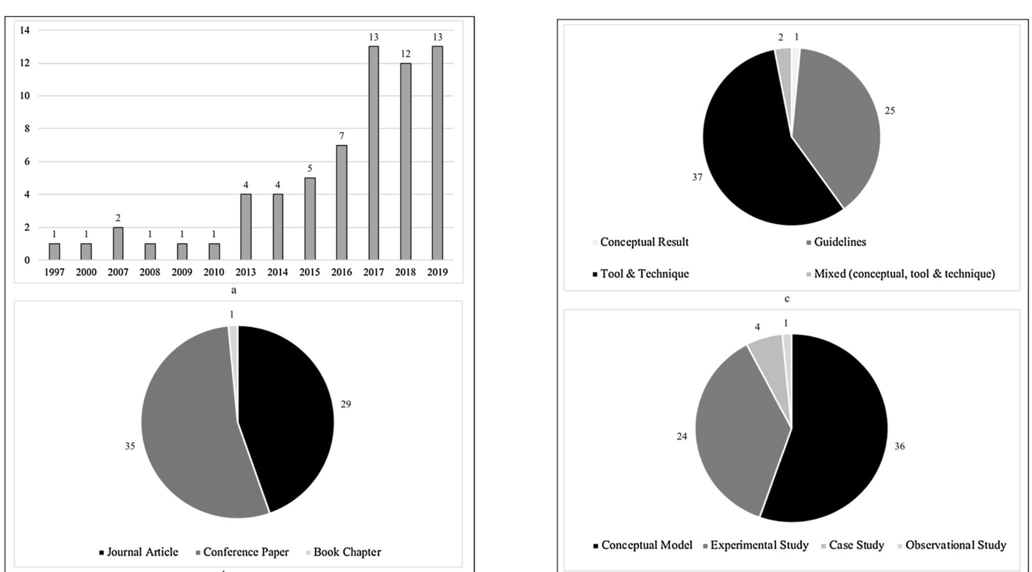

Fig. 2. Number of Articles by: Publication Year (a), Type of Publication (b), Type of Result (c), and Research Method (d).

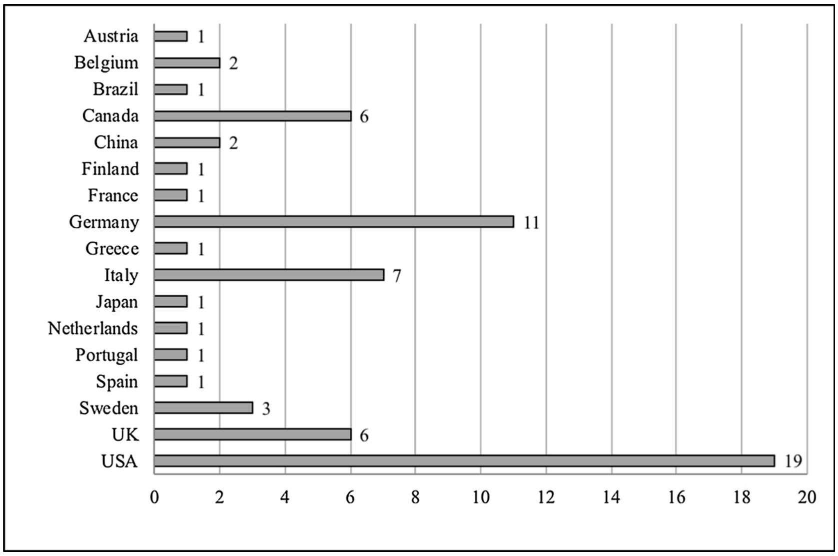

Fig. 3. Number of Articles by Country.

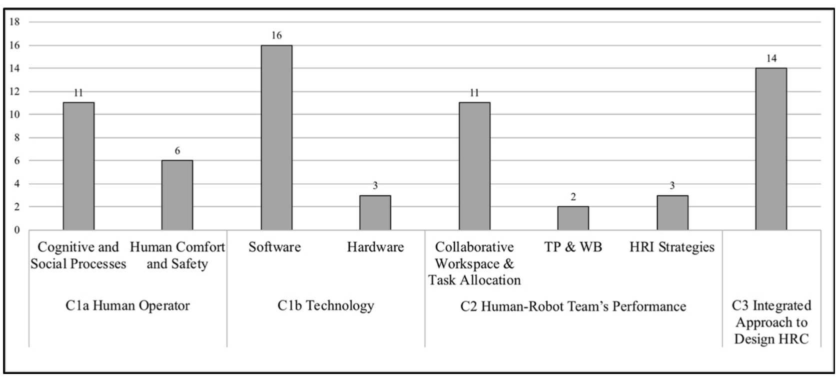

Fig. 4. Number of Articles by Category and Subcategory.

guidelines are presented according to the complexity levels (translated in categories) of the influencing factors presented in HRI contexts, and thus, the corresponding recommendations and guidelines. Fig. 4 show the distribution of the articles according to these categories and the subcategories. A detailed explanation of these categories and subcategories will be provided in the next section. More than fifty per cent of the articles (35 articles) are about one specific influencing factor in the HRI and therefore were classified in Category 1 (C1). This category was split in two: Human Operator (C1a) and Technology (C1b) and the distribution of articles between these two categories is almost similar, with the Human Operator category (C1a) having 16 articles, and the Technology (C1b) with 19 articles. In Category 2 (C2), were analysed articles related to the human-robot team's performance. Due to the "multidisciplinarity" of topics approached in this category, three subcategories emerged: i) Collaborative workspace and task allocation, the most representative with 11 articles; ii) HRI strategies (3 articles), and iii) Team performance and wellbeing (2 articles). Finally, in Category 3 (C3) were assigned the articles/studies describing the more complex and holistic approaches. In this category, 14 articles were analysed.

4.2. Content analysis

For the content analysis of the 65 articles selected in the literature an integrative theoretical perspective on human factors and ergonomics (HFE) in the domain of human-technology interactions, developed by [16] was applied. According to this perspective, the focus of the HFE discipline is the design and management of systems that satisfy human compatibility requirements. It is a human-centred approach to work systems design that considers physical, cognitive, social, organizational, environmental and other relevant factors.

