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A conceptual framework to evaluate Human-Robot collaboration

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Abstract Human-Robot Collaboration (HRC) is a form of direct interaction between humans and robots. The objective of this type of interaction is to perform a task by combining the skills of both humans and robots. HRC is characterized by several aspects, related both to robots and humans. Many works have focused on the study of specific aspects related to HRC, e.g. safety, task organization, etc. However, a major issue is to find a general framework to evaluate the collaboration between humans and robots considering all the aspects of the interaction. The goals of this paper are the following: (i) highlighting the different latent dimensions that characterize the HRC problem; (ii) constructing a conceptual framework to evaluate and compare different HRC configuration profiles. The description of the methodology is supported by some practical examples.

Keywords Human-Robot Collaboration · HRC dimensions · Collaborative robots · HRC framework

1 Introduction

Human-Robot Collaboration (HRC) is a form of direct interaction between humans and robots, principally aimed at achieving a common goal. The main idea of HRC is to combine the abilities of the human with those of robots. On the one hand, humans have innate flexibility, intelligence and problem solving abilities, on the other hand, robots provide precision, power and repeatability [43]. Collaborative robots are particular robots designed specifically to work safely alongside people or to assist them during certain tasks (Figure 1). This kind of robots can be employed in various contexts such as industrial plants, homes, and hospitals.

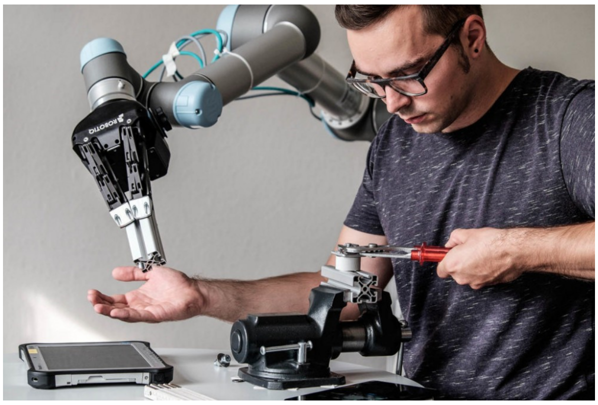

Fig. 1 A collaborative robot assisting an operator in an assembly task[77]

HRC is one of the fundamental cornerstones of Industry 4.0, which is characterized by smart and autonomous systems fueled by data and machine learning. Unlike classical industrial robots, collaborative robots allow humans to work alongside them and, as a result, the removal of confinement barriers in factories. Therefore, the implementation of HRC in the manufacturing sector allows to create a dynamic and flexible environment, where production lines may change and adapt quickly to new products. Some examples of industrial collaborative robots are UR5e (Figure 2(a)), LBR iiwa

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(Figure 2(b)), Sawyer (Figure 2(c)), and YuMi (Figure 2(d)).

For an effective comprehension and implementation of HRC it is necessary to study and analyze its various aspects. To this end, the use of multidimensional scales is a well-established approach for understanding complex phenomena characterized by multiple aspects [21, 52]. The creation of a "collaboration scale" allows a team of experts to evaluate and compare different solutions related to the implementation of collaborative robots [32]. A collaboration scale can also be a useful tool for finding solutions that optimize certain parameters of a process, such as efficiency or effectiveness. The main challenge in creating such a tool is to bring together different disciplines, such as engineering and social sciences, in the evaluation of HRC.

To this end, the main goal of this work is providing, through a top-down approach, a conceptual HRC framework which a team of experts can use to analyze and evaluate the collaboration between humans and robots, with particular attention to the manufacturing sector. The main novel elements of the proposed conceptual HRC framework are the following: (i) bringing together different HRC aspects from different disciplines; (ii) presenting an organic and structured set of evaluation methods for a comprehensive HRC evaluation; (iii) allowing to compare different HRC applications considering the various HRC aspects; (iv) allowing to evaluate HRC tasks also in application fields other than manufacturing.

The paper is organized as follows. In Section 2, a literature review on HRC is presented, also examining the concept of *collaboration*. The dimensions that characterize HRC are described and analyzed in Section 4, providing also some preliminary evaluation metrics. In Section 5, some HRC applications are described, showing an example of evaluation framework. Discussion and observations on the obtained results are reported in Section 6. Finally, Section 7 covers conclusions and future work.

2 Literature review

2.1 Meaning of "collaboration"

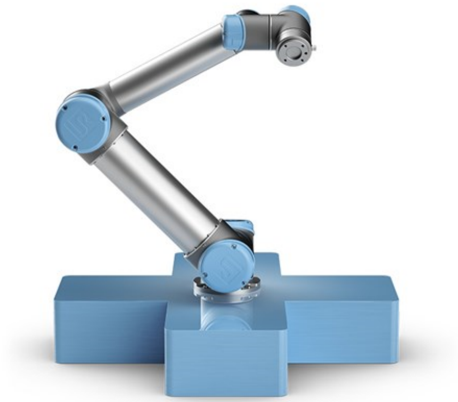
The first step in understanding HRC is to reflect on the meaning of the term *collaboration*. The term *collaboration* has received several definitions over time. Although the terms *cooperation* and *collaboration* sometimes are used as synonyms in the literature, it is important to note that they can have different meanings. Kozar [44] has highlighted the difference between these two terms by reporting the definitions given by different authors. According to Smith [71], cooperation can be defined as "working together to accomplish shared goals", while McInnerney and Robert [55] describe collaboration as "working in a group of two or more to achieve a common goal, while respecting each individual's contribution to the whole". Rochelle and Teasley [64] define a cooperative work as a task that is accomplished by dividing it among participants, where "each person is responsible for a portion of the problem", and collaborative work as "the mutual engagement of participants in a coordinated effort to solve the problem together". From these definitions it can be observed that cooperation is more focused on working together to create a final product, and can be achieved even if all participants do their assigned parts separately and bring their results to the table. However, collaboration also requires to share knowledge, implying direct interaction among participants by negotiations, discussions and accommodating other's perspectives [44]. Thus, compared to cooperation, collaboration is a more complex form of interaction and requires the fulfilment of additional conditions in order to be achieved.

2.2 Human-Robot Interaction and HRC

Human-Robot Interaction (HRI) is a field of study dedicated to understanding, designing, and evaluating robotic systems to be used by or with humans [34]. HRI addresses problems related to different ways of interacting with robots and their application. Over the years, robots have been employed in various domains, such as manufacturing [59], healthcare [60], and space [12]. Depending on the need for human intervention, different types of interaction can be established [84]. For example, in teleoperation the robot constantly needs to be guided by a human. On the other hand, fully-automated robots, such as industrial robots, may not involve human intervention during their operations.

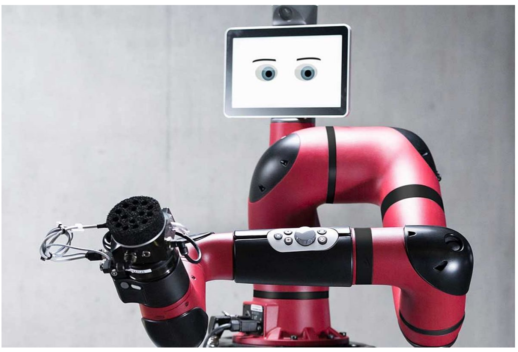
HRC shares many aspects with HRI and can be considered a sub-field of HRI [83]. HRC is related to the implementation of collaborative robots, which are particular robots designed to share space and tasks with people. One of the main challenges of HRC is to create robots that allow a safe coexistence and a natural interaction with humans [9]. This implies that collaborative robots need to have at least a minimum form of autonomy, and possibly show initiative.

The concept of collaborative robot was introduced for the first time in 1996 by Colgate *et al.* [23]. In this work, a *collaborative robot*, also called *cobot*, was defined as a robotic device which manipulates objects in collaboration with a human operator. In particular, the collaboration was interpreted as a form of assistance,



(a) UR5e from Universal Robots[77].

(b) LBR iiwa from KUKA[49].



(c) Sawyer from Rethink Robotics[63].

(d) YuMi from ABB[1].

Fig. 2 Examples of industrial collaborative robots.

by guiding and constraining some movements of the human in certain operations.

According to the standard ISO/TS 15066 [43], a collaborative robot is "a robot intended to physically interact with humans in a shared workspace". This is in contrast, for instance, with classical industrial robots, designed to operate autonomously and in separate spaces. Cobots can have many roles, from autonomous robots capable of working together with humans in an office environment that can ask you for help, to industrial robots having their protective guards removed. The aim of these robots is to support and relieve humans through conjoint work [46].

The implementation of HRC introduces several issues related mainly to safety, communication, task organization, social-related aspects, and psychological aspects [9,37]. From the safety point of view, working close to robots, without barriers, may introduce new risks for humans. Previous works proposed different methods for detecting the position of humans and robots to avoid collisions, allowing a safe co-existence [81]. Some of the most common methods include continuous 3D image processing [47] or acquiring data via inertial motion capture suits [24]. In recent years, health and safety regulations have been updated with the introduction of ISO 10218-2 [38] and ISO/TS 15066 [43], allowing the implementation of HRC also in an industrial setting. Several research works focused on how to perform task with the robots and how to instruct them. HRC has been explored in different tasks, such as pick&place[3, 45], assembly[59], transportation[65], 3D printing[7] etc.

Many works also focused on different social and psychological aspects related to HRC. For instance, Sauppè and Mutlu [66] studied the impact of a collaborative robot in the industrial field by interviewing operators that worked together with it for several months. Other research works focused on studying the trust of humans in collaborative robots [21,56], by analyzing the influencing aspects. Tan *et al.* [74] studied the mental strain due to the interaction with a robot both from a physiological and psychological point of view.

Since many different aspects characterize HRC, the contribution from different disciplines is fundamental to understand and design a complete HRC framework.

3 Methodology

The conceptual HRC framework has been built using a "top-down" approach. This heuristic method consists in starting from the general definition of a problem and gradually subdividing it into sub-problems[32, 50]. This approach allows to have a broad view of a problem and to identify its characterizing aspects. For these reasons, this methodology was chosen in order to create a conceptual framework able to provide a wide and complete vision on the HRC phenomenon and applicable in various contexts.

Starting from the concept and objectives of HRC, the latent dimensions of the conceptual framework have been identified. The identification of the HRC latent dimensions has been based on the following steps: 1) an extensive literature review on HRC problem; 2) focus groups with experts on the subject. Each latent dimension is characterized by different sub-dimensions, and for each sub-dimension an evaluation scale has been proposed. The proposed scales were mainly derived from existing methods, or created, where necessary, on the basis of information in the literature.

4 Conceptual HRC framework and HRC latent dimensions

In this section, the latent dimensions and sub-dimensions of the conceptual HRC framework will be presented. Table 1 contains the identified latent dimensions and references for each sub-dimension.

Goodrich and Schultz[34] presented a survey on HRI, where the HRI problem was analyzed and decomposed into the following aspects that a designer can shape: Autonomy, Information Exchange, Adaptivity and Training, Team Organization, Task. Since HRI is a more general research field that includes HRC, these aspects can be adapted to the HRC problem[83]. Other potential dimensions of HRC have emerged from the literature and focus groups, namely Human Factors, Ethics and Cybersecurity.

HRC latent dimensions will be discussed and analyzed in the next sections, highlighting their relevance in the representation of the HRC phenomenon. Moreover, for each sub-dimension, an evaluation scale will be proposed and described.

