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Human-robot collaborative systems: Structural components for current manufacturing applications

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ABSTRACT

The implementation of human-robot collaborative systems in industrial environments have widely extended during the last five years, from manufacturing applications reproduced in laboratory facilities or digital simulations to real automotive shop floors. Commonly, one way to guide their design has been through the adoption of international standards focused solely on the safe operation of collaborative robots. The main objective of this paper is the identification of basic components comprising human-robot collaborative systems design. This is supported by two steps, 1) Provide an extensive compendium of current applications and components within a varied set of manufacturing sectors and tasks. 2) Based on the latter, propose a selection of "structural components" for collaborative work. We conceptualized structural components as the organizational and technological alternatives necessary to fulfil the basic requirements and functionalities of human-robot collaborative systems. This document presents a systematic literature review that includes 50 exemplary case studies implemented in different manufacturing environments throughout the last five years praxis (2016–2020). Four structural components were identified in this paper: interaction levels, work roles, communication interfaces and safety control modes. Furthermore, it was found that physical contact-based collaboration for screwing assembly of small-sized parts and material handling of heavyweight objects are suitable applications for the automotive industry. Moreover, certified augmented and virtual reality devices were highlighted as convenient assistive technologies for safety and training manufacturing needs. The presented categorization will allow practitioners on selecting settings of compatible structural components that could respond better to trendy manufacturing requirements searching for highly personalized products.

1. Introduction

It has been reported that current manufacturing expectations for high-mix/low-volume production cannot be fully satisfied with rigid automation means (Malik and Bilberg, 2017), nor past continuous improvement strategies that aim to solve production drawbacks (i.e., lean manufacturing, just in time systems, and other management methods). Such deficiency exists despite the utilization of state-of-the-art robotic systems that provide robust automation features. Industrial and other type of robots (i.e., mobile robots) can be time-consuming in the installing, setting up and programming processes, reducing the changeability capacity of manufacturing organizations. Alternatively, the utilization of manual production systems makes use of human operators' cognitive skills, allowing them to manage changes among tasks, tools, materials and unexpected situations that challenge the sensing, planning and movement envelopes. However, human operator performance in terms of speed, quality and motivation tend to diminish as physical and cognitive fatigue sets in. Consequently, human-robot collaborative systems (HRCS) are being adopted in the manufacturing industry as a solution that mixes, within a shared workspace, the dexterity and cognitive faculties of human operators and the accuracy and repeatability skills of robots.

Collaborative robots (or cobots) have been developed with intuitive interfaces that support human operators in the physical workload of manufacturing tasks such as handling hazardous materials or executing repetitive actions with high reliability (Parra et al., 2020). Furthermore, direct interaction among human operators and robots has been enhanced with the use of sensors and software that allow safe physical

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interaction, intuitive manipulation, and collision free activities. With the inclusion of collaborative robots, HRCS seem to be a convenient strategy for manufacturing organizations seeking to reduce human operators' occupational risk and overall workload while increasing efficiency and productivity indicators (Realyvásquez-Vargas et al., 2019). It has to be noted, however, that executing a coordinated task with an avant-garde robotic system might be overwhelming for some human operators. This is especially true for human operators that do not have a clear understanding of the robot's power, speed, learning methods and communication capabilities, or simply do not trust robots as full-fledged teammates (Parra et al., 2020).

Due to its novelty the design of HRCS, which ultimately seeks to solve problems related to the basic functionalities of collaborative work, is a topic that has been reported in the literature as isolated case studies. This format, of proving a single alternative for the design of a particular application, cannot be replicated by practitioners who want to solve further manufacturing needs. In order to establish a broader basis for systematic HRCS design, it is required an extensive review of prior experiences, underlying components and implementation strategies.

The main objective of this article is to identify the basic components utilized in the design of HRCS within the last five years praxis. Specifically, this is supported by two steps: 1) Provide a compendium of applications, components and technologies for state-of-the-art manufacturing sectors and tasks. 2) Based on the latter, the proposal of what it is established as "structural components" for HRCS design is introduced. We conceptualized structural components as the organizational and technological alternatives necessary to fulfil the basic requirements and functionalities of collaborative work among human operator and robot. Ultimately, the proposed categorization aims to support current practitioners in supplying a roadmap of compatible structural components for satisfying a wider range of manufacturing needs and behaviours.

This paper presents a detailed analysis of 50 HRCS case studies from the last five years (2016–2020), where present-day applications and basic components in the manufacturing industry were highlighted. The methods used to collect and analyse the data are detailed in Section 2. A wide description of the proposed structural components is shown in Section 3. Qualitative analysis of common practices regarding HRCS applications by type of task and manufacturing sector, as well as the presence of HRCS structural components are presented in Section 4. Finally, overall remarks on current and future research in HRCS are provided in Section 5.

2. Methodology

In what follows we describe the methodology performed to analyse current HRCS, their applications, basic components, and the inclusion of assistive technologies for the manufacturing industry. To focus on the practical aspects of HRCS a systematic literature review was conducted, which consisted in the selection of research works applied in different types of environments while discerning common practices, strategies and emerging technologies. Case studies of real manufacturing settings and experimental works within laboratory facilities were the main focus of the analysis. Simulated tasks made in robust digital manufacturing software (i.e., Siemens Tecnomatix) were also considered to quantify the developments reported in the literature, as these can accurately reproduce industrial shop floors and resources.

2.1. Search strategy

With the purpose of assuring the quality level of the consulted research works, the selection for HRCS was carried out by utilizing the academic database Scopus. As a result, peer-reviewed journal articles and conference proceedings were the principal source of information. The search terms, or keywords, employed in the review were divided in two categories: manufacturing "sector" and "task". Such keywords, listed in Table 1, were not only individual inputs for the search, but they were also combined (a manufacturing sector plus a manufacturing task). Moreover, when using the term "robot" within this paper, it is implied that all mentioned robotic systems are endowed with collaborative capabilities. The above-mentioned facilitates the delimitation and identification of affined research works.

2.2. Review method

In order to conduct the literature review, the Preferred Reporting Items for Systematic Review and Meta-Analyses framework (Moher et al., 2009), also known as PRISMA, was followed and adjusted for the objective of this research. As presented in Fig. 1, the first step of the literature review resulted in the identification of 628 papers that contained the keywords listed in Table 1. The exclusion of duplicates was the first search filter, 354 papers remained in scope after removing repeated records. Afterwards, the titles and abstracts of the selected papers were examined, records with topics outside the review aim were discarded (i.e., human-robot collaboration in agriculture, social robotics, or medical applications). The third filter consisted in assessing the research objective of the remaining 122 records, 43 papers were excluded due to the lack of a concrete HRCS application within the manufacturing industry (i.e., isolated focus on the development of smart tracking devices, adaptive human-robot interfaces, or utilization of non-industrial components). Ultimately, 79 papers were deeply inspected and a final cut of 44 records was established. The last filter discarded papers without a detailed case study section within the document, as the main objective of this literature review is to extract basic components related to real manufacturing applications.

A compendium of 44 journal articles and conference proceedings, involving 50 HRCS (some papers have more than one suitable case study), was gathered and classified by type of manufacturing sector, task and environment. Based on the latter, a proposal of structural components for HRCS design was introduced. The obtained findings are presented via a series of charts, followed by an individual exploration of each application and structural component while describing the affinities, dependencies, and effectiveness between them.