Having this perspective in mind and after a meticulous analysis of the selected articles, a framework to systematize the recommendations and guidelines was developed by the authors (see Fig. 5). The main idea was to develop a framework that represents the complexity levels (translated in categories) of the influencing factors presented in HRI contexts, and thus, the corresponding recommendations and guidelines. Following this rationale, in Category 1 (C1) studies that only consider the contribution of one specific influencing factor in the HRI were assigned. Since the majority of the articles (35) analysed in this study mentioned aspects of the interaction focused on the human operator or the technology, with different topics and diversified contributions, this category was split in two: human operator (C1a) and technology (C1b). Additionally, during the analysis, it was possible to group the contributions according to subcategories. Therefore, in the human operator category (C1a), and the subcategory "Cognitive and Social Process", were included the studies with guidelines and recommendations on the influence of human behaviour in HRI. Regarding the subcategory "Human comfort and safety", articles focused on the influence of safety requirements in HRI were analysed. In the Technology category (C1b) were assigned the articles which contributions related to the software or the hardware components of the technology.

In Category 2 (C2) are the studies whose contributions are focused on

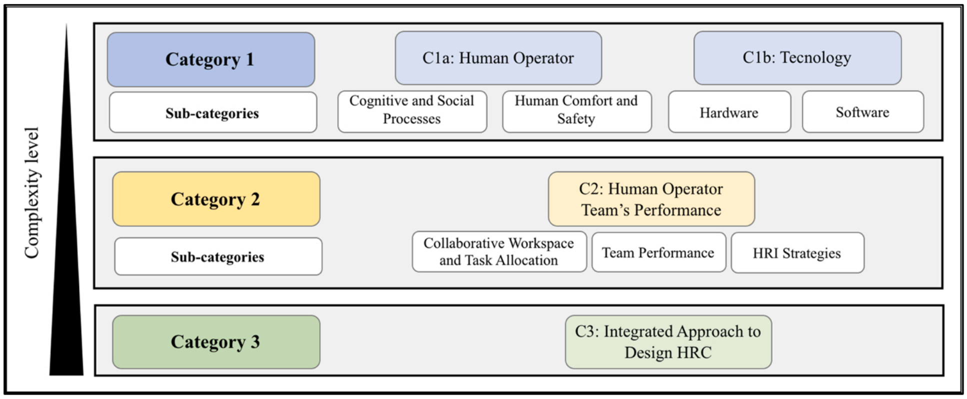

Fig. 5. Framework to Systematize the Results.

the human-robot team's performance. Due to the nature of these studies, they always involve the influence of more than one factor. In this category guidelines and recommendations regarding the capacities and limitations of humans and robots when they work together, to optimize their interaction, are reported. After the analysis of the articles in this category and according to its main focus, three subcategories emerged: collaborative workspace and task allocation, team performance and wellbeing and HRI strategies. Finally, in Category 3, the more complex and holistic approaches in HRI are presented, encompassing several influencing factors coming from different contexts such as physical, cognitive, social, organizational, environmental and economic to design HRIs.

Table 2 systematizes the guidelines and recommendations for each category and subcategory according to the topic that was approached.

4.2.1. Category 1a: human operator

In this section, guidelines are focused on the human operator in the collaborative workplace when a single influencing factor is presented. Due to the nature of the literature contributions, the recommendations and guidelines in this category are presented in two subcategories: (i) cognitive and social processes, and (ii) human comfort and safety.

4.2.1.1. Cognitive and social processes. During the analysis of the articles in the subcategory Cognitive and social processes, the topics: trust, attribution of blame, technology acceptance, and human cognitive performance emerged for guidelines and recommendations (see Fig. 6).

4.2.1.1.1. Trust. Feedback about human-robot trust can improve the allocation of autonomy control during a breach of trust, and in the sense of feedback interface designs, those using semantic symbols are more effective. Desai et al. [36] in their study present results based on real-time trust. According to these authors, initial breaches in trust have a strong negative impact on human workers than intermediate or late breaches. The trust dynamics result from the performance of both, the human (the performance depends on the accumulated workload) and the robot (the performance depends on the speed of the robot to perform a certain task). On one hand, trust is not correlated with the predictability of robot movements (whether they are dominant or submissive movement strategies), and, on the other hand, the relationship between trust and joint physical coordination, when human workers are interacting with robots in a collaborative task, is critical [37,38]. To conclude, "affective" trust better predicts the willingness to use a robot by human workers, and both types of trusts (cognitive and affective) are ensured by the statements of apology and competence that the robots manifest [39,40]. Regarding the autonomy for allocation of tasks at HRI, Saeidi et al. [41] propose a trust and self-confidence-based strategy to automatically choose between manual and autonomous control of (semi) autonomous mobile robots in guidance and navigation tasks.

4.2.1.1.2. Attribution of blame. Another topic mentioned in the literature is the attribution of blame, in the relationship between humans and robots. The greater the autonomy is given to a robot in carrying out the tasks, the greater the attribution of the blame on the part of human workers to the robots [42].

4.2.1.1.3. Technology acceptance. The technology acceptance (robot) by the human in a collaborative workplace is a predictive factor of the success of the human-robot interaction [43] and, thus, plays an important role. When confronted human workers with a communication robot that was not always attentive but diverted, humans established a communicative space with the robot and accepted it as a proactive agent [44].

4.2.1.1.4. Human cognitive performance. According to the literature, human performance and task complexity are related. If the task complexity, or the robot's mistake probability, increase, the human cognitive performance reduces over time [45,46].

4.2.1.2. Human comfort and safety. For the subcategory human comfort and safety, the recommendations and guidelines are presented in the topics: improve/measure safety and design of robots (see Fig. 6).

4.2.1.2.1. Improve/measure safety. The literature is rich in guidelines and recommendations to improve and measure safety in collaborative workplaces. To improve safety and reduce the potential risk of injuries, Meziane et al. [47] adapted an existing industrial robot to make it more interactive. In this way, they improved safety by planning safe paths. The system recognizes human worker activities and locates the operator's position in real-time through a safety helmet. The literature also mentioned some metrics to evaluate safety, dependability, and performance in HRI. Predictions of human motion and planning in time are crucial to executing efficient and safe motions [48]. In this sense, the collaborative robots can efficiently and safely deliver parts to humans at their workstations during, for example, the assembly of an automotive engine.