4.1 Autonomy

Autonomy is a concept that indicates self-sufficiency, i.e. the capability of an entity to take care of itself. The term also denotes the quality of self-directedness, or freedom from outside control [13]. The concept of autonomy has acquired different meanings in different fields [10]. In automation, autonomy is viewed as the extend to which a system can perform a task without human intervention. In this field, different taxonomies and categorization schemes related to levels of automation have been proposed [70, 30]. In the HRI, there are mainly two schools of thought on the concept of autonomy [10]. The first one is inspired by the concept of autonomy developed in automation, proposing that greater autonomy of the robot requires less frequent interactions with humans [36, 84]. This viewpoint is opposed to the other school of thought, which claims that higher robot autonomy enables more advanced and complex interactions [34, 75]. This last point of view is the one that best fits the context of HRC, where the continuous interaction between human and robot has a fundamental role. Autonomy of a robot should be considered in terms of its capabilities of sensing the surroundings, planning and acting according to the environment and other entities. In human-human collaboration, the entities involved (i.e. humans) have a high level of autonomy, allowing complex interactions and potentially high levels of collaboration to be achieved, while not excluding any entities during the task. Similarly, in HRC, a high level of robot autonomy should not imply the exclusion of the human, but allow for a deeper and richer interaction, leading to higher levels of collaboration. Based on this idea, Beer *et al.* [10] proposed the following definition of robot autonomy: "the extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal (either given to or created by the robot) without external control".

The evaluation of the *Autonomy* can be based on the taxonomy of Levels Of Robot Autonomy (LORA) proposed by Beer *et al.* [10]. In this model, levels of autonomy are conceptualized through descriptions and established based on the robot's abilities to sense, plan, and act with respect to a task and context. In Table 2 the autonomy scale based on LORA taxonomy is reported. Despite the level "Manual" represents a situation where no robot is involved during a task, it has been taken into account for a complete taxonomy continuum.

Table 1 Summary of the HRC latent dimensions and their sub-dimensions.

Latent dimension	Sub-dimension	References
Autonomy	-	Beer *et al.*, 2014[10]; Bradshaw *et al.*, 2004 [13]; [30]; Goodrich and Schultz, 2007 [34]; Huang *et al.*, 2004 [36]; Sheridan and Verplank, 1978 [70]; Thrun 2004[75]; Yanco and Drury, 2004 [84].
Information Exchange	Communication medium Communication format	Eimontaite *et al.*, 2019 [29]; Goodrich and Schultz, 2007 [34]; Maurtua *et al.*, 2017 [54]; Neto *et al.*, 2019 [57]; Papanastasiou *et al.*, 2019 [59]; Wang, 2019 [82].
Team Organization	Team structure Members role	Goodrich and Schultz, 2007 [34]; Scholtz, 2003 [69]; Yanco and Drury, 2004 [84].
Adaptivity and Training	Robot adaptivity Robot training method Operator training	Argall *et al.*, 2009 [5]; Astrom and Wittenmark, 1994 [6]; Biggs and MacDonald, 2003 [11]; Goodrich and Schultz, 2007 [34]; Krüger *et al.*, 2017 [48]; Raibulet, 2008 [62]; Rozo *et al.*, 2016 [65]; Tsarouchi *et al.*, 2016 [76]; Wang and Zhang, 2017 [83].
Task	Field of application Task organization Performance Safety	Bruno and Antonelli, 2018 [16]; BS 4778-3.1:1991 [17]; De Santis *et al.*, 2008 [26]; Goodrich and Schultz, 2007 [34]; ISO/TS 15066:2016 [43]; ISO 10218-2:2011 [38]; ISO 12100:2010 [39]; ISO/TR 14121-2:2012 [42]; Mateus *et al.*, 2019 [53]; Rozo *et al.*, 2016 [65]; Stanton, 2006 [73]; Tsarouchi *et al.*, 2016 [76]; Wang and Zhang, 2017 [83].
Human factors	Workload Trust Robot morphology Physical ergonomics Usability	Arai *et al.*, 2010 [4]; Bangor *et al.*, 2008 [8]; Brooke, 1996 [15]; Campana and Quaresma, 2017 [19]; Charalambous *et al.*, 2016 [21]; Eimontaite *et al.*, 2019 [29]; Hart and Staveland, 1988 [35]; ISO 26800:2011 [40]; ISO 9241-11:2018 [41]; Lindblom and Wang, 2018 [51]; Sauppè and Mutlu, 2015 [66]; Schaub *et al.*, 2013 [67]; Schmidtler, 2016 [68]; Tan *et al.*, 2009 [74]; Yanco and Drury, 2004 [84].
Ethics	Social impact Social acceptance	Bröhl *et al.*, 2016 [14]; BS 8611:2011 [18]; Charalambous *et al.*, 2015 [20]; Charalambous *et al.*, 2017 [22]; Davis, 1989 [25]; Venkatesh and Bala, 2008 [78]; Venkatesh and Davis, 2000 [79]; Veruggio, 2006 [80].
Cybersecurity	Identification Protection Detection Response Recovery	Dedeke, 2017 [27]; NIST, 2018 [58]; Priyadarshini, 2018 [61].

4.2 Information Exchange

Information Exchange represents the manner in which information is exchanged between the human and the robot. Communication is the basis of any type of interaction between entities and is used to transmit information, give commands, and make known their own status [34]. Voice and gestures are key channels that humans use to naturally communicate between them. Analogously, these channels can be important to achieve a natural communication between humans and robots [54, 29]. According to Goodrich and Schulz [34], *Information Exchange* can be characterized by *Communication medium* and *Communication format* (see Table 3).

4.2.1 Communication medium

Communication medium refers to the senses involved in the communication. In particular, there are three main possible senses involved: sight (vision), hearing (audition), and touch (somatosensation). Sight and hearing are the senses most involved in communication between people, while touch may represent an immediate way of exchange information. The evaluation of this dimension can be performed with the four-level scale reported in Table 3.

4.2.2 Communication format

Communication format refers to the means and ways in which communication takes place between humans and the robot system. There exist different devices that allow to exchange information between humans and robots. The technologies mostly implemented in HRC communication include displays, cameras, virtual reality, augmented reality, speakers, microphones etc. [34, 82, 57, 59]. The evaluation of this sub-dimension can be performed using the four-level scale proposed in Table 3.

4.3 Team Organization

Team Organization takes into account the organization of the agents involved in the collaboration. A collaborative task can involve multiple robots and people at the same time. It is important to take into account the balance between the number of robots and people in a team, as well as to analyze the roles of each member [34]. The *Team Organization* can be characterized by the following sub-dimensions: *Structure of the team* and *Role of members* (Table 4).

4.3.1 Structure of the team

Structure of the team refers to the composition of the team, i.e. number of humans and robots involved. Major problems are to understand how many robots a single human can manage or, conversely, how many humans a robot team needs to be managed. These kinds of problems highly depend on the context, the collaborative task and the robot's capabilities [34]. The evaluation may consist in listing the number of humans and robots involved in the collaboration, as reported in Table 4.

4.3.2 Role of members

Role of members refers to the role of each team member. Humans and robots can contribute to the same task in different ways according to the task. The description of the role of humans and robots involved in the collaboration can help to better understand the context. In the HRI context, Scholtz [69] provided a taxonomy with five different interaction roles that a human may have: supervisor, operator, teammate, mechanic, and bystander. Although this classification is suitable for representing human role, it is not particularly suitable for representing robot role. A scale containing the main roles potentially played by an entity (human or robot) is proposed in Table 4.

4.4 Adaptivity and Training

Adaptivity and Training latent dimension concerns robot adaptivity and instruction as well as human training. Training the robot system to perform various tasks is a key aspect of the HRC problem. There is a variety of ways to train a robot, from the most traditional, such as offline programming, to the most innovative, such as programming by demonstration (PbD) [76]. In addition to training the robot, it is often important to take into account the training of operators who have to interact with the robotic system [34]. Adaptivity is another key aspect that allows the robot to change its behaviour according to various situations. The implementation of adaptivity allows the robot to tackle unpredicted situations and accomodate to other entities, while potentially learning from experience. The sub-dimensions that characterize the *Adaptivity and Training* dimension are: *Robot adaptivity*, *Robot training method*, and *Operator training* (Table 5).

4.4.1 Robot adaptivity

Robot adaptivity represents the ability to accomplish a given task despite unexpected situations. The ability to

Table 2 Levels of Autonomy based on LORA taxonomy of Beer *et al.* [10].

LORA	Sense	Plan	Act	Description of the level
L0 - Manual	H	H	H	The human performs all aspects of the task including sensing the environment, generating plans/options/goals, and implementing processes.
L1 - Teleoperation	H	H	H	The robot assists the human with action implementation. However, sensing and planning is allocated to the human. For example, a human may teleoperate a robot, but the human may choose to prompt the robot to assist with some aspects of a task (e.g., gripping objects).
L2 - Assisted Teleoperation	H/R	H	H/R	The robot assists the human with action implementation. However, sensing and planning is allocated to the human. For example, a human may teleoperate a robot, but the human may choose to prompt the robot to assist with some aspects of a task (e.g., gripping objects).
L3 - Batch Processing	H/R	H	H/R	Both the human and robot monitor and sense the environment. The human, however, determines the goals and plans of the task. The robot then implements the task.
L4 - Decision Support	H/R	H/R	R	Both the human and robot sense the environment and generate a task plan. However, the human chooses the task plan and commands the robot to implement actions.
L5 - Shared Control With Human Initiative	H/R	H/R	R	The robot autonomously senses the environment, develops plans and goals, and implements actions. However, the human monitors the robot's progress and may intervene and influence the robot with new goals and plans if the robot is having difficulty.
L6 - Shared Control With Robot Initiative	H/R	H/R	R	The robot performs all aspects of the task (sense, plan, act). If the robot encounters difficulty, it can prompt the human for assistance in setting new goals and plans.
L7 - Executive Control	R	H/R	R	The human may give an abstract high-level goal (e.g., navigate in environment to a specified location). The robot autonomously senses environment, sets the plan, and implements action.
L8 - Supervisory Control	H/R	R	R	The robot performs all aspects of task, but the human continuously monitors the robot, environment, and task. The human has override capability and may set a new goal and plan. In this case, the autonomy would shift to executive control, shared control, or decision support.
L9 - Full Autonomy	R	R	R	The robot performs all aspects of a task autonomously without human intervention with sensing, planning, or implementing action.

adapt one's actions to a certain situation is essential to achieve a high level of collaboration. In the context of control engineering, adaptivity is implemented to address unexpected situations due to internal or external changes in order to ensure an optimal operation of a system [6]. In the field of robotics, adaptivity refers to the dynamic behaviour in response to situations and/or environmental changes [62]. By monitoring the environment and their current state, adaptive robot systems are able to reflect on collected information and change their behaviour. In HRI, especially in the social field, adapting behaviour to human characteristics and context is another key aspect [2]. It is worth noting that there is a difference between the terms *adaptability* and *adaptivity*, although they are sometimes used as synonyms in the literature [48]. *Adaptability* refers to the quality of being adaptable, i.e. the possibility of changing some parameters by the intervention of external entities (e.g. an office chair, in which it is possible to adjust the height and the inclination by the intervention of a human). *Adaptivity*, instead, indicates the quality of being adaptive, the ability to adapt autonomously, i.e. changing one's own parameters without the intervention of external entities. Thus, adaptivity can be seen as a deeper and more complex quality compared to adaptability. For the evaluation of the *Robot adaptivity*, a four-level scale based on the work of Krüger *et al.* [48] is proposed in Table 5.