2.3. Research behaviour

As detailed in Section 2.2, a total of 50 exemplary HRCS case studies, contained in 44 research papers, were selected for qualitative analysis. From such publications, 64% came from conference proceeding, while 36% were obtained from peer-reviewed journal articles. It was noticed that the early advances shown in conference proceedings have been improved and implemented during the next 1–2 years after the technology was initially proposed. Based on such observations, it is presumed that HRCS are still in their infancy, but the understanding and use of such systems is growing, as articles published in peer-reviewed journals have been gaining ground and sharing the learned lessons during the implementation process in manufacturing shop floors.

As a result, HRCS can be considered promising alternatives for manufacturing operations as they present a dynamic growth throughout the past five years. Laboratory and simulated reproduction of manufacturing processes, and industry case studies have provided the

Table 1
Keyword division contemplated in the literature review.

Manufacturing sector	Manufacturing task
Automotive	Assembly
Metals	Welding
Plastics	Material handling
Electronics	Machining process
Aerospace	Machine tending
Appliances	Quality inspection

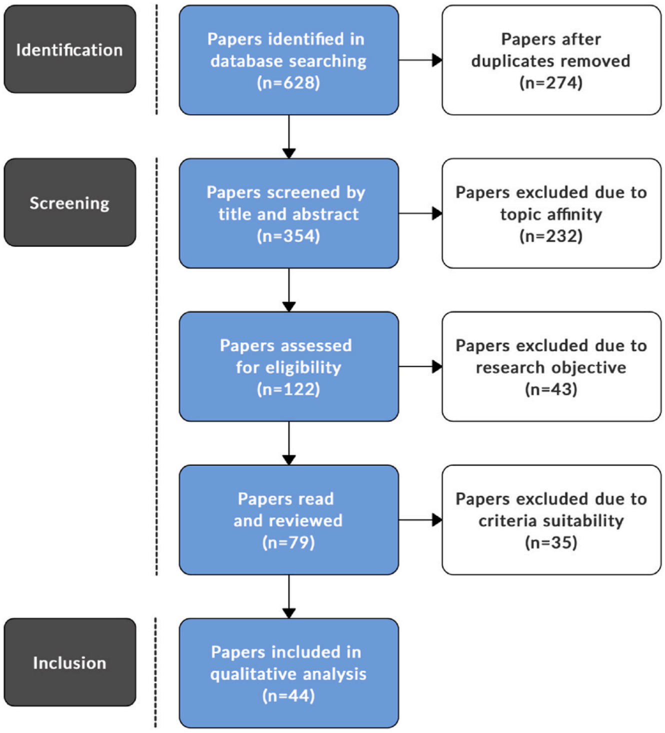


Fig. 1. Adapted PRISMA flowchart for systematic literature review.

means to enrich and update this active field. Furthermore, as seen in Fig. 2, it was observed that 68% of the advancements collected in HRCS have been published during the last two years of the analysis (2019–2020).

3. Structural components

The proposal for establishing an integrated framework of structural components can be recognized as the indispensability to identify the organizational and technological alternatives necessary to satisfy the basic requirements and functionalities of HRCS. According to the consulted literature, collaboration is shaped by the work dynamics that a human operator adopts in relation with a robotic counterpart; the allocation of individual and joint responsibilities; the responsiveness in critical data exchange; and the assurance of human operator's well-being. In Fig. 3, the proposal of four structural components is presented, then detailed descriptions of each structural component derivation is given according to the findings of the 50 case studies examined in the PRISMA inclusion stage (see Fig. 1).

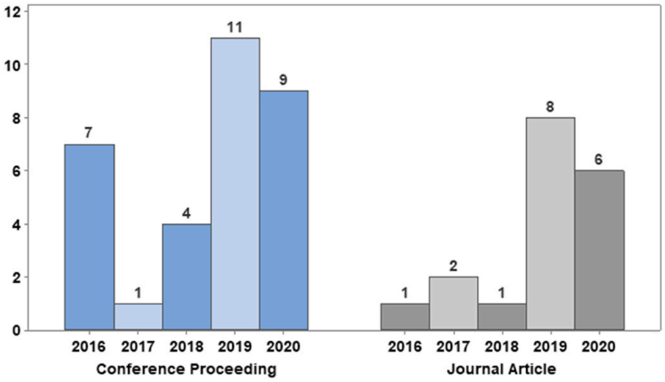


Fig. 2. Research works by publication year.

3.1. Interaction levels

Several HRCS conceptual frameworks have been developed in recent years, however, proposals varied on defining the exact meaning of concepts such as "collaboration, "interaction" and "cooperation" (El Zaatari et al., 2019). In addition to this, most of these categorizations are vague regarding the affinities and dependencies contemplated in each collaboration level (Aaltonen et al., 2018). The proposed classifications made by the literature are based on important aspects of the collaboration dynamic between human and robots. For instance (Helms et al., 2002), used time, workpiece and process as differentiator variables for building HRCS. Likewise (Krüger et al., 2009), employed time and type of task for their classification. (Michalos et al., 2015), in the same way, harness the prior concepts and aggregate workplace as a significant asset to be considered in HRCS design. In contrast (Behrens et al., 2015), contemplated related interaction concepts such as simultaneous co-working and physical contact between human operator and robot.

For the objective of this research paper and due to the wide focus for present and future applications, the demarcation proposed in (Cesta et al., 2016) and then complemented by (El Zaatari et al., 2019), based on human-robot work dynamics, workpiece and process will be the reference when "interaction levels" is mentioned within this document. It is also implied that collaboration, in all cases, is given by safe co-presence of both parties in the same fenceless workspace. The classification for interaction levels is described as follows:

- **Independent:** Human operator and robot work on separate workpieces and detached from each other.
- **Sequential:** Human operator and robot work on consecutive processes on the same workpiece at a separated time.
- **Simultaneous:** Human operator and robot work on separate processes on the same workpiece at the same time.
- **Supportive:** Human operator and robot work synchronously to complete a common process on the same workpiece.

3.2. Work roles

A team is formed when collaboration between human operator and robot takes place, leveraging the participants' joint advantages to ease a given task. Collaboration in this regard assumes three different requirements as established in (Bratman, 1992): "Mutual responsiveness, commitment to a joint activity and commitment to support the team". Hence, allocation of individual and shared responsibilities can be assigned for both resources. Nevertheless, as expressed in (Harriott et al., 2015), even if some activities are assigned individually, a task is not complete until the two parts have finished their individual and shared responsibilities. Furthermore, the pace of the task can be set individually by one of the participants or mutually (by human operator and robot); this is defined as a master-slave relationship and peer-based relationship respectively. Consequently, three different work roles for human operators, in relation with the robot counterpart, are established for the review of current HRCS:

- **Supervisor:** The human operator takes the master role in the master-slave relationship.
- **Peer:** Human operator and robot mutually set or follow the pace in a given task.
- **Subordinate:** The robot takes the master role in the master-slave relationship.