4.2.1.2.2. Design of robots. The contributions highlighted in the literature concerning the design of robots involve several aspects. The utilization of hand-guiding on the robot improves the human's ergonomic postures. In this case, the humans have the perception they are controlling the system and the robot was viewed, by the human, as an assistant [49]. It is also important to design workplaces that are physically and psychologically safe minimum-jerk trajectories. These trajectories can also mitigate wear and vibrations [50]. The actions performed by the human workers should be considered when they interact with robots. Unfortunately, the current task planners only consider the robot's actions and the unexpected external events in the planning process and do not consider expectations about the humans' actions [51]. New programming concepts allowed to build of robotic agents which can reason about their motions in terms of safety [52]. These authors showed the efficacy of a safety-aware approach to robot control in an experiment with an autonomous mobile manipulation platform. This

Table 2
Guidelines and Recommendations per Category and Subcategory.

Category	Subcategory	Guidelines and recommendations
‘C1a | Human operator	Cognitive and social processes	***Trust*** The feedback interface designs with semantic symbols are more effective for trust increase [36]. Trust is not correlated with the predictability of robot movements [37]. Trust and joint physical coordination in a collaborative task are fundamental [38]. Affective trust predicts better the willingness to use a robot by a human worker [39]. Trust cognitive and trust affective are ensured by the statements of apology and competence that robots manifest [40]. Choosing between manual and autonomous control of (semi) autonomous mobile robots in guidance and navigation tasks increase trust [41]. ***Attribution of blame*** The greater the autonomy is given to a robot, the greater the attribution of the blame on the part of human workers to the robot [42]. ***Technology acceptance*** The acceptance of the technology (robot) by the human is a predictive factor of the success of the HRI [43]. Humans established a communicative space with the robot and accepted it as a proactive agent [44]. ***Human cognitive performance*** If the task complexity increase, the human cognitive performance reduces over time [45]. If the robot’s mistake probability increases, the human cognitive performance reduces over time [46].
	Human comfort and safety	***Improve/measure safety*** Planning safe paths improve safety [47]. Predictions of human motion and planning in time are crucial to executing efficient and safe motions [48]. ***Design of robots*** The utilization of hand-guiding on the robot improves the human’s ergonomic postures [49]. Is important to design physically and psychologically safe minimum-jerk trajectories, that can also mitigate wear and vibrations [50]. Task planners should consider human actions in the planning process and not only the robot and external environment [51]. Build robotic agents that can reason about their motions in terms of related safety with new programming [52].
C1b | Technology	Hardware	To monitor the shared human-robot workspace: a dual-arm robotic system for industrial human-robot collaboration (HRC) with multiple sensor-based controllers and intuitive interaction methods was developed [4]. To avoid stopping robot motion: a robot that adaptively changes from normal to restrictive modes and changes its trajectory [55]. To enhance security performance of the collaborative robot: three-dimensional flexible robot skin made by the piezoresistive and composite [54].
	Software	***Improve control*** To predict the user’s intent, and assist in accomplishing it (instead of simply executing the user’s input, which is hindered by the inadequacies of the interface) this robot is programmed with an intuitive formalism that captures assistance as policy blending [56]. To decrease “task-completion-time” (TCT) and to reduce unwanted collisions, an asymmetric semiautonomous teleoperation (AST) control design framework for teleoperation of mobile twin-arm robotic manipulators was used [57]. To accomplish collaborative control of robots and machines to improve equipment utilization in unstructured and dynamic environments, Virtual Collaborative Control (VCC) was applied. It extends the techniques of collaborative design and visualization [58]. FlexHRC is sensing, representation, planning and control architecture for flexible human-robot cooperation to enable robots to deal at all levels with humans’ intrinsic variability (a requisite to a comfortable working experience for humans, and a capability for efficiently dealing with unexpected events) [59]. ***Safe interaction between human and robot*** To improve operator’s safety and acceptance in hybrid assembly environments, a tool using the immersion capabilities of augmented reality technology was applied [60]. To avoid collisions a methodology to analytically compute the minimum distance between cylindrical primitives with spherical ends is presented [61]. To collision detection and contact force estimation methods based on torque observer without any extra sensors [62]. ***Communication*** To support robust human-robot communication whereby a human operator can exploit multiple communication channels to interact with one or more robots to accomplish shared tasks using a novel multimodal interaction framework [63]. The possibility of different team configurations reacting to a robot’s failure to correctly complete the task and overall mission in a team environment led to the development of a methodology for

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Table 2 (*continued*)

