Computers & Industrial Engineering 163 (2022) 107801

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Development and validation of guidelines for safety in human-robot collaborative assembly systems

Luca Gualtieri, Erwin Rauch *, Renato Vidoni

Free University of Bozen-Bolzano, Industrial Engineering and Automation (IEA), Universitätsplatz 5, 39100 Bolzano, Italy

ARTICLE INFO

Keywords:
Collaborative robotics
Human-robot collaboration
Human-robot interaction
Safety
Digital twin industry 4.0

ABSTRACT

Industrial collaborative robotics is one of the most promising technologies of Industry 4.0. In particular, human-robot collaboration in assembly will be particularly interesting for manufacturing companies. In this context, the interaction between humans and robots opens new possibilities but also challenges. A major problem is related to safety: unwanted and unexpected contacts between the human and the robotic system may cause injuries and therefore limit the potential for collaboration. Nowadays, there is a lack of simple and practical tools for helping system designers in overcoming such limiting conditions. In this work, guidelines for the design of safe human-robot collaborative assembly are developed and classified, particularly focusing on the features characterizing the entire system. These are validated by means of a laboratory case study and a digital twin. The validation process is based on the assumption that a team of manufacturing engineers (not-experts in occupational health and safety) should be able to autonomously and gradually apply the given guidelines reducing the mechanical risk in a collaborative assembly system. The proposed solutions have been virtually modelled allowing the evaluation of their effectiveness. According to the results, the proposed guidelines effectively help non-expert users in the development and improvement of collaborative assembly systems from the safety perspective.

1. Introduction

1.1. Problem statement

With the spread of Industry 4.0, many technological advances have been introduced to enhance traditional manufacturing systems by implementing integrated, automated, and optimized production flows (Cimini, Pezzotta, Pinto, & Cavalieri, 2018). In this context, industrial collaborative robotics is one of the main enabling technologies of Industry 4.0 (Cimini, Pirola, Pinto, & Cavalieri, 2020) and is currently changing the way by which manufacturing systems are designed and organized. Cyber-Physical Systems (CPS), of which collaborative robotics is an important actor, are one of the main pillars of such an industrial revolution (Cimini et al., 2018). They can be defined as a high-performing integration of humans, machines and, information systems collaborating and linking together the physical and the digital world (Pinzone et al., 2020). In particular, Human-Robot Collaboration (HRC) is the most advanced application of Human-Robot Interaction (HRI) in industrial settings, since it involves a simultaneous sharing of tasks and workspaces between the operator and the robot's systems. Assembly is rivaling to be one of the most interesting and promising applications of collaborative robotics. Collaborative Assembly Systems (CAS) are defined as hybrid workstations where the robot's role is to support operators in critical and strategical assembly tasks (e.g. by acting as a physical assistance system or by taking charge of unskilled or not-value added activities).

In this context, HRC can provide many advantages but also challenges. In fact, ensuring the Occupational Health and Safety (OHS) of operators during collaborative activities (e.g. assemblies) might be very difficult. In particular, the main hazard category will be of mechanical type (Gualtieri, Palomba, Wehrle, & Vidoni, 2020). This is because it is possible to have potential, not-functional and, unwanted contacts between the human and the robot systems during the sharing of tasks and workspaces. Collaborative robotic arms present some inherent safety measures, which allow preventing such dangerous situations and the implementation of safe applications. Nevertheless, this state usually changes as soon as they are integrated into a working environment and equipped with different types of end-effectors. In addition, further complexities are related to the analysis and evaluation of the hazards which are subjective by nature (Gopinath & Johansen, 2016).

---

* Corresponding author.
E-mail address: erwin.rauch@unibz.it (E. Rauch).

https://doi.org/10.1016/j.cie.2021.107801

Furthermore, as often happens for new technologies and because of the topic's complexity and multidisciplinarity, a large part of manufacturers (especially Small and Medium-sized Enterprises - SME), do not have in-house knowledge and skills about this specific technology (Orzes, Rauch, Bednar, & Poklemba, 2018).