3.3. Communication interfaces

In a continuous effort to make robots more intuitive and safer to interact with, new software tools and sensor systems have been developed, known as single-mode communication interfaces. Their objective is to support human operators in controlling and programming robots in

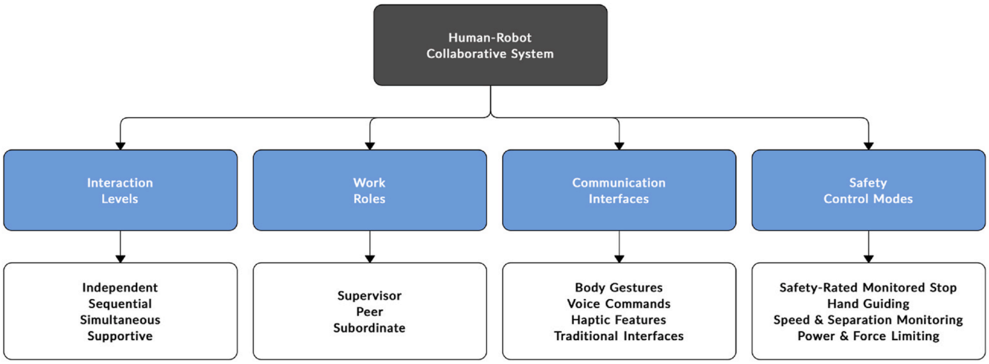


Fig. 3. Established structural components for human-robot collaborative systems.

a human-friendly language (Villani et al., 2018). Required inputs may vary from speech, body gestures or eye tracking to facial expressions and haptic features. In contrast, the combination of more than one single-mode interface is known as a multi-modal interface. These strengthened systems offer more alternatives and flexibility to the human operator when reliable communication with a robot is contemplated. Listed below are the descriptions of the above-mentioned communication interfaces:

- **Body gesture interfaces:** Based on vision systems that process human operator body gestures and physical movements into instruction commands.
- **Facial/Eye tracking:** Based on vision systems that process human operator facial expressions and eye activity (i.e., blinking, gazing) into hands-free instruction commands.
- **Voice command interfaces:** Based on speech recognition systems that process human operator natural language into hands-free instruction commands.
- **Haptic interfaces:** Based on robot hand-guiding features that are used for interacting, notifying and teaching instruction commands.
- **Traditional interfaces:** Based on widely adopted hardware such as buttons, keyboards, mouse or monitors used for data input or output.

Moreover, recent efforts for human-friendly communication in HRCS include artificial intelligence methods (Villani et al., 2018). This alternative utilizes algorithms that are endowed with learning capabilities and have the goal of reacting accordingly to human operator intentions, work patterns and performance.

3.4. Safety control modes

Independently from the HRCS to be implemented, a significant human concern when working directly with an industrial robot is safety. Standardized practices for HRCS safety control have been developed by the International Organization for Standardization (or ISO) and gradually adopted by the manufacturing industry. The norms ISO 10218-1 (2011a) and ISO 10218-2 (2011b) were established to define the basic safety requirements for industrial robot installation, operation and maintenance. Afterwards, the complementary ISO 15066 (2016) norm was issued. According to this official document by ISO: “This norm provides guidance for collaborative robot operation where a robot system and people share the same workspace.” It also establishes that: “In such operations, the integrity of the safety-related control system is of major importance, particularly when process parameters such as speed and force are being controlled”. The safety control modes classification by ISO 15066 (2016) is described below:

- **Safety monitored stop (SMS):** The robot is stopped immediately from any movement if a human operator enters a pre-designated safety area of the workstation.
- **Hand guiding (HG):** The robot is enabled to be manually controlled by a human operator without the need of extra devices or control interfaces.
- **Speed & separation monitoring (SSM):** The robot work area is divided into safety zones where both speed and distance are followed and adjusted based on the human operator’s location.
- **Power & force limiting (PFL):** The robot is programmed to work within certain levels of force and torque constrained by biomechanical load limits where damages or injuries are not expected to be caused in human operators.

4. Results

4.1. Results based on current applications

The presented review examined and categorized 50 exemplary HRCS found in state-of-the-art literature. According to the findings, results on manufacturing sectors and tasks were clustered based on similar behaviours and patterns. In order to streamline the analysis, manufacturing sectors were grouped in automotive, metals/plastics, industrial R + D and others (i.e., appliances, aerospace and electronics). Meanwhile, manufacturing tasks were grouped in assembly, material manipulation, machining process and quality inspection. In Fig. 4, the complete derivation of analysed manufacturing tasks is presented.

4.1.1. Applications overview in HRCS

A general overview of identified manufacturing applications by type of sectors and tasks was first deployed. For instance, manufacturing sectors such as automotive, metals/plastics, and industrial R + D (in collaboration with academia) were found to be the most common cases with 44%, 26% and 14% respectively. It was comprehensible to find out that automotive applications represent a large proportion of the total cases. Such sector has long-time experience on acquiring and installing industrial robots in their production processes, so it is envisioned that the automotive sector is more likely to be advancing faster in the adoption of collaborative work dynamics.

During the study, assembly tasks were found to be the most repeated term with a 72% presence in all research works related to collaborative tasks. Material manipulation tasks were found to be common in the manufacturing industry with 22% of the total cases. It was also observed

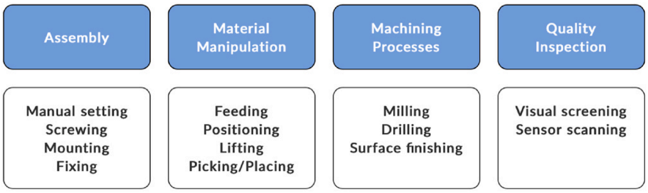


Fig. 4. Operations grouped for the selected manufacturing tasks.

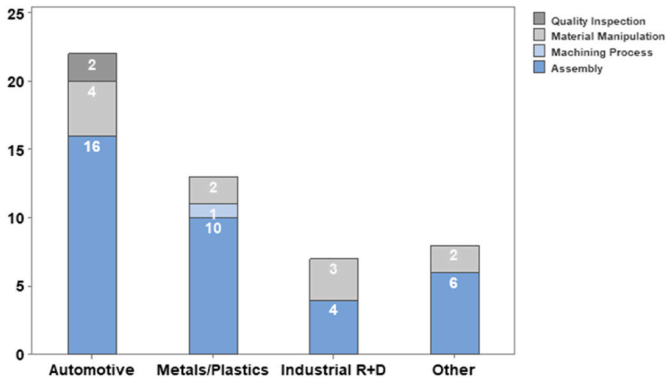


Fig. 5. Distribution of tasks by manufacturing sector.

that assembly and material manipulation tasks are continuously being enhanced for HRCS in a faster pace when compared to other tasks (i.e., packaging). This is due to the direct interaction dynamics that exists among human operator, workpiece, and robot that are relatively easier to be performed via collaborative robots and assistive technologies.

4.1.2. *Current applications in HRCS*

After presenting a general overview of manufacturing sectors and tasks, a more in-depth inspection is carried out in order to obtain a broader lecture regarding current HRCS applications. In Fig. 5, the distribution of tasks by type of manufacturing sector is presented. In the case of the automotive sector, a clear majority of the cases (83%) can be classified as assembly tasks. The applications are varied, from fixing large and heavy parts such as truck front and back doors (Andronas et al., 2020), to thin and deformable materials like wires in a harness taping task (Gualtieri et al., 2020). However, assistance in the screwing process of small or medium-sized objects is the most common example found in the literature for the automotive sector. Examples of the latter can be seen in (Rahman and Wang, 2018), where the assembly of automotive center consoles is carried out in a simultaneous manner by both robot and human operator; or in a screw tightening task for superchargers (Nikolakis et al., 2018).

Table 2
Case studies by type of industrial environment, sector and task.