Category	Subcategory	Guidelines and recommendations
		creating a computational simulation framework based on Work Models that Compute [64]. To design a collaborative environment to understand human reactions to both predictable and unpredictable robot motions a virtual reality digital twin of a physical layout can be used [65]. ***Cooperative and collaborative behaviours*** To describe layers to implement cooperative and collaborative behaviours among robots and human beings based on an appropriate model of rules, a new approach of multilayer architecture for distributed control of manipulator robots (Scara3D) can be used [66]. To design collaborative scenarios where the robot works with humans on a common construction, an embodied multimodal fusion to perform supportive and instructive robot roles in HRI was proposed [67]. For complex carrying tasks a novel HRC technique to monitor joint load variations in real-time during the collaborative task and to adaptively control the robotic partner's assistive behaviour when the overloading is detected [68]. For inspection tasks ('water leak test') and focused on ergonomics concerns a new automated in-line inspection system (Inspector robot) approach was proposed. This approach optimises the efficiency and capability of the test process. Thermographic images are taken by a lightweight robot system and then processed to locate the leak [69]. To support collaborative haptic training in virtual environments a new multilateral position shared control architecture for dual-user haptic training is proposed. In this system, the controller allows interaction between both users (the trainee and the trainer) as well as between the users and the virtual slave robot and environment [70]. To optimize and validate manufacturing processes to a better understanding of the risks, complexity of the assembly processes, an interactive simulation of Human-robot collaboration (first-person 3D experience) was proposed. This technique uses real-time physics simulation to immerse the design engineer or production planner inside a responsive virtual model of the factory [71]. ***Generic strategies in HRC***
C2 | Human-robot team's performance	Collaborative workspace and task allocation	To improve the design collaborative of workspace and simultaneously allocate tasks in HRC it is needed to follow these procedures: (i) hierarchical task analysis; (ii) predetermined time method systems, to the identification of possible collaborative modes; (iii) ergonomics assessment tool (RULA), to evaluate the system performance; and (iv) resource allocation [72]. To upgrade the design of collaborative workspace and simultaneously allocate tasks in HRC it is needed to base ourselves on computational work modelling for human-robot teams. The main advantage of this methodology is related to the analysis of dependencies and constraints in the work and the work environment giving information about the collective behaviour of human-robot teams and therefore providing a constant basis for the design [73], To raise the effectiveness of the system of HRC, before the task allocation must be done one procedure that includes three stages: work decomposition, creation of task options, and quantitative evaluation considering time and ergonomics concerns [74]. To improve the task allocation must exploit the different skills of humans and robots to classify tasks, load the robot instead of the human where possible, and allow the dynamic reassignment of tasks in case of unexpected delays in task execution [75]. The task allocation must be based on the workload, where the workload is shared through the agents according to their physical capabilities and skill levels [76]. To improve the task allocation between a single human and a single robot must be taking into consideration the minimizing task completion time and human physical strain [77]. It is essential for the success of human-robot collaboration that the task allocation must be done by several steps that refer to both to "human" or the "robot", for example, capability-oriented job assignment as a primary decision criterion for task allocation [78]. To optimize the interaction between a human and robot two criteria are essential for the task allocation: (1) the types and levels of automation, and (2) the automation reliability and the cost of action [79]. The task allocation can also be based on context information [80]. ***Human workers with cognitive disabilities*** The robots represent a critical role in HRI in the allocation of tasks to human workers with cognitive disabilities. This role corresponds to the supervision of the assembly instructions, providing stepwise indications of the assembly actions to be executed by the human, and providing quality assurance (by guaranteeing that actions have been carried out correctly and according to specification) [81].

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Table 2 (*continued*)

Category	Subcategory	Guidelines and recommendations
		Multi-human and multi-robot interaction; human – multi-robot interaction
		The performance of the interaction between multi-human multi-robot can be improved if the human factors are included along with the productivity metrics (e.g., performance, cost, time for processing information) [82].
		To improve the relationship between a human/multi-robot team three key factors must be accounted for by the human supervisors in making task-assignment decisions and how they correlate with workload: average domain density, critical task ratio and the tag disruption ratio [83].
		To optimize the interaction between a human and robot is for the robot to mimic the behaviours of their human counterparts. The allocating roles are perhaps more critical, knowing whether individuals (human or agent) are assigned as (1) supervisor, (2) operator, (3) teammate, (4) mechanic/programmer, or (5) bystander. Is also critical to understand the nature of the decision-making process and how the boundaries of such actions are shared and/or delegated between the two different team members [84].
		To optimize the productivity of the human and robot, the robot should not interfere directly with the human's physical or perceptual focus of attention [85].
	Team Performance and well-being	To improve teamwork/collaborative interaction, the human factors on task performance (e.g., type of task, fatigue, skill level, environment, etc.) must be taken into account [86].
		To maximize the objective and perceived performance of the human-robot team we must take into account the combination of goal inference and dynamic task planning [87].
	HRI strategies	To maximize the HRC the robot should maintain a distribution (i.e., belief) over the possible human interaction strategies, and update this belief during the task (i.e., exchange information while reasoning over this distribution) [7].
		Is essential to have an ecological interface design for human supervision of a robot team to help to provide information about states of functions that are necessary to achieve the top goal of a human-robot system [88].
C3 | Integrated approach to design HRC	–	To reduce human workload while maintaining the overall performance of the human-robot team may be used physical robot interaction (pHRI) and social HRI-based autonomous controllers (sHRI) rather than manual adjustments on the robot velocity [89].
		To make scheduling decisions in an HRC environment, it is important to include the preferences of human workers and the amount of work allocated [90].
		Humans prefer robot-led interactions for tasks with a higher cognitive load and human-led interactions for joint actions in tabletop tasks [91].
		To optimize the HRI, global navigation, object recognition, inverse kinematics, time constraints and task allocation need to be investigated [92].
		Interaction, human cognitive abilities, the collaborative system, as well as maintenance of appropriate expectations must be incorporated in HRC [93].
		Adequate levels of automation considering the capacities and abilities of both "human" and "robot" according to the situation must be defined [94].
		A procedure must be defined to initially check existing or future workplaces for their suitability for HRC [95].
		Key parameters, namely, technological complexity, HRC relevance, benefits/costs indicator, ergonomics and safety and logistic interface, are considered to identify the most suitable applicative use cases for profitable exploitation of HRC technology [96].
		The robot's behaviour must be perfectly predictable for the human operator [97].
		The definition of collaboration levels must include legal, technical, and psychological requirements and limitations of both the human and the robot [8,14].

platform was designed to perform pick-&-place tasks together with a human co-worker considering safety concerns. In this study, key concepts for specifying safety-aware control were presented, including a model of the human co-worker, the safety-relevant events, and the robot movements, which were explicitly represented in a high-level plan language. The most comprehensive study regarding recommendations to design and use a safe cobotic cell comes from [53]. These authors presented recommendations for three main intervenients in the cobotic cell: the owner, the worker, and the integrator. For the owner, they make two main recommendations: to keep human workers informed to minimize resistance to change and make available the user guide to the workers and all the stakeholders involved in the cobotic cell. For the worker, they recommend their own protection against collisions with cobot gripper, or the part it handles, and always face the robot, regardless of the activity performed by the human in the collaborative workspace. Finally, the majority of recommendations of this study are related to the integrator: to be informed about the prescriptions of the current regulations and standards; to perform a comprehensive risk assessment of the residual risk related to the cobot; to choose risk reduction measures based on the risk evaluation for each anticipated hazardous situation; to validate the effectiveness of the risk reduction measures; to identify the cobotic arm trajectory that is the best compromise between safety and productivity; to consult the human workers that are going to interact with the cobotic cell, making sure that