Table 3 Summary of Information Exchange sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Communication medium	**L0**	No senses are involved in the communication. (i.e. communication with the robot is not possible).
	L1	At least a sense between sigh, hearing, and touch is involved in the communication.
	L2	At least two senses between sigh, hearing, and touch are involved in the communication.
	L3	Sight, hearing, and touch are all involved in the communication.
Communication format	**L0**	No means of communication between humans and robot.
	L1	Information is exchanged only through a control panel and/or displays.
	L2	At least a human-natural way of communication is implemented (e.g. gestures, natural language, gaze) (control panels and displays may still be implemented).
	L3	At least two human-natural ways of communication are implemented (control panels and displays may still be implemented).

Table 4 Summary of Team Organization sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Team structure	-	List of robots and humans involved.
Members role	**L0**	Executor. The entity just executes given instructions.
	L1	Assistant. The entity is able to give suggestions to other entities while also providing support during some operations; it is not able to take final decisions.
	L2	Master. The entity is able to give orders to other entities and take definitive decisions.

4.4.2 Robot training method

Robot training method refers to the methods for instructing the robot to perform a certain task. Robot programming methods can be mainly distinguished in two categories: manual programming and automatic programming [11]. Manual programming is a method that requires the user to implement actions to be performed by the robot by hand using text-based or graphical programming languages. Manual programming systems are typically offline-programming systems, since the robot is not necessary during the creation of a robot program. This method allows to avoid interfering with any other tasks that the robot normally performs. In particular, in manufacturing, this method allows to not interrupt production and to robotize short-run production. However, a disadvantage of manual programming systems is the need for technical skills to be used, which makes them unsuitable for users not experienced in programming. On the other hand, automatic programming allows to create indirectly a robot program using various information that is provided. With this method the user does not interact with the program code, but mainly with the robot, allowing even people with minimal technical skills to perform robot training. Most of the automatic programming systems are online-programming systems, since the robot is often required during the training phase. Although automatic programming systems are typically more intuitive, the robot's downtime can be considerably higher. The most common method of automatic programming is Programming (or learning) by Demonstration (PbD). This method allows to instruct the robot by showing the sequence of operations it will have to reproduce. A traditional PbD system, implemented especially in industrial manipulators, is the teach-pendant. This technique allows the state of the robot to be recorded as the operator guides it, physically or using a controller, through the various operations of the task. The recorded states are then used to generate the robot program. There exist also more sophisticated and intuitive PbD techniques based on natural communication [11, 5]. These techniques allow the user to provide demonstrations to the robot via natural communication modalities (e.g. gestures, vision, voice, touch). Implementing these communication modalities can make training more intuitive, as they are based on those typically used by humans to give instructions. The evaluation of *Robot training method* sub-dimension can be carried out through the three-level scale reported in Table 5.

4.4.3 Operator training

Operator training indicates the effort in training the operators involved in a collaborative task. Understanding how to interact with the robot and interpret the information it provides is essential for optimal collaboration. The effort required in training the operator may vary significantly, depending on the type of collaborative robot, the communication interface and the task [34]. The effort can be evaluated, for instance, considering the time required to teach the operators how

Table 5 Summary of Adaptivity and Training sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Robot adaptivity [48]	**L0**	The robot has no form of adaptivity, it just executes the prefixed operations in a given task.
	L1	The robot has an underling model for its actions that produces flexible reactive behaviors, but the model itself is not flexible (e.g. a cleaning robot that bumps into walls to understand the presence of an obstacle and change path).
	L2	The robot shows adaptivity. The robot has the ability to change its own parameters according to environmental stimuli to fulfill a task. Thus, it has the ability to learn from experience (e.g. a cleaning robot that remembers the position of the obstacles in an environment it has already explored and adjusts the cleaning path consequently).
	L3	The robot shows adaptivity with respect to the human. In particular, the robot has the ability to model the behavior of another agent in relation to a goal as well as its own actions and abilities (*goal-oriented adaptivity*) (e.g. a cleaning robot that decides which rooms to clean according to human habits or according to which rooms have not yet been cleaned by someone else).
Robot training method	**L0**	Only manual programming methods are implemented.
	L1	Automatic programming methods are implemented.
	L2	Automatic programming methods based on natural communication (e.g. voice, gestures, touch, vision) are implemented.
Operator training	**L0**	Very heavy. Learning how to work efficiently with the robot requires time and is not intuitive.
	L1	Heavy. Learning how to work efficiently with the robot requires time and special attention on some operations.
	L2	Medium. Learning how to work efficiently with the robot is quite fast, but may require special attention on some operations.
	L3	Light. Learning how to work efficiently with the robot is fast and intuitive.

to perform the collaborative task, or the complexity of the required actions. The four-level scale proposed in Table 5 represents a way to evaluate this sub-dimension and follows the well-being of humans.

4.5 Task

Task dimension contains information on the task to be performed. The introduction of a robotic system changes the way a task is performed and, at the same time, new issues and hazards emerge [34, 76]. A careful organization of the task is necessary to ensure certain levels of performance and safety [53]. The *Task* dimension can be characterized by the following sub-dimensions: *Field of application*, *Task organization*, *Performance*, and *Safety* (Table 6).

4.5.1 Field of application

Field of application refers to the field in which the task takes place. The application field deeply influences the risks and goals involved in a collaborative task. Therefore, the description of the application context (e.g. Industry, Healthcare, Education) is necessary to identify requirements.

4.5.2 Task organization

Task organization refers to the assignation of individual operations to each team member. The task organization has a fundamental role, since it highly influences other aspects, such as performances or workload [53]. Operations should be assigned by trying to focus on the strengths of the entities involved and maintaining an adequate workload for each of them [16].

4.5.3 Performance

Performance refers to the evaluation of the outcome of the collaborative task. According to the application field, the outcome and its evaluation may vary. For instance, in manufacturing, efficiency and effectiveness are typical indicators considered in the evaluation of a product process. Efficiency refers to the required effort or resources to produce a specific outcome. A method to evaluate this aspect could be considering the number of products produced per minute. Effectiveness refers to the capability of producing a desired result. A method to evaluate this aspect could be the number of defective pieces over 100 produced (defectiveness percentage). Depending on the requirements of the collaboration outcome, the four-level scale proposed in Table 6 can be adapted to evaluate the performance.

Table 6 Summary of Task sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Field of application	-	Description of the application context.
Task organization	-	List of the operations.
Performance	**L0**	Low. The collaboration outcome is not acceptable (e.g. the process is too slow).
	L1	Medium. The collaboration outcome is almost not acceptable.
	L2	High. The collaboration outcome is acceptable, but not completely satisfactory.
	L3	Very high. The collaboration outcome is acceptable and satisfactory.
Safety [38,42]	**L0**	Low. Risk score >75% of maximum score.
	L1	Medium. Risk score between 50% and 75% of the maximum score.
	L2	High. Risk score between 25% and 50% of the maximum score.
	L3	Very high. Risk score <25% of the maximum score.

4.5.4 Safety

Safety concerns the identification of the risks and hazards involved in the task and the related safety measures implemented. In addition to the risks due to the task itself (e.g. welding), the physical interaction with a robot introduces new risks in a working space, mainly related to collisions [26]. The power and speed of the robots should be adjusted in such a way that they do not cause injury to people in the event of contact. In order to evaluate the safety dimension in a HRC task, a structured risk assessment can be taken offline during the initial design stages. A top-down approach can be used, based on a list of significant hazards for robot systems provided by ISO 10218-2 Annex A [38]. The list proposed by the standard takes into account different kind of hazards, such as mechanical, electrical, thermal, noise, vibration, radiation, material, and environmental hazards. The two main elements of the risk assessment that can be considered are the *severity of harm* and the *probability of occurrence of harm* [39,17]. For each hazard or hazardous situation, the severity of harm can be assessed according to the following 4-levels scale:

– L0: Minor. No injury or slight injury requiring no more than first aid (little or no lost work time).
– L1: Moderate. Significant injury or illness requiring more than first aid (able to return to same job).
– L2: Serious. Severe debilitating injury or illness (able to return to work at some point).
– L3: Catastrophic. Death or permanent disabling injury or illness (unable to return to work).

The probability of occurrence can be assessed according to the following 4-levels scale:

– L0: Remote. It is very unlikely to occur.
– L1: Unlikely. It is not likely to occur.
– L2: Likely. It can occur.
– L3: Very likely. It is almost certain to occur.

Once the severity and probability are estimated, a risk level for a harm can be derived from a risk matrix. The risk matrix assigns a risk level based on the combination of the levels of severity and probability of occurrence of the harm. A risk matrix which can be used for the assessment is the one proposed by ISO/TR 14121-2 [42], which is shown in Table 7. Each level is associated with a numeric risk indicator, on an ordinal scale from 0 to 3, where 1 indicates “low risk”, while 3 “high risk”. The value 0 is assigned when the risk is negligible. A summary risk score is obtained by summing up the risk levels of all hazards. According to the risk score obtained, Safety can be evaluated using the four-level scale proposed in Table 6, which follows the well-being of humans.

4.6 Human factors

Human Factors (or ergonomics) is defined by ISO 26800 as the ”scientific discipline concerned with the understanding of interactions among human and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance” [40]. In order to achieve an optimal level of collaboration, it is essential to take into account the psycho-physical state of the human involved in operations with the robot. The interaction of the human with his surroundings causes also psychological reactions. The introduction of new technologies, such as collaborative robots, in various context has an impact on the people involved [20]. Emotions and cognitive processes can influence the success of the collaboration and, consequently, the performance of the task [74]. Minimizing the stresses arising from the workplace or the interaction with the robot is necessary to make collaboration more effective [66,56,29]. *Human factors* dimension can be characterized by the following sub-dimensions: *Workload*, *Trust*, *Robot morphology*, *Physical ergonomics*, and *Usability* (Table 8).

Table 7 Risk matrix proposed in ISO/TR 14121-2 [42].

	Severity of harm			
Probability of occurrence	Catastrophic	Serious	Moderate	Minor
Very likely	High (3)	High (3)	High (3)	Medium (2)
Likely	High (3)	High (3)	Medium (2)	Low (1)
Unlikely	Medium (2)	Medium (2)	Low (1)	Negligible (0)
Remote	Low (1)	Low (1)	Negligible (0)	Negligible (0)

Table 8 Summary of Human Factors sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Workload [35]	**L0**	Very high. Workload score >55.
	L1	High. Workload score between 41 and 55.
	L2	Medium. Workload score between 26 and 40.
	L3	Low. Workload score <26.
Trust [21]	**L0**	Low. Trust score <20.
	L1	Medium. Trust score between 20 and 29.
	L2	High. Trust score between 30 and 39.
	L3	Very high. Trust score >39.
Robot morphology [84]	-	Description of robot morphology: anthropomorphic, zoomorphic, or functional.
Physical ergonomics [31, 67]	**L0**	Red (>50 points). High risk - to be avoided; action to lower the risk is necessary.
	L1	Yellow (26-50 points). Possible risk - not recommended; redesign if possible, otherwise take other measures to control the risk.
	L2	Green (0-25 points). No risk or low risk - recommended; no action is needed.
Usability [8, 15]	**L0**	Not acceptable. SUS score <51.
	L1	Marginal. SUS score between 51 and 70.
	L2	Acceptable. SUS score >70.