Publication	Environment	Sector	Task
Magrini et al. (2020)	Industrial	Automotive	Visual screening of polished metallic parts
Gualtieri et al. (2020)	Industrial	Automotive	Manual setting of wire harnesses
Murali et al. (2020)	Industrial	Automotive	Picking&Placing of wheel bearings
Gervasi et al. (2020)	Industrial	Automotive	Feeding of parking pawl components
Hanna et al. (2020)	Industrial	Automotive	Mounting of ladder frame on engines
Messeri et al. (2020)	Industrial	Metals/Plastics	Screwing of thermostatic heads
Aljinovic et al. (2020)	Industrial	Other	Fixing of wooden axles on sear baseplates
Tlach et al. (2019)	Industrial	Metals/Plastics	Screwing of pneumatic cylinders
Antonelli & Stadnicka (2019)	Industrial	Metals/Plastics	Mounting of flanges on metallic parts
Ding et al. (2019)	Industrial	Metals/Plastics	Disassembling of roller chains
Liu et al. (2019)	Industrial	Industrial R + D	Disassembling of computer hosts
Realyvásquez-Vargas et al. (2019)	Industrial	Other	Manual setting of pockets (storage units)
Vosniakos et al. (2019)	Industrial	Other	Lifting of plastic shells
Casalino et al. (2018)	Industrial	Other	Screwing of printed circuit boards
Gopinath et al. (2017)	Industrial	Automotive	Fixing of flywheel covers on engine blocks
Cherubini et al. (2016)	Industrial	Automotive	Manual setting of balls in homokinetic joints
Müller et al. (2016)	Industrial	Automotive	Visual screening of end-off line vehicles
Thomas et al. (2016)	Industrial	Automotive	Screwing of housing parts on pumps
Fast-Berglund et al. (2016)	Industrial	Metals/Plastics	Manual setting of O-rings
Fujii et al. (2016)	Industrial	Metals/Plastics	Positioning of metallic panels
Ore et al. (2020)	Simulation	Automotive	Fixing of flywheel covers on engine blocks
Land et al. (2020)	Simulation	Automotive	Lifting of valve hoods for engines
Andronas et al. (2020)	Simulation	Automotive	Fixing of turbocharger housings
Andronas et al. (2020)	Simulation	Automotive	Fixing of manifolds and pipes on turbochargers
Andronas et al. (2020)	Simulation	Automotive	Positioning of door hinges on chassis harnesses
Rückert et al. (2020)	Simulation	Other	Screwing of a marble mace
Weßkamp et al. (2019)	Simulation	Metals/Plastics	Assembling of confidential components
Berg et al. (2019a)	Simulation	Industrial R + D	Manual setting of transmission components
Berg et al., (2019b)	Simulation	Industrial R+D	Interacting with mobile robots
Berg et al., (2019b)	Simulation	Industrial R+D	Interacting with mobile robots
Li et al., (2019)	Simulation	Other	Disassembling of gear pumps
Costa Mateus et al., (2018)	Simulation	Metals/Plastics	Screwing of stop buttons
Aaltonen et al., (2018)	Simulation	Metals/Plastics	Welding of machine bodies
Haage et al., (2017)	Simulation	Other	Screwing of printed circuit boards
Thomas et al., (2016)	Simulation	Automotive	Lifting of car bodies
Liu et al., (2020)	Laboratory	Industrial R+D	Avoiding collision with obstacles
Bae et al., (2020)	Laboratory	Other	Lifting of heavy metallic parts
El Makrini et al., (2019)	Laboratory	Automotive	Screwing of a 3d printed gearbox
Hietanen et al., (2020)	Laboratory	Automotive	Positioning of rocker shafts on diesel engines
Huang et al., (2019)	Laboratory	Automotive	Disassembling of water pump components
Malik & Bilberg, (2019)	Laboratory	Metals/Plastics	Mounting of brackets for linear actuators
Raessa et al., (2020)	Laboratory	Metals/Plastics	Manual setting of boards for wood cabinets
Peternel et al., (2019)	Laboratory	Metals/Plastics	Surface finishing of a metallic surface
Peternel et al., (2019)	Laboratory	Metals/Plastics	Drilling of a metallic part
Ionescu & Schlund, (2019)	Laboratory	Industrial R+D	Screwing of semiconductors on heat dissipators
Rahman & Wang, (2018)	Laboratory	Automotive	Manual setting of center console components
Aaltonen et al., (2018)	Laboratory	Industrial R+D	Manual setting of seals on metallic components
Matthaiakis et al., (2017)	Laboratory	Automotive	Screwing of electrical appliances
Tsarouchi et al., (2016a)	Laboratory	Automotive	Manual setting of cables for vehicle dashboards
Tsarouchi et al., (2016b)	Laboratory	Automotive	Setting of fuse boxes on vehicle dashboards

Alternatively to screwing processes, attachment of pieces with different means can be done as presented in (Ore et al., 2020), where a robot applies silicone and inserts gaskets to a flywheel housing cover, so the human operator can processes it to the next step of the assembly; similarly, silicone strings are utilized to couple valve hoods in (Land et al., 2020). In the same way, robot assistance in manual setting tasks such as placing nuts in a rocker shaft for an engine mounting process (Hietanen et al., 2020), or inserting steel marbles in an homokinetic joint assembly (Cherubini et al., 2016) are feasible applications.

Material manipulation tasks were the second most repeated type of HRCS in manufacturing-related environments. Unlike assembly tasks, heavier and larger objects are the main focus of material manipulation in current HRCS. This is exemplified in (Thomas et al., 2016), where robots handle car bodies of 80 kg of weight for visual inspection (executed by the human operator). Likewise, for an automobile dashboard assembly, a dual-arm robot grasps a long metal component called traverse and a body computer so the human operator can install cables using plastic pins (Tsarouchi et al., 2016a). In Table 2, the 50 case studies are listed, detailing the type of environment, sector and the task involved in the construction of each HRCS.

4.2. Results based on structural components

Based on the collected data, the most common practices and behaviours found in HRCS were compiled and categorized. According to these findings, HRCS were deconstructed into four structural components: interaction levels, work roles, communication interfaces and safety control modes. These, so-called, structural components were identified as an essential operative framework for most HRCS' designs. Identifying the structural composition comprising HRCS was used as a pivotal point for the presented data analysis. Complementary information (i.e., augmented and virtual reality technologies, mobile robots, wearable tracking devices, human adaptation algorithms) was also highlighted in the different HRCS case studies.

4.2.1. Interaction levels in the manufacturing industry

A categorization of HRCS built on the four human-robot interaction levels from (El Zaatari et al., 2019) was performed. Figure 6 shows the results obtained based on the distribution of HRCS and their corresponding interaction level. It was observed that HRCS with supportive interaction levels dominate the landscape with 52%. An example of the latter can be seen in flanges assembly (Antonelli & Stadnicka, 2019), where a robot holds a flange in a steady position so a human operator can screw bolts on a metallic base. Likewise, in (Gopinath & Johansen, 2016), a human operator couples a cover in a flywheel housing assembly that is being lifted by an industrial robot with hand-guiding capabilities. These cases illustrate how supportive HRCS are being applied in manufacturing, robots are in charge of holding complex objects in a given position while the cognitive ability and dexterity of human operators is employed synchronously in smaller parts or tool manipulation.

The second dominant interaction level was found to be sequential HRCS which represent 24% of the identified cases. Research on sequential systems has focused on optimizing work performance by harnessing task allocation and real time adaptation tactics. Welding of a machine housing is accomplished in (Aaltonen et al., 2018), by using the robot and its gripper as a rotary table and intelligent fixture respectively. The human operator starts welding until the parts are safely settled in the robotic fixture. In (Realyvásquez-Vargas et al., 2019), a sequential HRCS is utilized for assembling plastic storage units (called pockets) where a human operator preassembles the pockets so the robot counterpart can validate quality specifications with an ultraviolet lighting system. Accordingly, identified sequential HRCS are suitable when presumed risky or hazardous materials need to be handled but immediate human action is still required in preceding or subsequent processes.