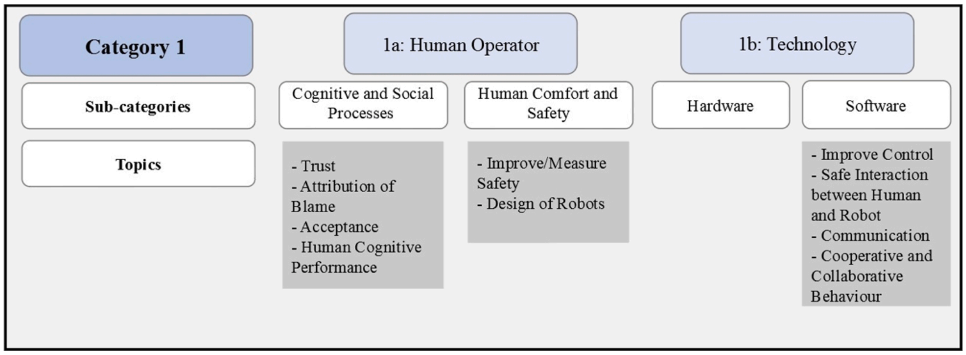

Fig. 6. Category 1 in detail.

the design fits with the real work. Moreover, these authors also recommend that, when presence-sensing devices are added to achieve a mode of collaborative operation, it should be ensured that the required level of reliability for the safety-related control system is still met.

4.2.2. Category 1b: technology

As previous referred, in C1b recommendations and guidelines focused only on the technology (robot) as a single element in the collaborative workplace are present. These recommendations and guidelines were split into two subcategories, the “hardware” and the “software” aspects of the technology.

4.2.2.1. Hardware. A few contributions to the design of collaborative spaces were given in the literature concerning the hardware. To enhance the security performance of the collaborative robot [54] designed and produced a three-dimensional flexible robot skin made by the piezoresistive and composite. The experiment results showed that the implemented robot skin can provide an efficient approach for natural and secure human-robot interaction. To ensure a safe collaborative environment [4] proposed a dual-arm robotic system for industrial human-robot collaboration (HRC) with multiple sensor-based controllers and intuitive interaction methods for the monitoring of the shared human-robot workspace. This robotic system is equipped with the ability for real-time collision-free dual-arm manipulation. To avoid stopping robot motion [55] proposed a robot that adaptively changes from normal to restrictive modes and changes its trajectory.

4.2.2.2. Software. The recommendations and guidelines in the software subcategory are related to the development of algorithms, architectures, frameworks and models in the following topics: Improve control, Safe interaction between human and robot, Communication and Cooperative and collaborative behaviours (see Fig. 6).

4.2.2.2.1. Improve control. One of the main concerns in the HRC scenarios is to improve control. Some technical proposals were found in the literature to accomplish this objective: intuitive formalism that captures assistance as policy blending in order [56]; control strategies using a novel asymmetric semiautonomous teleoperation control design framework for teleoperation of mobile twin-arm robotic manipulators [57]; virtual collaborative control to improve equipment utilization in unstructured and dynamic environments [58]. More focused on enabling robots to deal at all levels with humans’ intrinsic variability [59] proposed sensing, representation, planning, and control architecture for flexible human-robot cooperation, referred to as FlexHRC.

4.2.2.2.2. Safe interaction between human and robot. The safe interaction between a human and a robot is referred to in the literature as one of the most important aspects in designing a collaborative workplace. Several tools and frameworks are presented in the literature to achieve this goal. Aiming the operator’s safety and acceptance in hybrid assembly environments [60], developed a tool through the immersion capabilities of augmented reality technology. Avoiding collisions is a requisite to a safe interaction. In this regard, a methodology to analytically compute the minimum distance between cylindrical primitives with spherical ends [61] and collision detection and contact force estimation methods without any extra sensors [62] can be useful frameworks.

4.2.2.2.3. Communication. Strictly related to safety interaction aspects, the communication concerns are also translated in the literature with tools and frameworks proposed that aims to improve the communication between “human” and the “robot”. The possibility to support robust human-robot communication whereby the human operator can exploit multiple communication channels to interact with one or more robots to accomplish shared tasks was proposed through a novel multimodal interaction framework [63]. The possibility of different team configurations reacting to a robot’s failure to correctly complete the task and overall mission in a team environment led to the development of a methodology for creating a computational simulation framework based on Work Models that Compute [64]. Understanding human reactions to both predictable and unpredictable robot motions should also be considered in the design of a collaborative environment. In this sense, a virtual reality digital twin of a physical layout [65] can respond to this challenge.

4.2.2.2.4. Cooperative and collaborative behaviours. Cooperative and collaborative behaviours among robots and humans are also pointed in the literature. A multilayer architecture for distributed control of manipulator robots can be used to this intend (Scara3D) [66]. In collaborative scenarios, the support, between the human and the robot, in task execution originated some important contributions. Therefore, collaborative scenarios where the robot works with humans on a common construction task was explored by [67] where they proposed an embodied multimodal fusion to perform supportive and instructive robot roles in HRI. For complex carrying tasks a novel HRC technique to monitor joint load variations in real-time during the collaborative task and to adaptively control the robotic partner’s assistive behaviour when the overloading is detected was presented by [68]. For inspection tasks and focused on ergonomics concerns a new automated in-line inspection system (Inspector robot) was developed by [69]. In this system, thermographic images are taken by a lightweight robot system and then processed to locate the leak. Focused on supporting collaborative haptic training in virtual environments a new multilateral position shared control architecture for dual-user haptic training was proposed by [70]. In this system, the controller allows interaction between both users, the trainee and the trainer, as well as between the users and the virtual slave robot and environment. Finally, to optimize and validate manufacturing processes to a better understanding of the risks, complexity of the assembly processes [71] proposed an interactive simulation of Human-robot collaboration (first-person 3D experience). The proposed technique uses real-time physics simulation to immerse the design engineer or production planner inside a responsive virtual model of the factory.

4.2.3. Category 2: human-robot team's performance

Some contributions regarding the collaborative interactions between humans and robots to improve performance and wellbeing exist in the literature. According to the literature, these "mixed teams" can work in an optimally way. Category 2 describe contributions and guidelines to improve the human-robot team's performance found in the literature. After the analysis of the articles in this category, three subcategories stood out: (i) collaborative workspace and task allocation, (ii) team performance and wellbeing, and (iii) HRI strategies.