4.6.1 Workload

Workload refers to the effort of the human operators during a task. Depending on the operations to be performed in a task, the operator may accumulate fatigue resulting mainly from mental or physical efforts. Mental effort includes aspects such as *mental strain*, which is the nervousness (i.e. a state of excitability, with great mental and physical unrest) resulting from mental stresses, due to cognitive aspects or external factors [4]. To evaluate this dimension, the NASA-TLX can be used [35]. This tool consists in a questionnaire with six items to evaluate: Mental demand, Physical demand, Temporal demand, Effort, Frustration and Performance. Each of these items is evaluated on a scale between 0 and 100, with an interval of 5. To obtain a final score that represent the level of workload, a weighted mean of these values is performed. The weight of each dimension is obtained through a process of pair-wise comparison of importance operated by the evaluator. This operation allows to capture the importance of each dimension on the workload depending on the task, avoiding a priori assumptions. Moreover, it also allows to capture the importance that each subject assigns to each dimension, as the perceived importance for each of them may vary depending on individuals. The maximum final score that can be achieved is 100, and the closer the final score is to this value, the greater the operator's workload. The scale reported in Table 8 follows the well-being of humans and can be used to interpret the workload score.

4.6.2 Trust

Trust is the attitude that an agent will help to achieve an individual's goals in a situation characterized by uncertainty and vulnerability [21]. Trust is a key aspect for optimal collaboration: if people do not believe in the collaborative capabilities of a robot, they may underutilize it, leading to possible drops in performance in certain tasks, or even not use it. Therefore, it is important to maintain appropriate levels of trust. The evaluation can be performed through a trust questionnaire proposed by Charalambous *et al.* [21]. The questionnaire is composed of ten items, and each item is evaluated on a 5-points Likert scale. The sum of the points returns a score that indicates the level of trust, with a maximum score of 50. The scale proposed in Table 8 follows the well-being of humans and can be used to interpret the trust score.

4.6.3 Robot morphology

Robot morphology refers to the evaluation of the morphology and design of the collaborative robot. Depending on the context or the task, some types of design may be more appropriate, encouraging a greater propensity to collaborate or inspiring greater trust. For example, a

Table 9 Structure of EAWS.

Macro-Section	Section
Whole body	0 - Extra Points 1 - Body Postures 2 - Action forces 3 - Manual materials handling
Upper limbs	4 - Upper limb load in repetitive tasks

too big robot may discourage a human to collaborate, while a robot with drawn eyes may help the operator to feel more comfortable [66]. The morphological aspect of a robot is important as it also helps to establish expectations in people. Yanco and Drury [84] distinguished between three morphology types: anthropomorphic (the robot has a human-like appearance), zoomorphic (the robot has an animal-like appearance), and functional (the robot has an appearance that is neither human-like nor animal-like, but is related to its function).

4.6.4 Physical ergonomics

Physical ergonomics addresses the anatomical, anthropometric, physiological and biomechanical characteristics of humans in relation to physical activity. In this sub-dimension, postures, materials handling, force applications, and repetitive movements required by the collaborative task are analyzed. A tool that can help in the evaluation of physical ergonomics is the "Ergonomic Assessment Work-Sheet" (EAWS) [31,67]. This tool is widely used in the manufacturing sector and has been developed under the coordination of the International MTM Directorate, based on international and national standards and pre-existing assessment methods [67]. EAWS is composed of five sections (Extra Points, Body Postures, Action forces, Manual materials handling, and Upper limb load in repetitive tasks) divided among two macro-sections (Whole body, and Upper limbs), as shown in Table 9. For more details on EAWS structure, see Appendix A. Through checklists representing various situations, scores are generated for each section. Next, the macro-sections scores are obtained by adding up the scores of their respective sections. The final score is derived by taking the maximum value between the scores of the two macro-sections. Lastly, the final score is interpreted using a traffic light scale that represents the levels of ergonomic risk [67]. The scale is reported in Table 8.

4.6.5 Usability

Usability sub-dimension represents the evaluation and design of the interaction between human and robot that is supposed to take place. According to ISO 9241-11:2018, usability is defined as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [41]. In HRC, taking into account the operator experience is essential for an optimal interaction design and to enhance collaboration with robots [19,51]. High levels of usability can improve performances, human wellness, and level of acceptance of a collaborative robot [68]. A tool often used to evaluate usability is the System Usability Scale (SUS) [15]. SUS is a questionnaire composed of ten items, which are evaluated using a 5-point Likert scale. Odd items represent positive statements, while even ones negative statements. According to the answer, a score between 0 and 4 is assigned to each item. By multiplying the sum of the scores by 2.5, the overall SUS score is obtained. The SUS score ranges between 0 and 100 (the higher, the better) and can be interpreted using the acceptability ranges proposed by Bangor *et al.* [8], reported in Table 8.

4.7 Ethics

Ethics represents the common understanding of the principles that constrain and guide human behavior [18]. An effective implementation of new technologies requires special attention to the people involved in the use of them [22]. The introduction of robots in some contexts is not only associated with physical hazards, but also with ethical hazards [80]. According to BS 8611 [18], ethical hazards are "potential source of ethical harm", i.e. "anything likely to compromise psychological and/or societal and environmental well-being". The following sub-dimensions can characterize *Ethics* dimension: *Social impact*, and *Social acceptance* (Table 10).

4.7.1 Social impact

Social impact refers to the consequences of introducing a collaborative robotic system within a community. The introduction of a collaborative robot in a work context can lead to a change in the roles of some workers or even job losses. Studying these effects is critical to understanding how to introduce collaborative robots while minimizing the impact on workers. A first evaluation of this sub-dimension is provided by the three-level scale reported in Table 10, which follows the well-being of humans.

Table 10 Summary of Ethics sub-dimensions and related evaluation scales.

Sub-dimension	Level	Description of the level
Social impact	**L0**	Heavy. The introduction of the collaborative robot involves the dismissal of humans.
	L1	Medium. The introduction of the collaborative robot involves a change of human tasks, but not the dismissal of humans.
	L2	Light. The introduction of the collaborative robot does not involve any effect on human tasks.
Social acceptance [14]	**L0**	Low. Acceptance score <46.
	L1	Medium. Acceptance score between 46 and 70.
	L2	High. Acceptance score between 71 and 90.
	L3	Very high. Acceptance score >90.

4.7.2 Social acceptance

Social acceptance indicates the perception of the collaborative robotic system within a community. It is important that the community in which the collaborative robot is introduced has a good level of predisposition for such forms of technology. Otherwise, some of the main risks could be poor robot usage or frustration. An effective creation of workforce awareness can improve the acceptance of new technologies, such as collaborative robots [20]. Social acceptance evaluation can be performed using a hybrid model developed by Bröhl *et al.* [14], which is based on the Technology Acceptance Model (TAM) [25], TAM 2 [79] and TAM 3 [78]. The model takes into account context-specific factors of the interaction between humans and robots in an industrial setting. The factors and items taken into account for the social acceptance questionnaire are reported in Table 11. Each item is evaluated on 7-point Likert-scale [14]. According to the answer and the type of item (positive or negative), a score between 0 and 6 is assigned to each item. The sum of points returns a score that indicates the level of acceptance, with a maximum score of 102. The four-level scale proposed in Table 10 is used to interpret the acceptance score.

4.8 Cybersecurity

Cybersecurity is the process of protecting information by preventing, detecting, and responding to attacks [58]. As technology grows, robots are increasingly connected

Table 11 Items and factors selected from Bröhl acceptance model [14]. Items with " * " negatively affect acceptance.

Factor	Negative item	Item
Subjective norm		In general, the organization supports the use of the robot.
Image		People in my organization who use the robot have more prestige than those who do not.
Job relevance		The use of the robot is pertinent to my various job-related tasks.
Output quality		The quality of the output I get from the robot is high
Result demonstrability		I have no difficulty telling others about the results of using the robot.
Perceived enjoyment		I find using the robot to be enjoyable.
Social implication	*	I fear that I lose the contact to my colleagues because of the robot.
Legal implication (Occupational safety)		I do not mind if the robot works with me at a shared workstation.
Legal implication (Data protection)		I do not mind, if the robot records personal information about me.
Ethical implication	*	I fear that I will lose my job because of the robot.
Perceived safety		I feel safe while using the robot.
Self-efficacy	*	I can use the robot, if someone shows me how to do it first.
Robot anxiety	*	Robots make me feel uncomfortable.
Perceived usefulness		Using the robot improves my performance in my job.
Perceived ease of use		My interaction with the robot is easy.
Behavioral intention		If I could choose, whether the robot supports me at work, I would appreciate working with the robot.
Use behavior		I prefer the robot to other machines in the industrial environment.

to the network, constantly exchanging information [61]. This makes robots exposed to cyber attacks that can lead to data leakage, malfunction or even damage to people or property. For these reasons, it is important to implement security measures that protect robots and minimize the vulnerabilities of the network to which they are connected. In the NIST Cybersecurity Framework (CSF) Core [58], five basic cybersecurity activities are identified, namely identify, protect, detect, respond, and recover. Based on this classification, *Cybersecurity* can be characterized by the following sub-dimensions: *Identification*, *Protection*, *Detection*, *Response*, and *Recovery* (Table 12, 13, and 14).

4.8.1 Identification

Identification represents the actions related to the understanding of policies, governance structures, asset categorization, cybersecurity risks, and priorities relevant for managing cybersecurity risks to systems, assets, data, and capabilities [58]. The evaluation of this sub-dimension can be performed using the four-level scale proposed by Dedeke [27], which is reported in Table 12.

4.8.2 Protection

Protection concerns activities related to the development and implementation of safeguards to protect critical infrastructure services and to train staff and employees [58]. This sub-dimension can be evaluated using the four-level scale proposed by Dedeke [27], which is reported in Table 12.

4.8.3 Detection

Detection includes activities related to the development and deployment of appropriate searching, monitoring, and detection activities to identify cybersecurity events [58]. The evaluation of this sub-dimension can be carried out using the four-level scale proposed by Dedeke [27], which is reported in Table 13.

4.8.4 Response

Response represents activities related to the development and implementation of appropriate plans and processes to take action regarding a detected cybersecurity event [58]. This sub-dimension can be evaluated using the four-level scale proposed by Dedeke [27], which is reported in Table 13.

Table 12 Summary of Cybersecurity sub-dimensions and related evaluation scales (Part 1).

Sub-dimension	Level	Description of the level
Identification [27]	**L0**	Partial. The relevant outcomes are pursued by untrained staff, inadequate policies, using no/few tools, ad hoc processes, inadequate technology, and no information references.
	L1	Risk informed. The relevant outcomes are pursued by trained staff, using adequate policies, tools, and processes. The outcomes conform to expectations and are monitored, controlled, and reported.
	L2	Repeatable. The relevant outcomes and practices are operated as in L1, but the policies and practices are now risk informed and updated to adapt to changing threats. The outcomes fall within acceptable risk tolerance.
	L3	Adaptive. The relevant outcomes and practices are operated as in L2, and the outcomes are regularly monitored, assessed, and reported organizationwide. The practices and policies are institutionalized and regularly assessed and improved.
Protection [27]	**L0**	Partial. The relevant outcomes are limited by poor awareness and training, inadequate policies, few access controls, inadequate data security tools, ad hoc policies, and inadequate protective technologies.
	L1	Risk informed. The relevant outcomes are pursued by informed employees and trained staff, adequate policies, adequate access controls, adequate data security tools, adequate policies, and adequate protective technologies.
	L2	Repeatable. The relevant outcomes and practices are operated as in L1, and risk-informed management is used to select, deploy, evaluate, and review fitness of controls, policies, access controls, data security tools, and technologies.
	L3	Adaptive. The relevant outcomes and practices are operated as in L2, and protection controls are monitored, assessed, and reported organizationwide. The policies are institutionalized. The policies and controls are regularly assessed and improved.