For these reasons, safety requirements and measures for collaborative robotics must be studied and harmonized. This is necessary to provide system designers adequate tools for supporting a safe implementation of industrial HRIs and to overcome the difficulties and the technological barriers related to the effective and efficient integration of HRI in manufacturing companies (Gualtieri, Rauch, & Vidoni, 2021). This work aims at simplifying the design process of the features characterizing a CAS from the point of view of the prevention against mechanical hazards by presenting a set of structured guidelines. These are validated by means of a laboratory case study and a digital twin model.

The article is structured as follows. Section 1 describes the problem statement, the literature review and the related research questions. Section 2 describes the proposed design guidelines and presents the materials and methods adopted for their validation. Section 3 explains the validation process in an experimental setup in the laboratory and Section 4 comments on the achieved results. Finally, the discussions and conclusions are exposed in Section 5.

1.2. Literature review

The safety guidelines presented in this work are based on preliminary research presented in (Gualtieri, Rauch, Vidoni, & Matt, 2020). The current development enlarges and deepens the previous one and considers the contribution of: (i) main safety standards and deliverables in the field of safety of machinery and industrial robotics, (ii) the indications provided by main producers of industrial collaborative robots and, (iii) the scientific literature about the topic. This multidisciplinary approach has been selected to integrate the current and consolidated technological state-of-the-art of collaborative robotics, provided by the standards and manufacturers, with the last scientific innovations and advancements, provided in the research.

Indications on how to realize machines and systems that are safe for their intended use are given in the safety of machinery standards and deliverables (Jespen, 2016). Considering the mechanical risks in industrial robotics, the following documents were identified and analyzed:

- The type-A standard ISO 12100 (International Organization for Standardization, 2010); which deals with the risk assessment for machinery;
- The type-C standards ISO 10218 part 1 and 2 (International Organization for Standardization, 2011; International Organization for Standardization, 2011), that specify the general safety requirements for industrial (traditional and collaborative) robots and integrated robot systems;
- The technical specification ISO TS 15066 (International Organization for Standardization, 2016); which explains the safety requirements specifically defined for collaborative operations;
- The technical report ISO TR 20218-1 (International Organization for Standardization, 2018); which defines the main safety measures for the design and integration of end-effectors used for robot systems, also considering collaborative operations.

Furthermore, the indications provided by some of the main producers of industrial collaborative robots (Universal Robots and Kuka) were also included by analyzing the related user's manual (Kuka Roboter GmbH, 2016; Universal Robots, 2018).

Finally, a detailed study of the scientific literature was integrated into the abovementioned results. Following, the main results are summarized and classified into three main categories related to different aspects of safety in industrial HRI.

)1. Frameworks for the design and implementation of safe HRC

In this field, Antonelli and Stadnicka (Antonelli & Stadnicka, 2019) presented a novel Process Failure Mode and Effects Analysis (PFMEA) to be used for the organization of collaborative work cells. Awad et al. (Awad, Fechter, & van Heerden, 2017) proposed a new automatic design method for HRC workspaces by providing decision support. Gervasi et al. (Gervasi, Mastrogiacomo, & Franceschini, 2020) provided a conceptual framework for the evaluation of HRC in manufacturing. Gopinath et al. (Gopinath, Johansen, & Derelöv, 2018) developed a methodology for the proposal of safety solutions for HRC. Michalos et al. (Michalos et al., 2018) implemented a robot system for advanced HRC in assembly by discussing multiple technological approaches. Saenz et al. (Saenz et al., 2020) modeled the safety aspects of collaborative applications featuring speed and separation monitoring. Finally, Zacharaki et al. (Zacharaki, Kostavelis, Gasteratos, & Dokas, 2020) studied prior research addressing safety during HRI to find various potential methods of ensuring safe HRI.

These works emphasize the need for smart computer-aided, application and safety-oriented tools able to reduce the current complexity in the design of HRIs. This has to be done by considering the latest OHS requirements (including ergonomics) and the company's objectives in terms of process performance (the solution must be safe as well as cost-effective considering the investments and cycle time).