4.2.3.1. Collaborative workspace and task allocation in teams. The recommendations and guidelines in this subcategory are approached in the three main topics: task allocation in a generic way, task allocation for human workers with cognitive disabilities, and, for multi-human and multi-robot interaction; human-multi robot interaction (see Fig. 7).

4.2.3.1.1. Generic strategies in HRC. An approach to design a collaborative workspace and simultaneously allocates tasks in HRC was proposed by [72] and comprised the following procedures: (i) hierarchical task analysis, (ii) predetermined time method systems – to the identification of possible collaborative modes, (iii) ergonomics assessment tool (RULA) – to evaluate the system performance, and (iv) resource allocation. Another methodology based on computational work modelling for human-robot teams was made by [73]. The main advantage of this methodology was related to the analysis of dependencies and constraints in the work. Additionally, information about the collective behaviour of human-robot teams in the work environment should be given continuously for the design of the collaborative space. A previous step, before task allocation, is work decomposition. A procedure for improving work decomposition, instance generation, and HRC workplace evaluation, was proposed by [74]. This procedure includes three stages: work decomposition, creation of task options, and quantitative evaluation considering time and ergonomics concerns.

Different approaches have been proposed for task allocation. For example, the allocation is based on a new working paradigm by [75]. This procedure exploits the different skills of humans and robots to classify tasks, load the robot instead of the human (when possible) and allows the dynamic reassignment of tasks in case of unexpected delays in task execution. Task allocation is based on the workload, where the workload is shared through the agents, "human" and "robot", according to their physical capabilities and skill levels [76]. These authors use task complexity, agent dexterity and agent effort as indexes to represent the agent features at the team level. Another approach present in the literature concerns the task allocation between a single human and a single robot to minimize task completion time and human physical strain [77]. Using capability-oriented job assignment, as the primary decision criterion for the allocation task (using a multi-stage procedure) between human and robot, can also be found in the literature. Therefore [78], proved that the task of planning a working system that includes human-robot collaboration applications is a big challenge, even for those who are experienced in working with robot technology in an industrial context. To address the identified implementation challenge (allocate tasks between human and robot) these authors suggest a multi-stage procedure that facilitates the allocation of jobs between the two resources: human and robot. They used capability-oriented job assignment as the primary decision criterion for task allocation.

A model of human interaction to decide if a system functions should be automated and to what extent, was presented by [79]. According to the authors, there are two successful criteria for the task allocation: (1) the types and levels of automation, and (2) the automation reliability and the cost of action. The task allocation can also be based on context information [80]. These authors found that cognitive task load was the factor with more importance in the task allocation, followed by task capability and preference.

4.2.3.1.2. Human workers with cognitive disabilities. An alternative task-sharing approach in a collaborative workplace where the human workers with cognitive disabilities and the collaborative robots share the same place is proposed by [81]. The results of this study showed the critical role of automation (cobot) in HRI. This role corresponds to the supervision of the assembly instructions, providing stepwise indications of the assembly actions to be executed by the human, and providing quality assurance (by guaranteeing that actions have been carried out correctly and according to the specifications). In doing so, the cobot creates a record of all actions executed, including whether there were any deviations, making each step in the process traceable.

4.2.3.1.3. Multi-human and multi-robot interaction, human-multi robot interaction. Besides the criteria to allocate tasks the literature also gives valuable contributions to the general process of task allocation. Therefore, in multi-human multi-robot interaction systems, where an agent allocates information to multiple teams of operators (humans or robots), if human factors are included along with the productivity metrics (such as performance, cost, and time for processing information), then the performance of the interaction can be improved [82]. In their work [83], explored an approach to human/multi-robot team interaction that captures the complexity of task scheduling problems from the human operator's perspective. Their study was conducted to assess the efficacy of a graph-based model. From this model, three key factors were identified: average domain density, critical task ratio and the tag disruption ratio. These key factors have an impact on the way how the supervisors (human) make task-assignment decisions, and how they correlate it with the workload.

Several insights related to task allocation, in the context of teamwork involving humans and robots, were given by [84]. According to this author, the best way to achieve high levels of interaction between a human and a robot is for the robot to mimic the behaviours of its human counterpart. He suggests that allocating roles is the most critical aspect of task allocation. These roles (for the human or the robot) can be: (1) supervisor, (2) operator, (3) teammate, (4) mechanic/programmer, or (5) bystander. For this author is also critical to understand the nature of the decision-making process and how the boundaries of such actions are shared and/or delegated between the two different team members.

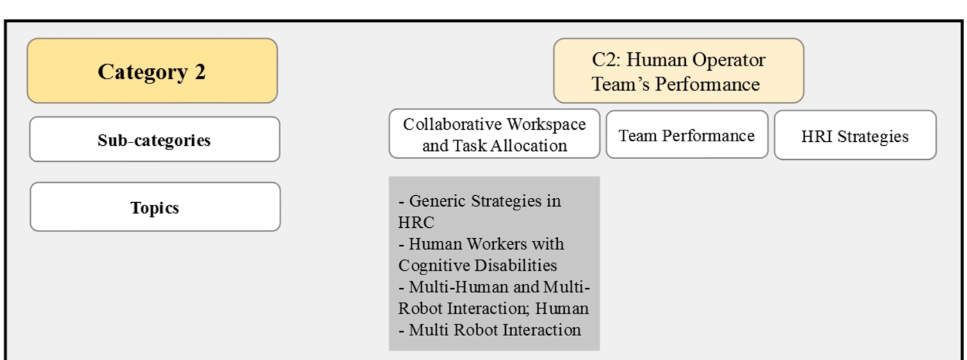

Fig. 7. Category 2 in detail.

4.2.3.2. Team performance and wellbeing. The literature gives several recommendations on this topic. In terms of a human worker that efficiently complete independent tasks in a shared physical workspace without explicitly communicating planned actions, studies are concluding that human productivity in a shared workspace is comparable to human productivity alone, as long the robot does not interfere directly with the human's physical motions or attention [85]. To improve teamwork/collaborative interaction with humans [86], use human factors on task performance, (such as type of task, fatigue, skill level, environment, emotional state, satiety and caffeine consumption) to provide appropriate adaptability of the human to the robotic elements. Still in the field of behavioural experiment [87], study concluded that the combination of goal inference and dynamic task planning significantly improves both objective and perceived performance of the human-robot team. They also report that combining motion-level inference with task-level plan adaptation in the context of human-robot collaboration is beneficial.