The last two interaction levels, simultaneous and independent, jointly form 24% of the observed cases. The type of manufacturing sectors, tasks, and assistive technologies related to these two types of HRCS are varied and, as a result, a clear behaviour on the use of such systems could not be identified.

4.2.2. Work roles in the manufacturing industry

The reviewed HRCS were classified based on the work role (subordinate, peer, or supervisor) that a human operator adopts with respect to a robot companion while executing a collaborative task. As presented in Figure 7, the obtained results show that 8.6 out of 10 of the consulted cases belong to peer work roles while the remaining cases were accounted in the supervisor role (played by the human operator). The supervisor role was identified to be related to teach-by-demonstration tasks, where the human operator indicates (normally with intuitive communication interfaces) how a robot has to execute a given task. The supervisor role regularly inspects that the robot is complying with quality specifications and production times.

Furthermore, there were no cases found in manufacturing environments belonging to the subordinate role. It must be noted that implementing a subordinate role (played by the human operator) in any HRCS requires robots with substantial learning capabilities and vision systems to inspect, validate, and conduct a desired process in physical collaboration with a manufacturing operator.

Interesting, as presented in (Ionescu & Schlund, 2019), HRCS allow switching work roles between human operator and robot with the purpose of relieving physical and cognitive workload. The human operator decides if the robot counterpart holds a dissipator (supportive task) or screws bolts (simultaneous task), changing the work role from peer to

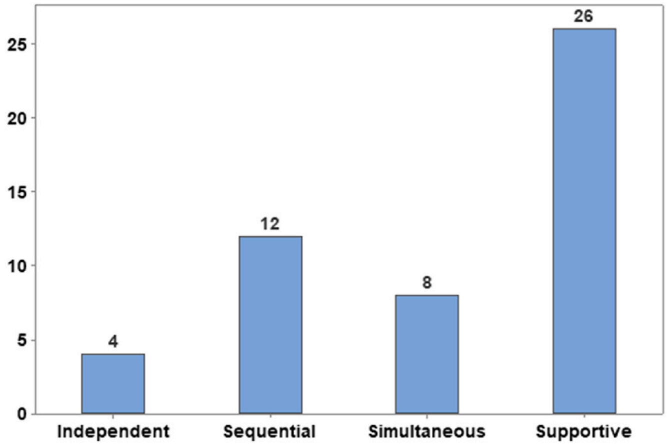


Figure 6. Distribution of case studies by interaction level.

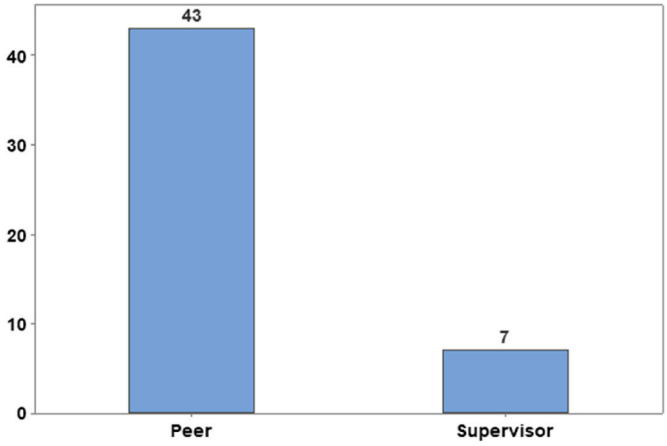


Figure 7. Distribution of case studies by work role.

supervisor. The success of work role exchange workstations depends on the organization needs, available resources and prior HRCS implementation experience.

4.2.3. *Communication interfaces in the manufacturing industry*

The distribution of HRCS by applied communication interface was also analysed. The obtained results are shown in Figure 8. It was found that traditional communication means including keyboards, mouse, monitors, teach pendants, and buttons are the most utilized systems for information input with a 40% appearance. The latter is partly explained due to the fact that traditional means are less expensive and more accessible to acquire by manufacturing organizations. In contrast, it was noted that some case studies, mostly from laboratory environments, did not utilize a concrete or identifiable communication interface.

It was found that advance communication tools such as body gesture communication represents 8% of the total cases reviewed. A metal polishing task for surface finishing is carried out using hand and arm gestures (Magrini et al., 2020). This intuitive interaction enables the human operator to stop, resume and modulate the speed of a robot's trajectory path. Similarly, the task of manipulating heavy objects (i.e., automobile parts) can be accomplished with great simplicity with haptics communication interfaces as shown in (Tsarouchi et al., 2016b). Emerging voice commands applications were not found in the review, but an example outside manufacturing can be seen in (Wang et al., 2019), where a speech recognition system is utilized by a human operator to coordinate the assembly of plastic blocks. Finally, it was highlighted that the implementation of mixed gestures or multi-modal communication is still limited in current HRCS.

4.2.4. *Safety control modes in the manufacturing industry*

In the area of HRCS safety within the manufacturing industry context, safety-rated monitored stop (SMS) modes were identified to be used in 28 HRCS tasks. Specifically, 56% of the reviewed HRCS include this specific safety control mode. SMS was found to be a suitable entry point for human operators that have little experience working with HRCS. The reason for this, is that collaboration is only executed when the robot is completely stopped, continuously monitored and de-energized in the presence of human operators as exemplified in (Li et al., 2019; Peternel et al., 2019). Similarly, 40% of the reviewed collaborative systems applied the speed & separation monitoring (SSM) mode, indicating it as a useful safety control as well. Control modes like SSM are necessary to have safe execution of collaborative tasks in real manufacturing shop floors as portrayed in (Vosniakos et al., 2019; Weßkamp et al., 2019).

In physical contact driven tasks where direct interaction is expected to occur between human operators and robots, hand guiding (HG) and power & force limiting (PFL) modes were found to be often required to manipulate the trajectory of a robot that, at the same time, is handling a heavier object. Examples of the latter can be seen in (Andronas et al., 2020; Ore et al., 2020). Furthermore, Figure 9 shows the distribution of safety control modes found in present HRCS. In most case studies, predominately found in real industrial environments, more than one safety control mode is contemplated for assuring human operators wellbeing.

4.3. *Strategies and emerging technologies in HRCS*

4.3.1. *Roadmap for current manufacturing applications*

After a systematic review of HRCS applications and the presence of structural components, a general roadmap for practitioners can be drawn. In Figure 10, a series of manufacturing tasks are listed along with compatible settings of structural components. For this case, a deeper level of detail is derived, so the manufacturing operations listed in Figure 4 will be examined individually. The presented summary is a compendium of the research community's current vision in a context where every HRCS application satisfies a particular end. Practitioners can take this roadmap as a starting point to build ad hoc solutions for their organizational needs. If more detail is required Table A1, in Appendix A, presents a dissection of all 50 case studies according to their structural components.

In addition to general lines of action regarding HRCS design, key performance indicators for industrial applications need to be established. According to the literature, the dominant targets of current HRCS are associated to optimize cycle or idle times, ergonomic and safety indicators. Relevant improvements in cycle time reduction range from 10% to 25% as seen in (Casalino et al., 2018; Cherubini et al., 2016; Realyvásquez-Vargas et al., 2019). Moreover, robot idle time is decreased in (Aljinovic et al., 2020; Ding et al., 2019) by 25% and 12.5% respectively. In human-centered indicators, (Gualtieri et al., 2020) decreased biomechanical overload by 20% in manual handling activities and 50% in working postures. Alternatively, (Messeri et al., 2020) improved the human operators' learning process (of a screwing task) by 25% through holographic standard operating instructions (or SOIs). Furthermore, safety results can be foreseen as the development of new or updated organizational policies suitable for collaborative work, such as risk assessment processes (i.e., Failure Mode and Effect Analysis or Poka-Yoke controls) as explored in (Antonelli & Stadnicka, 2019; Gopinath & Johansen, 2016).