)2. Risk assessment for risks identification and mitigation

The topic was addressed by Askarpour et al. (Askarpour, Mandrioli, Rossi, & Vicentini, 2019), which developed automated techniques for the formal verification of the safety of collaborative applications by considering human erroneous behaviors. Chemweno et al. (Chemweno, Pintelon, & Decre, 2020) reviewed the state of the art about safety safeguards and risk assessment processes. Gopinath et al. (Gopinath, Ore, & Johansen, 2017) proposed a design approach for collaborative assembly based on risk assessment. In another work, Gopinath and Johansen (Gopinath & Johansen, 2016) introduced a risk assessment that emphasizes the interactions between the operator, the robot and, the work environment. Liu et al. (Liu et al., 2020) presented an approach for dynamic risk assessment in HRC and related active response strategy. Maeda et al. (Maeda et al., 2018) proposed a new safety concept and related safety level for a safe collaboration. Finally, Poot et al. (Poot, Johansen, & Gopinath, 2018) investigated the application of design automation in incorporating risk assessment in the early stages of HRC design.

Collaborative robotics has profoundly changed the way by which robots can be used in the industry. In that regard, they introduced a new paradigm in terms safety of machinery and human-machine interaction. These works discussed the new definition and role of "safety" in industrial HRI, also presenting dynamic and formal approaches to risk assessment and case studies. This further confirms the need for evaluation approaches that are integrated with the design.

)3. Safety measures and devices for risk reduction in HRC

In this context, Schlotzhauer et al. (Schlotzhauer, Kaiser, Wachter, Brandstötter, & Hofbaur, 2019) studied the ability of sensitive robots to safeguard contact situations from the point of view of the biomechanical load. Koch and Soltani (Koch & Soltani, 2019) presented a device that enables robots to detect clamping and allow an easy release of the human hand. Beluško et al. (Beluško, Hegedüš, & Fedorko, 2016) developed a new approach to solving work instruction for safe HRC workplaces. Marvel (Marvel, 2017) analyzed the sensor-enabled areas of research in collaborative robotics. Robla-Gomez et al. (Robla-Gomez et al., 2017) reviewed the main safety systems that contribute to the achievement of safe collaborative works. Finally, Salvietti et al. (Salvietti, Iqbal, Hussain, Prattichizzo, & Malvezzi, 2018) presented

Table 1
Guidelines for the design of CAS considering safety requirements (main objective: minimize specific mechanical hazards related to the entrapment of human body parts).

Objective: Minimize specific mechanical hazards related to the entrapment of human body parts

Guideline	Code	Priority level	Example of application
Prevent trap due to the exposed parts of the workstation elements	EH.S. 1	Lev. 1	■ Consider the relative positions between supports, components in assembly and robot systems to avoid possible trapping and/or obstructions during the operator's free movements; ■ Round the edges of supports or equipment in the work area; ■ Remove all possible points of entanglement for clothing or wearable devices from supports and work area; ■ If it is necessary to introduce a part of the body (e.g. fingers) into a work area or support, provide an entry/exit point that allows a rapid extraction;
Prevent trap due to exposed parts of the robot systems	EH.S. 2	Lev. 1	■ Remove all possible points of entanglement for clothing or wearable devices from robot systems; ■ Round the edges of robot systems; ■ Remove all possible points of entanglement for hands and fingers within the end-effector; ■ Keep the robot harnesses together and possibly anchored to the arm;
	EH.S. 3	Lev. 1	■ Use workstation layout to limit the reach of the robot beyond the robotic workspace; ■ Use fences (physical or optical) to constrain the operator's movement to eliminate the risk of entering a hazardous zone; ■ Promote devices that bring body parts away from danger zones to be used (e.g. tools, storage areas, two-hands commands, etc.);
Use sensing to anticipate contacts with the workstation elements (e.g. proximity detection to reduce quasi-static forces)	EH.S. 4	Lev. 2	■ Define the performance level of the safety functions (e.g. sensor systems) according to the risk assessment results (software and hardware); ■ Limit the monitored safety area to the smallest possible; ■ Control the fulfillment of sensors parameters according to the requirements of the specific application (e.g. resolution, reaction time, accuracy, etc.); ■ Find the safest sensors configuration and arrangement (if multiple configurations are permitted - e.g. laser scanners); ■ Use a safety function for workspace monitoring (axis-specific workspace monitoring, cartesian workspace monitoring, cartesian protected space monitoring); ■ Use sensor-fusion techniques for the integration of the information coming from different safety sensors (e.g. fixed and wearable);
Use sensing to anticipate contact with the robot systems (e.g. proximity detection to reduce quasi-static forces)	EH.S. 5	Lev. 2	■ Define the performance level of the safety functions (e.g. sensor systems) according to the risk assessment results (software and hardware); ■ Limit the monitored safety area to the smallest possible; ■ Control the fulfillment of sensors parameters according to the requirements of the specific application (e.g. resolution, reaction time, accuracy, etc.); ■ Find the safest sensors configuration and arrangement (if multiple configurations are permitted - e.g. laser scanners); ■ Use a safety function for workspace monitoring (axis-specific workspace monitoring, cartesian workspace monitoring, cartesian protected space monitoring); ■ Use sensor-fusion techniques for the integration of the information coming from different safety sensors (e.g. fixed and wearable);
Highlight objects and obstacles into the workspace	EH.S. 6	Lev. 2	■ Highlight the supports, the working areas (or part of them) and the limits of the machine (robot) of interest from a safety point of view (e.g. by using light indicators, ribbons, special colors, floor signals, etc); ■ Highlight potentially obstructive supports and/or work areas (or part of them) (e.g. by