4.2.3.3. HRI strategies. HRI strategies are related to supervision and shared control. [7]'s study concluded that the robot should maintain a distribution (i.e., belief) over the possible human interaction strategies, and update this belief during the task (i.e., exchange information while reasoning over this distribution). By reasoning over this belief, the robot can be adapted to everyday humans' actions, instead of requiring each human to comply with its single pre-defined strategy. To provide information about functions states that are necessary to achieve the top goal of a human-robot system, [88] developed a design concept based on ecological interface design for human supervision of a robot team: This design concept provides information about functions states that are necessary to achieve the top goal of a human-robot system.

4.2.4. Category 3: integrated approaches to design HRC

The recommendations and guidelines included in Category 3 (C3) (see Table 2) offers a holistic approach to human-robot interaction, considering simultaneously the contribution of diverse influencing factors from different contexts such as physical, cognitive, social, organizational, environmental and economic to design of HRC.

The physical Human-Robot Interaction (pHRI) and social HRI-based autonomous controllers (sHRI) can reduce human workload while maintaining the overall performance of the human-robot team compared to the manual adjustments on the robot velocity [89]. Moreover, it is shown in these authors experiments that human trust in a robot can remarkably increase if sHRI factors are integrated into the pHRI-based framework. The robot usability can also significantly increase if the emotion is added to the integrated framework while the objective measures (e.g., robot average velocity and assembly time) do not show statistical significance among the automated condition. In fact, human situational awareness is poorer when the robotic agent has full autonomy over scheduling decisions [90]. According to these authors, the preferences of human workers are important to include in the HRC environment when making scheduling decisions. In addition, the amount of work allocated has also a strong impact on the workers subjective perceptions of their team's interactions. So, these authors considered that the balance between preserving human's situational awareness, optimizing workload allocation and production efficiency, is essential to designing intelligent collaborative robots.

Communication about shared plans using gaze and speech aids effective collaboration in task execution in which a human and robot work together [91]. According to these authors, humans prefer robot-led interactions for tasks with a higher cognitive load and human-led interactions for joint actions in tabletop tasks. To improve coordination between humans and robots, both (robot and human) have to adapt to each other's preferences and abilities. These authors also refer that the interaction style and the design of the task to be collaboratively completed by the human and by the robot may also affect how the collaboration is perceived by the human concerning efficiency, comfort, safety, and fluency. Claes [92] presented a human robot-team interaction solution for automated task handling in an industrial work environment, integrating an approach based on the combination of basic global navigation, object recognition, inverse kinematics and human-robot interaction. These authors considered that this approach had good feasibility, however, they also recognized that time constraints and task allocation are also factors that need to be investigated to optimize the interaction.

In an even more holistic perspective, the definition of collaboration levels must include legal, technical, and psychological requirements and limitations of both the human and the robot [8,14]. Based on the theoretical background, the conceptual model developed by these authors considered the understanding of the nuances of interaction, human cognitive abilities, the whole collaborative system, as well as maintenance of appropriate expectations when designing systems that incorporate HRC. Other similar conceptual models, or methodological approaches, to optimize the design of HRC exists in the literature. For example, a morphological framework that integrates all relevant characteristics for HRC design in assembly work and includes five dimensions (objectives and economics, product, process; HRC work systems, and safety). Each of these dimensions integrates 41 attributes and 169 characteristics [93]. Moreover, these authors argue that for HRC task allocation is necessary a multi-criteria model for optimizing time, cost, and quality. In an attempt to integrate two fundamental entities (the know-how, which refers to the ability of an agent to control the process and the know-how-to-cooperate, which concerns the agent ability to cooperate with other agents involved in the same process), a methodological approach was developed based on a human-machine cooperation model [94]. The idea was to identify different interactions between humans and robots and, then to define adequate levels of automation taking into account the capacities and abilities of both humans and robots according to the situation.

With the main aim of quickly verifying whether a process is suitable for HRC or not, a conceptual method to support companies implementing HRC was presented in the literature [95]. The authors proposed two evaluation stages: (i) where the enablers and inhibitors that influence the suitability for HRC (as ergonomics, tools, skills…) are identified, and (ii) where the process is divided into its sub-processes and both are analysed, according to a procedural model with nine steps. In this study, the level of assignment and level of interaction were used to classify the workplaces. In the same line, a methodology to identify the most suitable applicative use cases for profitable exploitation of HRC technology is presented in the literature [96]. This methodology is based on preliminary values assignment to multiple key parameters, namely technological complexity, HRC relevance, benefits/costs indicator, ergonomics and safety and logistic interface.

To assess ergonomic risk, but also considering optimization criteria for planning and evaluating HRC in assembly collaboration scenarios a comprehensive model was developed by [97]. Considering humans and robots separately, they divided criteria into five categories: function allocation, physical ergonomics, cognitive ergonomics, environmental ergonomics and technical. For the allocation decision, the availability of the resources as well as the feasibility of and execution time for the task were used. On the other hand, for ergonomic evaluation, stress and strain, some changes in the workflow between the human and the robot as well as between the robotic tools are considered to estimate the physical ergonomics. These factors were directly related to mental workload (cognitive ergonomics). Moreover, the authors state that is essential that the robot's behaviour is perfectly predictable for the human operator. According to these authors, in the HRC, the human contributes extensive cognitive and sensorimotor skills and the robot accounts for force, accuracy and endurance.

4.3. Emergent future research topics

Further research to design HRC workspaces could benefit from a more multidisciplinary approach. The literature recognizes the existence of complex scenarios of interaction between humans and robots in manufacturing, however, most studies have not tested these scenarios or not included all dimensions of human factors and ergonomics in their experiments. HRC sustainability depends on a human-centred approach. Therefore, it will be necessary to develop systemic studies in control environments that investigate specific tasks that come from manufacturing and explore the effects of collaborative workspaces on humans, considering physiological, biomechanical and psychosocial data. This approach intends to maximize human involvement in the decision chain and to promote human health, wellbeing and quality of life. It is critical to develop research in this field by multidisciplinary teams, with expertise in the engineering/technological field, ergonomics and human factors, medicine and psychology, to create complete and complex scenarios (closer to reality) and to study in-depth the impact on humans resulted by the implementation of collaborative environments.