4.3.2. *Emerging technologies for industrial environments*

A meaningful number of emerging technologies were spotted in the consulted research works. Proofs of concept that enhance the collaboration dynamic between human operator and robot were the principal scope of laboratory and simulated environments. In Table 3, a classification of these assistive technologies is presented. Four large groups can

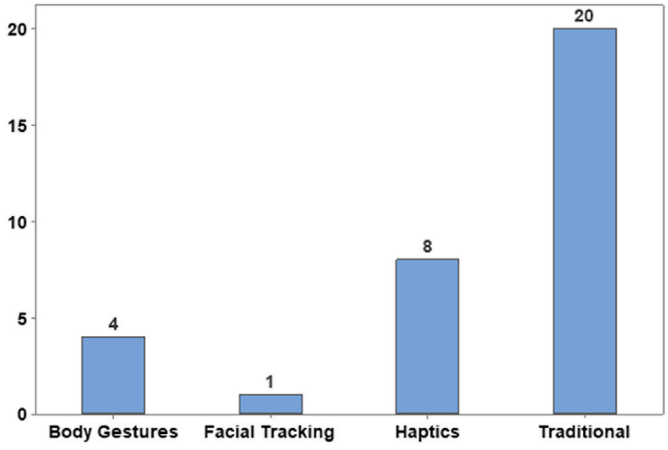


Figure 8. Distribution of case studies by communication interface.

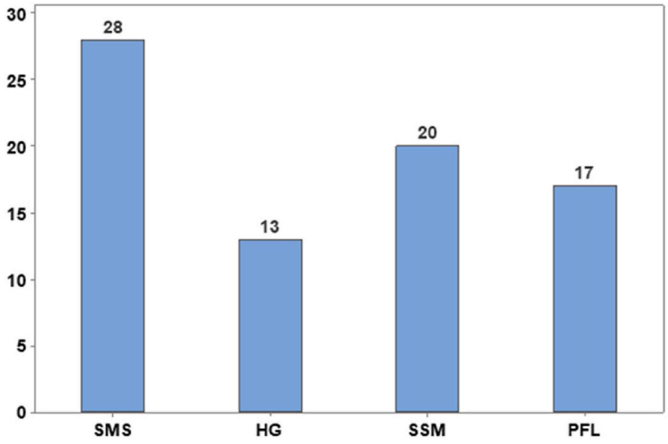
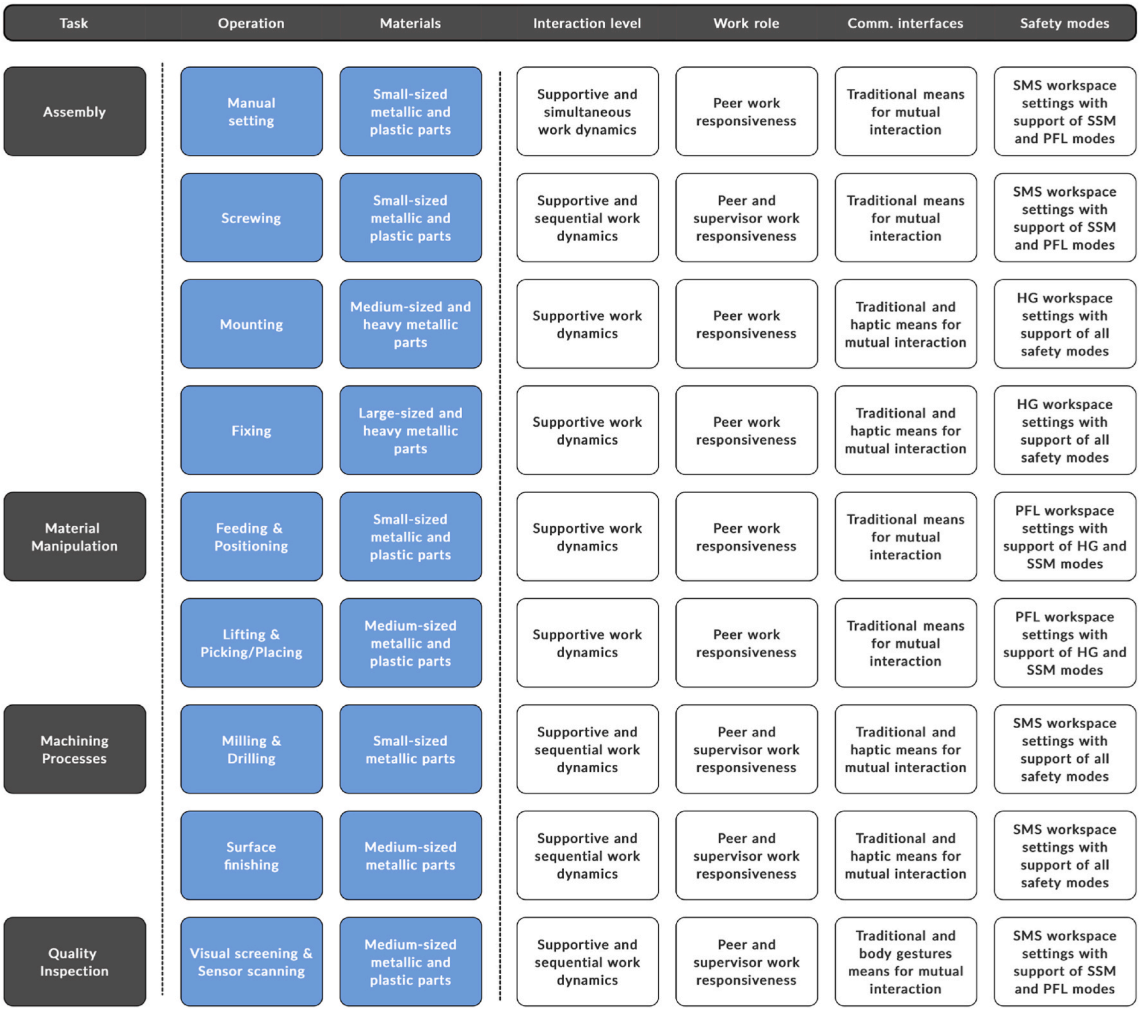


Figure 9. Distribution of case studies by safety control mode.