Table 13 Summary of Cybersecurity sub-dimensions and related evaluation scales (Part 2).

Sub-dimension	Level	Description of the level
Detection [27]	**L0**	Partial. The relevant outcomes are limited by poor detection of events, inadequate monitoring, ad hoc processes, and inability to recognize penetrations and invasions.
	L1	Risk informed. The relevant outcomes are pursued by informed employees and trained staff, adequate policies, event detection and monitoring tools, formal processes, and adequate ability to recognize penetrations and invasions.
	L2	Repeatable. The relevant outcomes and practices are operated as in L1, and risk-informed management is used to determine appropriateness of detection and monitoring tools and formal processes.
	L3	Adaptive. The relevant outcomes and practices are operated as in L2, and the effectiveness of detection and monitoring tools is monitored, assessed, improved, and reported organizationwide. The practices and policies are institutionalized.
Response [27]	**L0**	Partial. The relevant outcomes are limited by slow response to detected events due to poor response planning, lack of analysis, slow mitigation, and poor communications.
	L1	Risk informed. The relevant outcomes are pursued by informed and trained employees who deploy adequate response planning, adequate analysis, mitigation capabilities, and communications.
	L2	Repeatable. The relevant outcomes and practices are operated as in L1, and risk-informed management is used to determine appropriate response plans, analysis, mitigations, and communications.
	L3	Adaptive. The relevant outcomes and practices are operated as in L2, and the effectiveness of response plans, analysis, mitigations, and communications is monitored, assessed, improved, and communicated. The practices are institutionalized.

Table 14 Summary of Cybersecurity sub-dimensions and related evaluation scales (Part 3).

Sub-dimension	Level	Description of the level
Recovery [27]	**L0**	Partial. The relevant outcomes are limited by lack of recovery planning, poor recovery process practices and readiness, and lack of effective communications.
	L1	Risk informed. The relevant outcomes are pursued by informed and trained employees who possess adequate recovery planning and readiness. Adequate communications and improvements are used.
	L2	Repeatable. The relevant outcomes and practices are operated as in L1, and risk-informed management is used to determine appropriate recovery plans, improvements, and communications.
	L3	Adaptive. The relevant outcomes and practices are operated as in L2, and the effectiveness of recovery plans, analysis, mitigations, and communications is monitored, assessed, improved, and communicated.

4.8.5 Recovery

Recovery involves activities related to the development and implementation of appropriate plans and processes to recover from cybersecurity events and to restore services and capabilities impacted by such events. The evaluation of this sub-dimension can be performed using the four-level scale proposed by Dedeke [27], which is reported in Table 14.

4.9 Summary

Eight different HRC latent dimensions has been identified, specifically *Autonomy*, *Information Exchange*, *Adaptivity and Training*, *Team Organization*, *Task*, *Human Factors*, *Ethics*, and *Cybersecurity*. For most of the HRC latent dimensions, sub-dimensions have also been detected and an evaluation method has been proposed for each of them. Table 15 summarizes the conceptual framework structure with the evaluation scales.

5 Examples of HRC framework application

To make explicit the meaning of the analysis conducted on the HRC, some application examples are presented.

Table 15 Summary of the HRC conceptual framework with latent dimensions, sub-dimensions and evaluation methods.

Latent dimension	Sub-dimension	Evaluation method
Autonomy	-	LORA [10]
Information Exchange	Communication medium	4-level scale
	Communication format	4-level scale
Team Organization	Team structure	Categorical scale
	Members role	3-level scale
Adaptivity and Training	Robot adaptivity	4-level scale (based on [48])
	Robot training method	3-level scale
	Operator training	4-level scale
Task	Field of application	Categorical scale
	Task organization	List of operations
	Performance	4-level scale
	Safety	Risk assessment with 4-level scale (based on [38, 42])
Human factors	Workload	NASA-TLX [35] (4-level scale)
	Trust	Trust Scale Questionnaire [21] (4-level scale)
	Robot morphology	Categorical scale [84]
	Physical ergonomics	EAWS [67]
	Usability	SUS [15] (3-level scale [8])
Ethics	Social impact	3-level scale
	Social acceptance	Bröhl TAM [14] (4-level scale)
Cybersecurity	Identification	Dedeke framework [27]
	Protection	Dedeke framework [27]
	Detection	Dedeke framework [27]
	Response	Dedeke framework [27]
	Recovery	Dedeke framework [27]

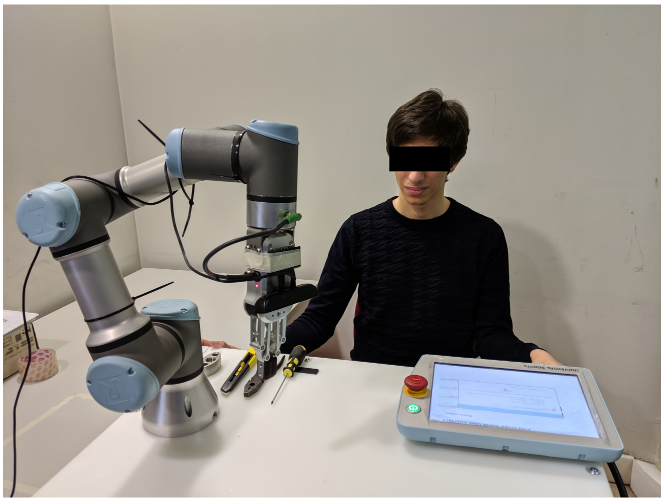


Fig. 3 Collaborative robot UR3 [77].

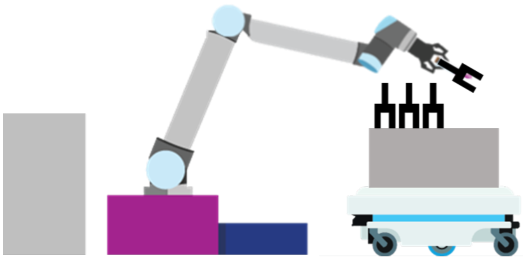
In sub-section 5.1, an assembly task in manufacturing context is analyzed. In sub-section 5.2, a navigation task in healthcare context, where an elder has to reach a place with the support of a collaborative robot, is presented. This second case study has been chosen to explore the potential application of the conceptual framework in non-manufacturing contexts.

5.1 Collaborative assembly task in manufacturing

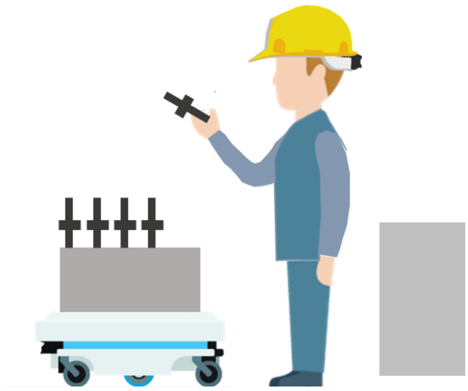
Let us consider an assembly task, designed within the technology labs of "Politecnico di Torino". The team is composed of a human and the single-arm collaborative robot UR3 (Figure 3) [77]. The task is to join two pieces by means of a snap-in mechanism. The robot takes a component and approaches the operator holding it; the operator takes the other component and assembles it with the other; the robot moves away with the assembled workpiece and places it in a specific location. The human has control of the process by sending a command when the robot can proceed with the next operation, leading to a master-executor relationship. The list of the operations is schematically represented in Figure 4 and can be summarized as follows:

1. Picking Piece 1 (Robot);
2. Picking Piece 2 (Human);
3. Joining Piece 1 and Piece 2 (Human);
4. Placing joined piece (Robot).

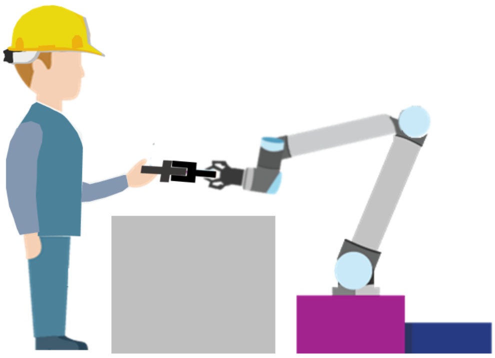
Table 16 summarizes the evaluation profile created by a team of experts. *Autonomy* has been rated L3 (Batch Processing). The robot is able to sense the environment and to implement actions, however the human decides the objectives and manages the phases of the



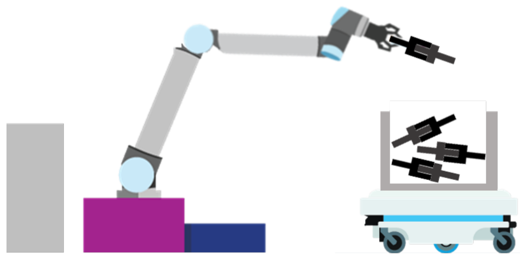
(a) Step 1: Robot picks Piece 1.



(b) Step 2: Human picks Piece 2.



(c) Step 3: Human joins Piece 1 and 2.



(d) Step 4: Robot places joined piece.

Fig. 4 Sequence of assembly task operations.

task by giving commands to the robot. Communication with the robot takes place via a screen that displays various status information. The operator informs the robot when to proceed with the next operation by means of a hand panel. Therefore, *Communication medium* and *Communication format* are both evaluated L1. The robot is able to stop if a certain force limit is reached, mainly for safety reasons, and has a form of adaptivity for the task that allow it to correctly grab the piece through the vision system. These features lead to level L1 for *Robot adaptivity*. The instruction of the robot can be achieved by manual programming or teach-pendant, which is a traditional PbD technique, leading to level L1 for *Robot training method*. The *Operator training* has been evaluated L3 (Light). The operator training is estimated to last around 60 minutes, and the operations involed in the task are not difficult. *Safety* has been evaluated L3 (Very high): the risk score obtained was 20/90, meaning that the task presents a fairly low safety risk for the operator. The performance of the collaborative task has been evaluated taking into account effectiveness and efficiency. The outcome of the process resulted acceptable and *Performance* has been rated L2 (High). *Workload* has been rated 32.5/100, meaning that the operator workload is evaluated L2 (Medium-low). *Trust* has been evaluated L2 (High), since a trust score of 36.5/50 was obtained. *Physical ergonomics* has been rated L2 (Green). The task implies a low biomechanical load on the operator, as it requires the handling of low load objects and the application of low forces while maintaining a non-fatiguing posture. This is confirmed by the EAWS score of 12 (<25), indicating a low biomechanical overload risk (see Appendix A). *Usability* obtained a SUS score of 72.5/100, leading to an L2 (Acceptable) rating. *Social impact* has been rated L2 (Light), since the introduction of the robot does not imply dismissals of humans or changes of tasks. Assuming an operator between 20 and 35 years of age, the *Social acceptance* score obtained was 71/102, leading to an L2 (High) rating, which indicates a good level of propensity to collaborate with the robot. Regarding cybersecurity, *Identification*, *Protection*, *Detection*, *Response*, and *Recovery* have been estimated L1 (Risk informed). The presence of trained personnel to take care of IT security is necessary to ensure the continuity of the production process.