From manufacturing companies' perspective, future work needs to be a focus on the development of validated tools that allows understanding the sustainability of HRC. These tools should support decision-makers on the activities/tasks in which HRC implementation is viable, considering workers physical and mental wellbeing, performance and productivity. Additionally, it is also imperative the development of strategies (e.g., training programs) to demonstrate to workers that HRC can promote safe, healthy and inclusive working environments.

5. Discussion

The manufacturing workplace is evolving, and recently with technological advances, it is possible to have humans and robots sharing not only the physical space but also the tasks. Nowadays it is possible to see humans and cobots interact with each other to accomplish defined objectives towards the improvement of productivity, efficiency and flexibility. The literature review conducted in this research proved that designing a collaborative workplace implies considering several influencing factors that are involved in the human-robot interaction. Therefore, designing a collaborative workplace/work needs to be approached in an integrated and multidisciplinary way to maximize human involvement in the decision chain and to promote wellbeing and quality of work. The results of this study highlighted the diversity of knowledge fields involved in the design, as well as the topics that needed to be considered when designing HRC industrial environments.

Several challenges arise from this multidisciplinary and diversity of knowledge fields that need to be considered when designing HRC industrial environments. Therefore, the development of a framework that supports the systematization of the guidelines and recommendations found in the literature, has proved to be critical in accomplishing the aim of this research. Based on the proposed framework, this study presents a set of guidelines and recommendations for designing collaborative workplaces where humans and cobots successfully interact with each other to achieve higher levels of efficiency, productivity, and flexibility that is impossible to achieve on their own. The guidelines and recommendations were presented according to different levels of complexity (categories) that are directly related to the influencing factors presented in HRI contexts. The effort of classifying the recommendations and guidelines in terms of their complexity level, as well as in topics, following the framework structure, revealed itself to be a great challenge. In Category 1, human operator (C1a) or technology (C1b), where the majority of the articles were assigned, only the contribution of one specific influencing factor in the HRI were considered: In the human operator category (C1a) and the cognitive and social processes subcategory, guidelines and recommendations from the literature approached topics related to trust, attribution of blame, technology acceptance, and human cognitive performance. It was interesting to notice a concentration of literature related to the trust topic which reveals a great concern related to the most important aspect in a relation, even when a human and a robot are being considered. In the guidelines and recommendations related to the human comfort and safety subcategory, topics related to improving (or measuring) safety and the design of the robots were reported. These results are aligned with the aim of achieving a safe and comfortable workplace.

There are a few recommendations and guidelines related to the hardware subcategory in the Technology category (C1b). However, the literature is rich in guidelines and recommendations in the software subcategory. The majority of the guidelines and recommendations were related to models and algorithms that intend to improve the control in the collaborative environment. The literature is also rich in terms of recommendations and guidelines of algorithms/software to design workplaces with cooperative and collaborative behaviours, as well as algorithms that improve the communication between the human and the robot. In the human-robot team's performance Category (C2) some recommendations and guidelines regarding the collaborative interactions between humans and robots to improve performance and wellbeing exist in the literature. They are generically divided into three subcategories: collaborative workspace and task allocation; team performance and wellbeing; and HRI strategies. Undoubtedly, the literature has focused, according to the material produced, much more on the collaborative workspace and task allocation, with a prominence of generic recommendations on the subject, and specific (for the case of human workers with cognitive disabilities, and, for multi-human and multi-robot interaction; human-multi robot interaction). It is not surprising the vast literature on this topic since it is an essential issue in collaborative environments and to an effective HRC. Although team performance and wellbeing, and HRI strategies recommendations and guidelines are less present in the literature, they were not forgotten. Finally, the most holistic level of human-robot interaction (C3), where guidelines and recommendations about the simultaneous contribution of different influence factors associated with human or robot performance (e.g., safety), team performance (e.g., trust) and/or task performance (e.g., process performance indicators) were presented. In this third category several insights were collected, of which the following should be highlighted: In the HRI, the human contributes with extensive cognitive and sensorimotor skills and the robot accounts for force, accuracy and endurance. Communication about shared plans using gaze and speech aids effective collaboration for a task in which a human and robot work together. Moreover, the balance between preserving human's situational awareness, optimizing workload allocation and production efficiency, is essential to designing intelligent collaborative robots.

6. Conclusions

This research has important scientific and technical contributions, considering the urgency of adapting the workplace to humans and cobots, improving simultaneously physical and mental wellbeing, performance, productivity and sustainability. Guidelines and recommendations to support technology developers not only in terms of the technology itself but also with interesting inputs that put the human in the centre of the system providing the safety and wellbeing environment. The main contribution of this research is intended to better characterize the effects of cobots on physiological, biomechanical and psychosocial parameters and overall knowledge about the design of a human-centred collaborative environment.

Despite the vast contribution of this article, some limitations should be kept in mind mainly related to the search approach and the related inclusion/exclusion criteria. To have high-quality results as well as recent inputs, book chapters, journal and conference articles were considered in the analysis. As a consequence, it might be that in this work we did not consider the latest research studies already published in article reviews. Trying to focus on the manufacturing context, some important inputs coming from other contexts, mainly the application of cobots in social and security/military contexts, were not included. The inclusion of recommendations to design collaborative spaces coming from other contexts could enlarge the findings of this research. Additionally, it is possible to enlarge the review by adding other search keywords to the search expression used in this research. For example, keywords related to sustainability, older workers, and/or people with physical and psychological disabilities. Finally, the framework proposed in this research to systematize the results of the literature according to their degree of complexity was developed by the research team consisting of researchers from multiple research areas (human factor and ergonomics, psychology, technology management and computer science) to present diverse perspectives efficiently. Although the framework developed intends to cover multidisciplinary research areas, there is always the possibility to include other researcher areas in the framework, and different categories being created.

While the valuable contributions of this article, with contribution from multidisciplinary areas, other research areas can also be integrated, to put the human in the centre of the system when he/she works as a teammate with a robot. It becomes clear that the literature offers contributions from several knowledge areas capable to design safety, ergonomic, sustainable and well-being human-centred workplaces where social and psychophysical aspects of collaboration are considered.

Declaration of Competing Interest

The authors report no declarations of interest.

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