Task	Operation	Materials	Interaction level	Work role	Comm. interfaces	Safety modes
Assembly	Manual setting	Small-sized metallic and plastic parts	Supportive and simultaneous work dynamics	Peer work responsiveness	Traditional means for mutual interaction	SMS workspace settings with support of SSM and PFL modes
	Screwing	Small-sized metallic and plastic parts	Supportive and sequential work dynamics	Peer and supervisor work responsiveness	Traditional means for mutual interaction	SMS workspace settings with support of SSM and PFL modes
	Mounting	Medium-sized and heavy metallic parts	Supportive work dynamics	Peer work responsiveness	Traditional and haptic means for mutual interaction	HG workspace settings with support of all safety modes
	Fixing	Large-sized and heavy metallic parts	Supportive work dynamics	Peer work responsiveness	Traditional and haptic means for mutual interaction	HG workspace settings with support of all safety modes
Material Manipulation	Feeding & Positioning	Small-sized metallic and plastic parts	Supportive work dynamics	Peer work responsiveness	Traditional means for mutual interaction	PFL workspace settings with support of HG and SSM modes
	Lifting & Picking/Placing	Medium-sized metallic and plastic parts	Supportive work dynamics	Peer work responsiveness	Traditional means for mutual interaction	PFL workspace settings with support of HG and SSM modes
Machining Processes	Milling & Drilling	Small-sized metallic parts	Supportive and sequential work dynamics	Peer and supervisor work responsiveness	Traditional and haptic means for mutual interaction	SMS workspace settings with support of all safety modes
	Surface finishing	Medium-sized metallic parts	Supportive and sequential work dynamics	Peer and supervisor work responsiveness	Traditional and haptic means for mutual interaction	SMS workspace settings with support of all safety modes
Quality Inspection	Visual screening & Sensor scanning	Medium-sized metallic and plastic parts	Supportive and sequential work dynamics	Peer and supervisor work responsiveness	Traditional and body gestures means for mutual interaction	SMS workspace settings with support of SSM and PFL modes

Figure 10. Roadmap for current HRCS in the manufacturing industry.

be foreseen: flexible/intelligent task allocation, virtual and augmented reality assistance, adaptation to human fatigue or workload, and in-process robot control and teaching. Within these groups, different approaches are highlighted, such as the utilization of digital twins for fast product lifecycle information exchange (Rückert et al., 2020), the development of mobile robots enabled with body gestures and eye tracking recognition systems for human-friendly interaction (Berg et al., 2019a), or the teach-by-demonstration framework for smartphones assembly proposed by (Haage et al., 2017).

Table 3
Emerging technologies in HRCS

Flexible/ intelligent task allocation	Virtual/ augmented reality assistance	Adaptation to human fatigue/ workload	In-process robot control and teaching
Berg et al., (2019a)	Hietanen et al., (2020)	Liu et al., (2020)	Bae et al., (2020)
Ionescu & Schlund, (2019)	Messeri et al., (2020)	El Makrini et al., (2019)	Magrini et al., (2020)
Weßkamp et al., (2019)	Rückert et al., (2020)	Li et al., (2019)	Murali et al., (2020)
Costa Mateus et al., (2018)	Vosniakos et al., (2019)	Liu et al., (2019)	Haage et al., (2017)
Rahman & Wang, (2018)		Peternel et al., (2019)	
		Casalino et al., (2018)	

In contrast to laboratory and simulated environments, few assistive technologies are currently applied in industrial shop floors, however, solutions based on virtual and augmented reality (also referred as VR and AR respectively) were found to be suitable for this type of environment. Hololens, the AR headset from Microsoft, is utilized in (Hietanen et al., 2020) for safety zones visualization in an engine assembly task. Likewise, in (Vosniakos et al., 2019), the Facebook's VR headset Oculus Rift is employed for robots' motion path screening in a shell handling task. The latter exemplifies that certified AR/VR devices can offer robust and reliable virtualization solutions for current manufacturing safety and training needs.

4.3.3. *Differences among application environments*

The selection of case studies was divided according to their application environment (as shown in Table 2). The distribution of HRCS comes as follows: 20 from industrial shop floors, 15 from simulation software and 15 from laboratory facilities. The prior selection was established in order to reproduce the implementation process of a collaborative task from its proof of concept in experimental and simulated settings to its deployment in real manufacturing scenarios. This was useful, as mentioned in Section 2, in providing the common practices, strategies and emerging technologies presented within this document. Nevertheless, it has to be noted that several differences between the three application environments were identified during the literature review.

For instance, in Figure 11, the distribution of status indicator tools by type of environment is presented. Data indicators, displayed in teach pendants, monitors or tablets, are especially useful to deliver standard operating instructions and key performance indicators (SOI and KPI respectively) to shop floor operators. In the same way, visual indicators such as Andon lights or Pick-by-light systems also support human operators cognitively by notifying process states or reporting emerging issues. An additional advantage of screen-based devices is the capacity to display both data and visual indications, improving the flexibility of data output presented to manufacturing operators.

In terms of workstation design, 42 of the 50 case studies (85%) were classified as open workstations (see Figure 12). These case studies take advantage of the no-fences and safe-collision features that robots offer assembly and material manipulation tasks alike. Similarly, 2 close workstations (meaning that the robot is protected by safety guards and laser-based sensors) and 2 hybrid workstations (which have both open and close features) were convenient for shop floor environments. These collaborative workstations utilize conventional industrial robots for their production objectives. In a close workstation from (Fujii et al., 2016), metallic panels are collaboratively positioned in pre-established coordinates. Support of all safety control modes and additional laser curtains are necessary to create a safe workspace for human operators. In the same way, one process step in a hybrid workstation demands hand guiding capabilities to manipulate a standstill robot, so a human operator can fix a flywheel cover on an engine block (Gopinath et al., 2017). Such types of designs are feasible alternatives to convert rigid automation cells to collaborative workstations.

5. Conclusion

The main objective of the presented paper was to identify the basic composition comprising current human-robot collaborative systems (HRCS). As a first step, and based on a systematic review of available literature, a compendium of the last five years praxis was provided along with a general roadmap for building applications in present-day manufacturing sectors and tasks. It was found that such systems are being rapidly adopted in the automotive, metal, and plastic sectors as they have longer experience implementing industrial robots among other automation solutions in their shop floors. Furthermore, a clear tendency for assembly tasks in every type of sector was highlighted. Screwing operations appeared predominately in this type of task. Similarly, material manipulation tasks also have a solid presence in every manufacturing sector, but fewer cases were identified.

In a second step, and according to an extensive analysis of 50 exemplary case studies, four structural components for current manufacturing applications were proposed. The so-called structural components were de facto identified as the organizational and technological alternatives necessary to fulfil the basic requirements and functionalities of the examined human-robot collaborative systems. The proposed four structural components for HRCS design are: interaction levels, work roles, communication interfaces and safety control modes. As portrayed in this paper, the combination of structural components and assistive technologies shape (as building blocks) the collaboration dynamic between human operator and robot, where different affinities and dependencies can be formed.

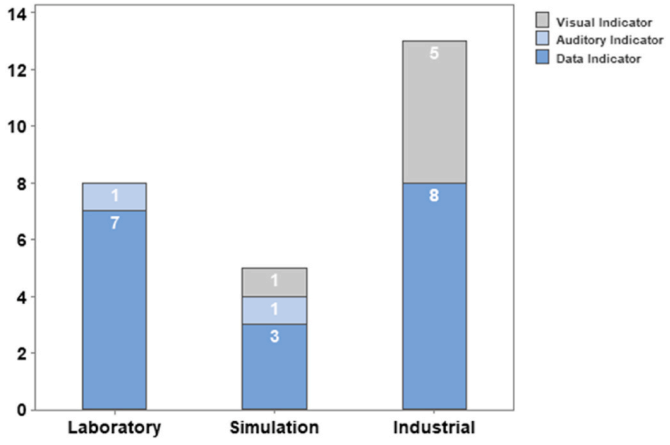


Figure 11. Status indicator by type of environment.