Table 16 Summary of the evaluation of the latent HRC dimensions for assembly task.

Latent dimension	Sub-dimension	Evaluation
Autonomy	-	L3 (Batch Processing)
Information Exchange	Communication medium	L1
	Communication format	L1
Team Organization	Team structure	1 Human, 1 Robot
	Members role	Human (L2), Robot (L0)
Adaptivity and Training	Robot adaptivity	L1
	Robot training method	L1
	Operator training	L3 (Light)
Task	Field of application	Industry
	Performance	L2 (High)
	Safety	L3 (Very high)
Human Factors	Workload	L2 (Medium)
	Trust	L2 (High)
	Robot morphology	Functional (Single arm)
	Physical ergonomics	L2 (Green)
	Usability	L2 (Acceptable)
Ethics	Social impact	L2 (Light)
	Social acceptance	L2 (High)
Cybersecurity	Identification	L1 (Risk informed)
	Protection	L2 (Repeatable)
	Detection	L1 (Risk informed)
	Response	L1 (Risk informed)
	Recovery	L1 (Risk informed)

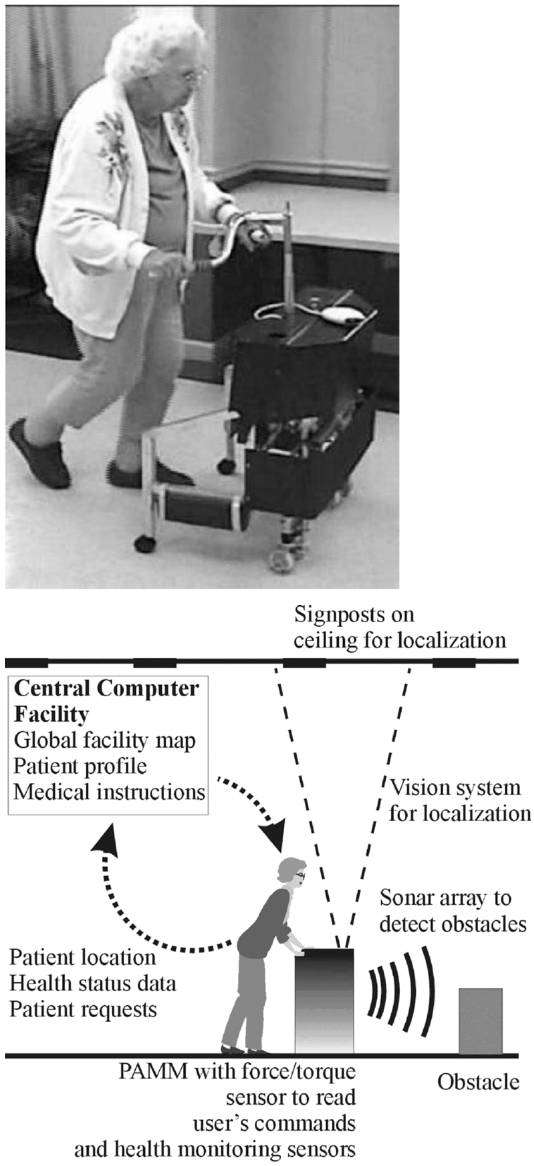


Fig. 5 PAMM SmartWalker. On the upper side, a user with the SmartWalker. On the lower side, the system concept of the PAMM SmartWalker [85].

5.2 Collaborative navigation task in healthcare

An example of HRC task where the collaboration level is potentially high concerns the assistance to people, in particular guiding elders to a specific destination. The SmartWalker (Figure 5) is a robotic system belonging to a group of devices termed PAMM (Personal Aid for Mobility and Monitoring) [28, 72, 85]. PAMMs are robotic systems intended to assist the elderly in senior assisted living facilities, providing support, guidance, and health monitoring while walking. The system concept of the SmartWalker, and of PAMMs in general, is presented in Figure 5. The SmartWalker has three main sensors: a sonar array for obstacle avoidance, a six axis force/torque sensor for reading the user's input, and a camera for localization. The sonar array is used to identify the position of objects not given on the facility map, allowing the system to avoid them. The six axis force/torque sensor reads the forces and torques applied to the handle, allowing the user to give commands to the SmartWalker. The upward looking camera is used to read passive signposts placed on the ceiling, which allow to locate the system in the facility.

The PAMM SmartWalker constantly communicates with a central computer, which provides the facility map with the position of fixed obstacles, a user profile, and instructions. On the other hand, the Smart-

Walker sends to the central computer the current position, user's health conditions, and requests [72]. The main task of the PAMM SmartWalker is to guide elders to a planned destination in the facility, while providing physical support. An adaptive shared control is implemented in the system, which allows to give the user as much control as he can safely handle, mediating between the computer instructions and the user's intention [72]. The main idea is to provide support to the user only when he needs it. Once the destination is chosen, an optimal path is generated based on the facility map. If the user deviates from the pre-planned path, and there are no obstacles on the way, the computer controller will gently guide the user back. The SmartWalker has also an adaptive model that makes it feels slow and steady at the beginning and end of the motion, and light and responsive while is moving faster [72]. This feature allows users to feel more confident and reduce fatigue.

Table 17 summarizes the collaboration profile obtained with the HRC framework. The evaluation has been performed by a team of experts, taking also into account the evaluation results obtained in previous works [72,85]. The collaborative task takes place in healthcare context and consists in reaching a destination. *Autonomy* has been rated L5 (Shared Control With Human Initiative). The robot is able to sense the environment and to plan a path to reach a specific location, but the human decides when starting and pausing the navigation. Communication with the robot takes place via the force/torque sensor and the power wheels. The user communicates his intentions by applying forces and torques to the handle of the SmartWalker, which in turn guides the user applying forces. Therefore, *Communication medium* and *Communication format* are evaluated L1 and L2, respectively. The robot is able to avoid obstacles and to guide the user to the right path, while leaving the control to the user. These features shows adaptivity with respect to the environment and the human, leading to level L3 for *Robot adaptivity*. The instruction of the SmartWalker is achieved by manual programming, leading to level L0 for *Robot training method*. The *Operator training* has been evaluated L3 (Light). Since the system is thought to be used by elders and the robotic system resembles a classic walker, the user learns easily how to move with it. The *Physical ergonomics* has been evaluated L2 (Green), since the EAWS score obtained was 12.5, which is less than 25 points. Based on the results obtained by Spenko *et al.* [72] and Yu *et al.* [85], *Performance* of the collaborative task has been evaluated L3 (Very high). The evaluation was performed by taking into account the proximity to obstacles, the deviation from the ideal path, the excessive or high-frequency oscillation about the path, and the tip over margins [85]. *Safety* has been evaluated L3 (Very high), since the task requires reaching a destination and the SmartWalker provides support and guides the user, limiting harm.

Table 17 Summary of the evaluation of the latent HRC dimensions for navigation task.

Latent dimension	Sub-dimension	Evaluation
Autonomy	-	L5 (Shared Control With Human Initiative)
Information Exchange	Communication medium	L1
	Communication format	L2
Team Organization	Team structure	1 Human, 1 Robot
	Members role	Human L2, Robot L1
Adaptivity and Training	Robot adaptivity	L3
	Robot training method	L0
	Operator training	L3 (Light)
Task	Field of application	Healthcare
	Performance	L3 (Very high)
	Safety	L3 (Very high)
Human Factors	Workload	L2 (Medium)
	Trust	L3 (Very high)
	Robot morphology	Functional (Walker)
	Physical ergonomics	L2 (Green)
	Usability	L2 (Acceptable)
Ethics	Social impact	L2 (Light)
	Social acceptance	L3 (Very high)
Cybersecurity	Identification	L1 (Risk informed)
	Protection	L1 (Risk informed)
	Detection	L1 (Risk informed)
	Response	L1 (Risk informed)
	Recovery	L1 (Risk informed)

Based on the results obtained by Yu *et al.* [85] from the analysis of user experience, Workload, Trust, Usability, and Social acceptance can be evaluated. *Workload* has been rated L2 (Medium), as the SmartWalker relieves the user's mental fatigue by guiding him, however the elderly user may get physically fatigued during the task. *Trust* has been evaluated L3 (Very high), as

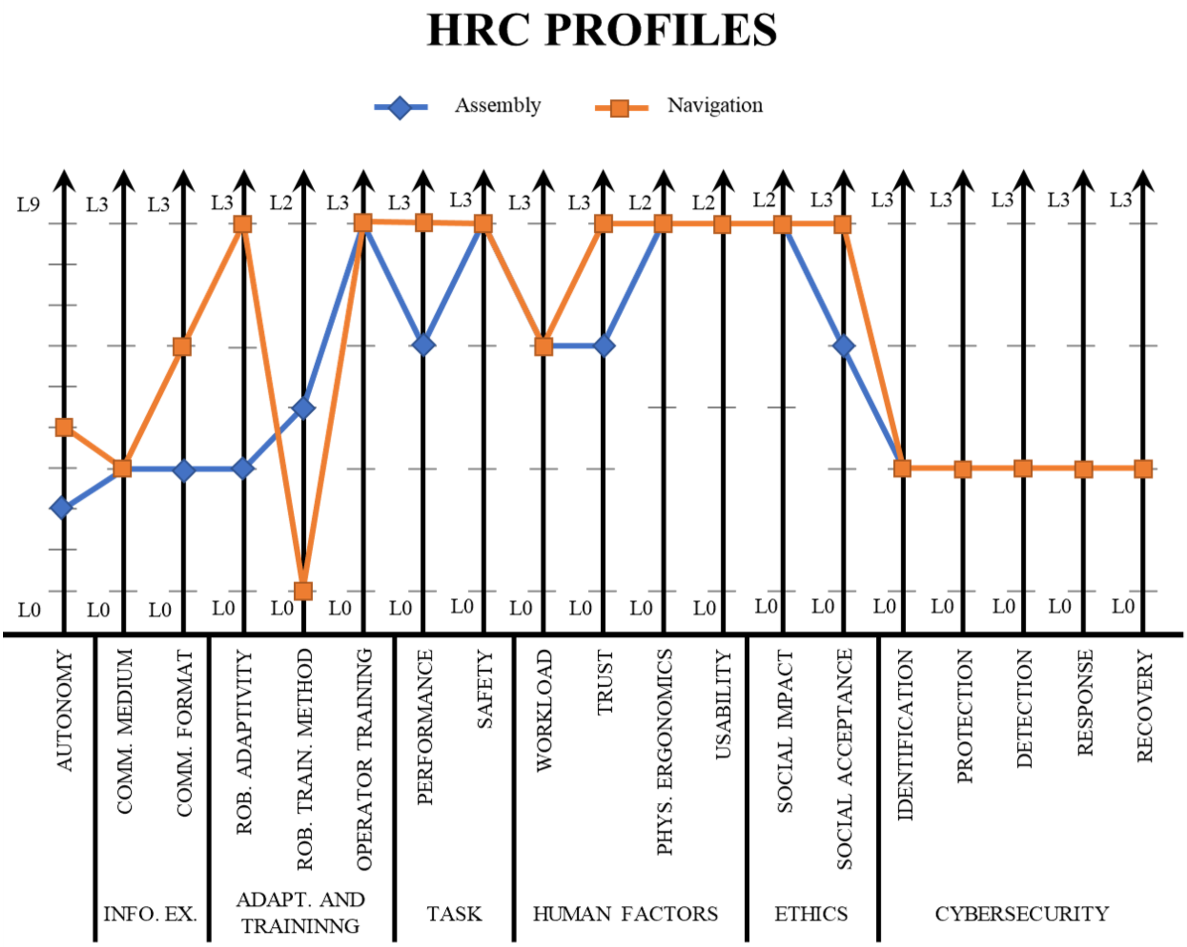


Fig. 6 Graphical comparison between the evaluation profiles of the examples in sub-section 5.1 (blue) and sub-section 5.2 (orange).

users have found the SmartWalker reliable and similar to a classic walker. *Usability* can be rated L2 (Acceptable), since the SmartWalker interface is intuitive for elders and similar to how a classic walker is used. *Social acceptance* has been evaluated L3 (Very high), since the SmartWalker gives assistance during the task while leaving the control to the user. *Social impact* has been rated L2 (Light), as the introduction of the SwartWalker does not imply dismissals of humans or changes of their tasks.

Regarding the Cybersecurity latent dimension, *Identification*, *Protection*, *Detection*, *Response*, and *Recovery* have been estimated L1 (risk informed). These evaluations can be justified by the need for specific staff to properly manage the system of the SwartWalkers, without however investing too many resources.

Figure 6 shows a graphical comparison between the two HRC profiles obtained in the two application examples.

6 Discussion

The main goal of this work was to provide a conceptual framework to analyze and compare HRC profiles of different applications (Table 15), highlighting the dimensions that characterize the HRC problem. The proposed conceptual framework brings together different viewpoints on HRC, representing a meeting point between several disciplines: from engineering to cognitive and social sciences. For a complete description of the HRC problem it is necessary to analyze aspects concerning both the collaborative robotic system and the people involved. However, these aspects are not completely independent of each other, as suggested in a previous work [33]. It can be also observed that some dimensions mostly concern the collaborative robotic system, while others concern humans. Dimensions like Autonomy, Information Exchange, and Robot training method are mainly related to the characteristics of the collaborative robot involved in a certain task. On the other hand, dimensions like Human Factors and Ethics are highly related to the humans involved in the collaboration. In fact, the success of collaboration depends not only on the context of application, but also on the predisposition and previous experiences of the people. It is important to create an environment that encourages HRC, making the people involved feel gratified by the interaction and the outcome.

The conceptual HRC framework provided in this paper includes also an organic and structured set of operational tools (i.e. evaluation metrics) for carrying out a comprehensive evaluation on HRC. A team of experts can use the framework to evaluate collaborative tasks taking into account all the different aspects of HRC. In order to test the conceptual framework, two HRC tasks from two different contexts were considered. The framework was able to provide a comprehensive description and evaluation for both HRC applications, demonstrating that the sub-dimensions taken into account are adequate. The framework has also proven to be potentially suitable to be applied in non-manufacturing contexts. Moreover, as shown in Section 5, this framework allows to compare different tasks or settings of an application, highlighting the differences on the various dimensions and sub-dimensions. A team of experts can use the results obtained from the HRC framework to make decisions or focus on the improvement of certain aspects of the collaboration.

Some limitations are present. The framework is deliberately general, which allows the comparison between different fields of application. The comparison can be useful, for instance, to assess the "maturity degree" of HRC in one field compared to another. A summary of the various dimensions of the conceptual framework has not been deliberately proposed. This is mainly due to the high heterogeneity and possible relationships between sub-dimensions, but also to prevent the synthesis from losing the informative detail given by the individual sub-dimensions. For these reasons, in-depth investigations into the relationships between sub-dimensions in different application fields are necessary in order to create appropriate composite indicators.

7 Conclusion

In this paper a conceptual framework to evaluate HRC has been proposed. The aspects related to HRC has been analyzed and discussed. HRC is characterized by several aspects related to different fields of research, from robotics to human factors. Eight HRC latent dimensions (Autonomy, Information Exchange, Team Organization, Adaptivity and Training, Task, Human Factors, Ethics, and Cybersecurity) have been identified, with their respective sub-dimensions. For each sub-dimension, an evaluation method has also been provided, leading to the creation of a conceptual HRC framework. Within this framework, different collaborative applications can be evaluated and compared on the various dimensions that characterize HRC.

This work contributes to providing a broad view of HRC, combining technical aspects with human-social factors. Future works will be focused on the creation of a collaboration scale, and the improvement of evaluation methods for each HRC dimension and sub-dimension. Future investigations will also concern the application of mathematical modelling techniques to build HRC evaluation systems for specific application contexts.

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Appendix A EAWS structure

In this section, the structure of EAWS [67], a tool for the evaluation of physical ergonomics, is reported in more detail. Moreover, the evaluation of physical ergonomics through EAWS for the assembly task example, introduced in Section 5.1, is shown in detail. EAWS is divided in two macro-sections: Whole body and Upper limbs. The Whole body macro-section is composed of four sections:

- Extra Points (Figure 7), which contains additional types physical work load;
- Body Postures (Figure 8), which addresses static working postures and high frequent movements;
- Action forces (Figure 9), which concerns body forces and forces of the hand–finger system;
- Manual materials handling (Figure 10), which addresses the handling of loads of more than 2-3 kg.

The Upper limbs macro-section has only one section: Upper limb load in repetitive tasks (Figure 11), which covers gripping modes, forces, postures of the upper limbs in repetitive task.

Moreover, Figures 7, 8, 9, 10, and 11 contain the evaluation of each EAWS section for the assembly task example, introduced in Section 5.1. Manual materials handling section was not taken into account, due to the absence of handling of loads exceeding 2-3 kg. Adding up the scores, the Whole body macro-section obtained 12 points, while the Upper limbs macro-section 2.8 points (Figure 7). Therefore, the final score of the EAWS is 12, as it is the maximum between the scores of the two macro-sections. The final EAWS evaluation is "Green", since the final score is less than 25.

Result of overall evaluation: *Calculate the total score of whole body and compare it to the UL score. The overall result is determined by the higher value and the appropriate traffic light is checked. Anyway, interpretation should take into account both values.*

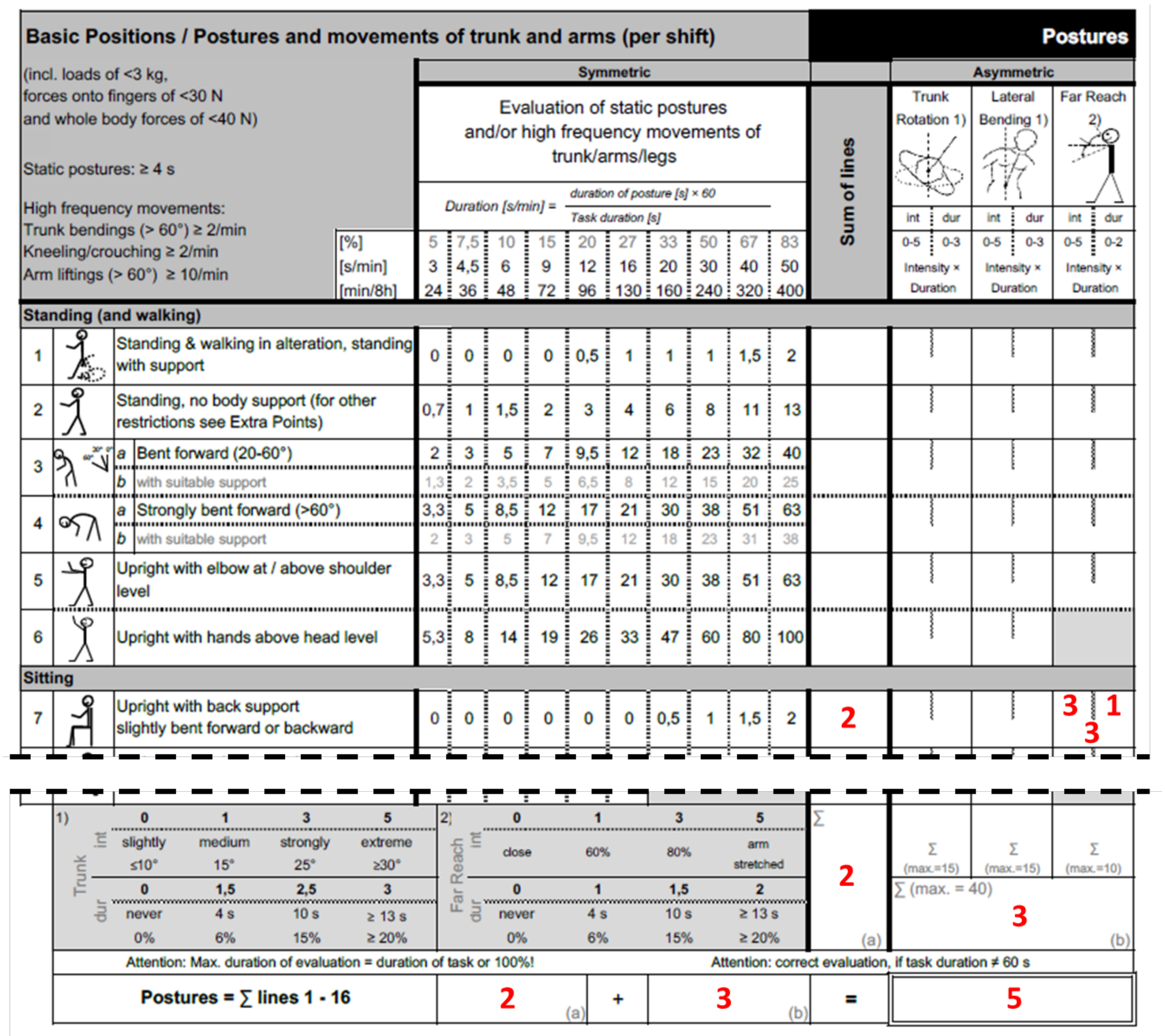
	Whole Body	=	Postures	+	Forces	+	Loads	+	Extra	Upper Limbs
☒ Green ☐ Yellow ☐ Red	12	=	5	+	3	+	0	+	4	2.8

EAWS evaluation			
	0-25 Points	Green	Low risk: recommended; no action is needed
	>25-50 Points	Yellow	Possible risk: not recommended; redesign if possible, otherwise take other measures to control the risk
	>50 Points	Red	High risk: to be avoided; action to lower the risk is necessary

	Extra points "Whole body" (per minute / shift)							Extra points
0a	Adverse effects by working on moving objects	0 none	3 middle		8 strong		15 very strong	Intensity
0b	Accessibility (e.g. entering motor or passenger compartment)	0 good	2 complicated		5 poor		10 very poor	Status
0c	Countershocks, impulses, vibrations 	0 light	1 visible		2 heavy		5 very heavy	Intensity × frequency
		0 [n]	1 1 - 2	2,5 4 - 5	4 8 - 10	6 18 - 20	8 > 20	
0d	Joint position (especially wrist) 	0 neutral	1 ~ 1/3 max		3 ~ 2/3 max		5 maximal	Intensity × duration or frequency 1 x 4 = 4
		0 [s] [n] [%]	2 3 1 5	2,5 10 8 17	4 20 11 33	6 40 16 67	8 60 20 100	
0e	Other physical work load (please describe in detail)	0 none	5 middle		10 strong		15 very strong	Intensity
	Extra = ∑ lines 0a – 0e	Attention: Max. score = 40 (line 0c, 0d); Max. score = 15 (line 0a, 0e); Max. score = 10 (line 0b)			Attention: correct evaluation, if duration of evaluation ≠ 60 s			= 4

Lines 0a-b mainly relate to the Automotive Industry, for other sectors additional elements may be necessary. For details see the EAWS manual.