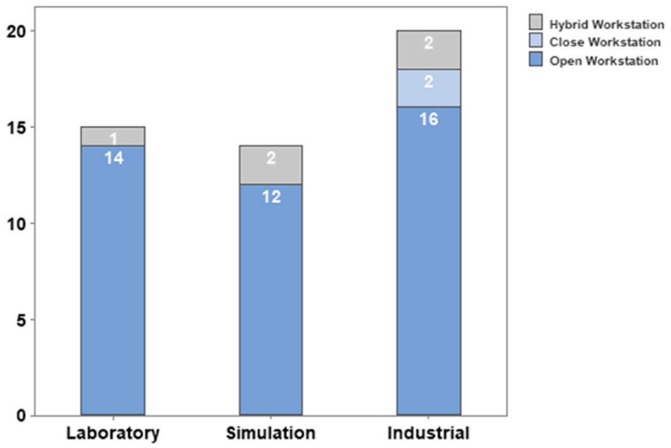


Figure 12. Workstation design by type of environment.

In terms of structural components presence, it was found that the growing number of case studies that selected supportive and sequential interaction levels, indicates a clear attempt from the research community to improve and simplify collaborative technologies in order to obtain broader industry adoption. Speed & separation monitoring, power & force limiting, and haptic features, were noted to be suitable safety control modes and communication interfaces for these specific interaction levels. Likewise, independent and simultaneous levels were found to utilize safety-rated monitored stop modes and traditional communication interfaces as strategies to accomplish human-robot collaboration. This approach is an appropriate choice for cases where no physical contact nor direct interaction between the two parts is required or even desired. In contrast to earlier behaviours reported by (Blankemeyer et al., 2018; Kildal et al., 2018; Schou et al., 2018), it is observed that independent-based industrial applications are being consistently substituted by supportive and sequential designs within the last two years.

Overall, having interaction with different degrees of collaboration and technologies not only increases the flexibility but also the complexity of the system. Consequently, structural components can be a starting point for practitioners who want to adopt human-robot collaborative systems in a more systematic fashion and satisfy high-mix/low-volume manufacturing requirements. Proofs of concept of novel health tracking devices (smart watches or clothing), virtualization tools (augmented and virtual reality hardware), and real time adaptation technologies (powered by machine learning methods) have set in as complementary solutions with the goal of improving the dynamics and performance of collaborative tasks. Nevertheless, these emerging technologies are not completely indispensable when designing and implementing current human-robot collaborative systems, and for that reason discarded from the established structural components.

As described in (Pacaux-Lemoine et al., 2017), a techno-centered approach was observed in human-robot collaborative systems literature. This implies a favouring pattern tilted to automated systems both in the definition and allocation of tasks. Henceforth, as an Industry 4.0 challenge, (Mattsson et al., 2020) suggest that the design and implementation processes of human-robot collaborative systems should be done with an active role from human operators as experts of their own jobs so that relevant aspects can be considered (e.g., demography, human development, organization, complexity and transparency). Implications in work design are highly dependent on manufacturing organizations' policies regarding levels of automation and how tasks are grouped into jobs, which ultimately affect the potential to substitute, simplify and enrich jobs (Waschull et al., 2020). Therefore, future research should focus on generating novel conceptual models for human-centered collaborative systems with the purpose of finding optimal settings of structural components and assistive technologies for a wider spectrum of manufacturing applications, while contemplating process efficiency and human operator wellbeing alike.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Case studies by type of structural component.

Publication	Interaction level	Work role	Comm. interface	Safety mode*
Magrini et al., (2020)	Sequential	Peer	Body gestures	SSM
Gualtieri et al., (2020)	Simultaneous	Peer	Traditional means	N/A
Murali et al., (2020)	Supportive	Peer	Traditional means	SSM+PFL
Gervasi et al., (2020)	Supportive	Peer	Traditional means	SSM+PFL
Hanna et al., (2020)	Supportive	Peer	Traditional means	SMS+SSM+PFL
Messeri et al., (2020)	Sequential	Supervisor	Traditional means	SMS
Aljinovic et al., (2020)	Supportive	Peer	N/A	N/A
Tlach et al., (2019)	Sequential	Peer	Traditional means	SMS
Antonelli & Stadnicka, (2019)	Supportive	Peer	Body gestures	SMS
Ding et al., (2019)	Supportive	Peer	Traditional means	N/A
Liu et al., (2019)	Simultaneous	Peer	N/A	SMS
Realyvásquez-Vargas et al., (2019)	Sequential	Peer	Traditional means	SSM
Vosniakos et al., (2019)	Supportive	Peer	Traditional means	SMS+HG+SSM+PFL
Casalino et al., (2018)	Simultaneous	Peer	N/A	N/A
Gopinath et al., (2017)	Supportive	Peer	N/A	SMS+HG
Cherubini et al., (2016)	Supportive	Peer	N/A	SMS+SSM+PFL
Müller et al., (2016)	Simultaneous	Peer	Traditional means	SSM+PFL
Thomas et al., (2016)	Sequential	Supervisor	Haptics	HG+PFL
Fast-Berglund et al., (2016)	Supportive	Peer	N/A	N/A
Fujii et al., (2016)	Supportive	Peer	Traditional means	SMS+HG+SSM+PFL
Ore et al., (2020)	Supportive	Peer	Haptics	HG+PFL
Land et al., (2020)	Supportive	Peer	Haptics	HG
Andronas et al., (2020)	Independent	Peer	Traditional means	SMS+SSM
Andronas et al., (2020)	Sequential	Peer	Traditional means	SMS+HG+SSM+PFL
Andronas et al., (2020)	Supportive	Peer	Traditional means	SMS+HG+SSM+PFL
Rückert et al., (2020)	Supportive	Peer	Haptics	HG
Weßkamp et al., (2019)	Sequential	Peer	N/A	SSM
Berg et al., (2019a)	Sequential	Peer	N/A	SMS+SSM
Berg et al., (2019b)	Supportive	Peer	Body gestures	SMS
Berg et al., (2019b)	Supportive	Peer	Facial tracking	SMS
Li et al., (2019)	Sequential	Peer	N/A	SMS+SSM
Costa Mateus et al., (2018)	Sequential	Peer	N/A	N/A
Aaltonen et al., (2018)	Sequential	Peer	Traditional means	SMS+SSM
Haage et al., (2017)	Independent	Supervisor	Haptics	PFL
Thomas et al., (2016)	Simultaneous	Supervisor	Traditional means	SMS+SSM
Liu et al., (2020)	Supportive	Supervisor	Haptics	HG
Bae et al., (2020)	Supportive	Peer	Haptics	SMS+HG+SSM+PFL
El Makrini et al., (2019)	Sequential	Peer	N/A	PFL
Hietanen et al., (2020)	Supportive	Peer	Haptics	HG+SSM+PFL
Huang et al., (2019)	Supportive	Peer	Traditional means	SMS+PFL
Malik & Bilberg, (2019)	Simultaneous	Peer	N/A	N/A
Raessa et al., (2020)	Supportive	Peer	Traditional means	SMS+PFL
Peternel et al., (2019)	Supportive	Peer	N/A	SMS
Peternel et al., (2019)	Supportive	Peer	N/A	SMS
Ionescu & Schlund, (2019)	Supportive	Peer	Traditional means	HG
Rahman & Wang, (2018)	Simultaneous	Peer	N/A	SMS+SSM
Aaltonen et al., (2018)	Independent	Peer	N/A	SMS+SSM
Matthaiakis et al., (2017)	Independent	Supervisor	Traditional means	SMS
Tsarouchi et al., (2016a)	Sequential	Supervisor	N/A	SMS
Tsarouchi et al., (2016b)	Supportive	Peer	Body gestures	SMS

*Safety-Rated Monitored Stop (SMS), Hand-Guiding (HG), Speed&Separation Monitoring (SSM), Power&Force Limiting (PFL)

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