Fig. 7 Overall result and Extra Points section of EAWS [67]. The evaluations for the assembly task are provided in red.



Basic Positions / Postures and movements of trunk and arms (per shift)			Symmetric: Evaluation of static postures and/or high frequency movements of trunk/arms/legs										Sum of lines	Asymmetric: Trunk Rotation 1)	Lateral Bending 1)	Far Reach 2)
(incl. loads of <3 kg, forces onto fingers of <30 N and whole body forces of <40 N) Static postures: ≥ 4 s High frequency movements: Trunk bendings (> 60°) ≥ 2/min Kneeling/crouching ≥ 2/min Arm liftings (> 60°) ≥ 10/min		[%] [s/min] [min/8h]	5 3 24	7,5 4,5 36	10 6 48	15 9 72	20 12 96	27 16 130	33 20 160	50 30 240	67 40 320	83 50 400		int 0-5 dur 0-3 Intensity × Duration	int 0-5 dur 0-3 Intensity × Duration	int 0-5 dur 0-2 Intensity × Duration
Standing (and walking)																
1		Standing & walking in alteration, standing with support	0	0	0	0	0,5	1	1	1	1,5	2				
2		Standing, no body support (for other restrictions see Extra Points)	0,7	1	1,5	2	3	4	6	8	11	13				
3	a	Bent forward (20-60°)	2	3	5	7	9,5	12	18	23	32	40				
	b	with suitable support	1,3	2	3,5	5	6,5	8	12	15	20	25				
4	a	Strongly bent forward (>60°)	3,3	5	8,5	12	17	21	30	38	51	63				
	b	with suitable support	2	3	5	7	9,5	12	18	23	31	38				
5		Upright with elbow at / above shoulder level	3,3	5	8,5	12	17	21	30	38	51	63				
6		Upright with hands above head level	5,3	8	14	19	26	33	47	60	80	100				
Sitting																
7		Upright with back support slightly bent forward or backward	0	0	0	0	0	0	0,5	1	1,5	2	2			3 1 3

1) Trunk	0	1	3	5
int	slightly ≤10°	medium 15°	strongly 25°	extreme ≥30°
	0	1,5	2,5	3
dur	never 0%	4 s 6%	10 s 15%	≥ 13 s ≥ 20%

2) Far Reach	0	1	3	5
int	close	60%	80%	arm stretched
	0	1	1,5	2
dur	never 0%	4 s 6%	10 s 15%	≥ 13 s ≥ 20%

Σ (a): 2 — Σ (max.=15) | Σ (max.=15) | Σ (max.=10) — Σ (max. = 40) (b): 3

Attention: Max. duration of evaluation = duration of task or 100%! Attention: correct evaluation, if task duration ≠ 60 s

Postures = Σ lines 1 - 16	2 (a)	+	3 (b)	=	5

Fig. 8 Body Postures section of EAWS [67]. The evaluations for the assembly task are provided in red.

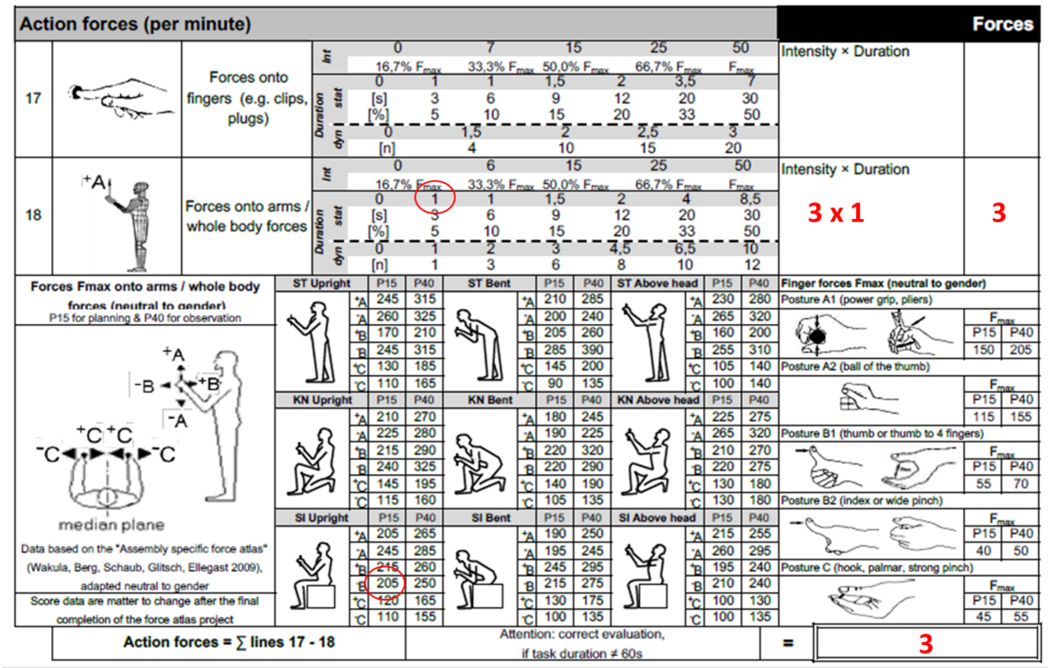


Fig. 9 Action forces section of EAWS [67]. The evaluations for the assembly task are provided in red.

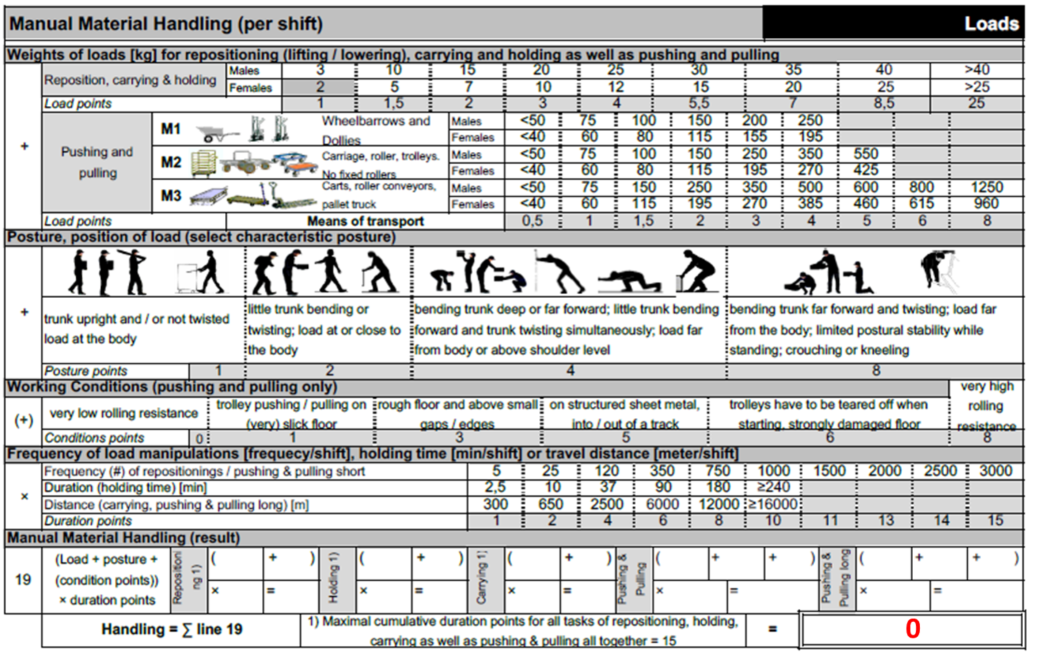


Fig. 10 Manual materials handling section of EAWS [67]. The evaluations for the assembly task are provided in red.

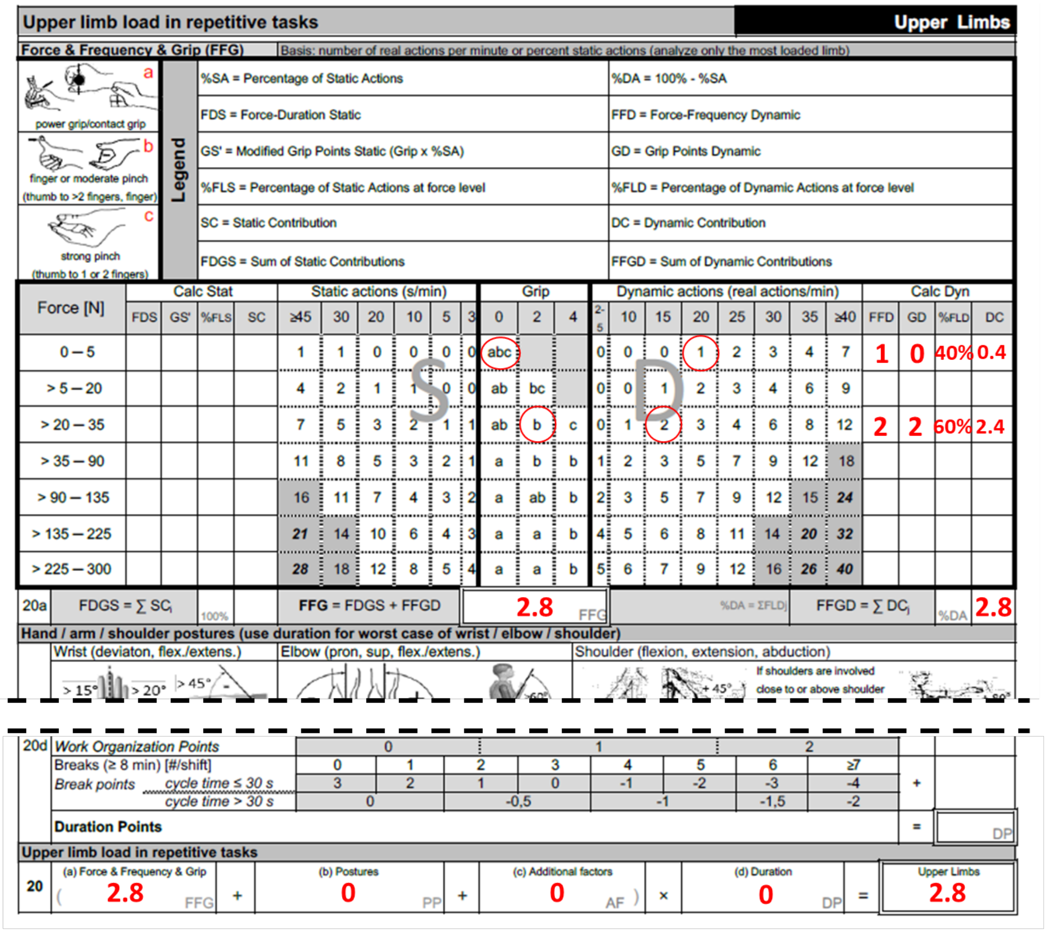


Fig. 11 Upper limbs macro-section evaluation for assembly task. The evaluations for the assembly task are provided in red.