(*continued on next page*)

Table 1 (*continued*)

Objective: Minimize specific mechanical hazards related to the entrapment of human body parts

Guideline	Code	Priority level	Example of application
			using light indicators, tapes, special coloring, floor signals, etc); ■ Signal collaborative and non-collaborative areas;
Set trajectories and configurations in such a way human body parts will not be easily trapped in/within the robot systems	EH.S. 7	Lev. 2	■ Avoid trajectories and robot configurations such as creating obstructions to free movements of the operator in the working areas and between the supports; ■ Define the robot trajectories so that its motion is predictable; ■ Define robot trajectories in such a way as to make moving robot systems visible to the operator; ■ Eliminate unintentional robot motion;
Set trajectories and configurations in such a way human body parts will not be easily trapped between the robot systems and the elements of the workstation	EH.S. 8	Lev. 2	■ Avoid trajectories and robot configurations such as creating obstructions to free movements of the operator in the working areas and between the supports; ■ Define the robot trajectories so that its motion is predictable; ■ Define robot trajectories in such a way as to make moving robot systems visible to the operator; ■ Eliminate unintentional robot motion; ■ Avoid operator's position underneath the robot arm;
Limit the robot to work in a defined volume to prevent traps with robot systems	EH.S. 9	Lev. 2	■ Limit the work volume of the robot systems so that it is as small as possible within the workstation; ■ Use task-based constraints for motion planning; ■ Set safe virtual-plane-systems or space limiting functions; ■ Limit one or more axis by using mechanical stops to ensure that even under manual mode, the robot reach is limited;
Limit the robot to work in a defined volume to prevent human's trap between the robot systems and the workstation elements	EH.S. 10	Lev. 2	■ Limit the work volume of the robot systems so that it is as small as possible within the workstation; ■ Provide sufficient space to ensure the free movement of the operator between the operating volume of the robot and supports \and/or work areas; ■ Use task-based constraints for motion planning; ■ Set safe virtual-plane-systems or space limiting functions (considering that the usually safety plans only limit the motion of the tool center point without considering the configuration of the robot, e.g. without limiting the motion of the other joints); ■ Use safety-rated soft axis (implemented via software); ■ Limit one or more axis by using mechanical stops to ensure that even under manual mode, the robot reach is limited;
Set collaborative robot speed limits for quasi-static contacts	EH.S. 11	Lev. 2	■ Set the speed limit values for quasi-static contacts in consideration of the risk assessment and ISO TS 15,066 (note that the speed limit which is possible to set into the robot controller is usually referred to tool-center-point only); ■ Limit and prevent the potential quasi-static contacts by considering the involved body parts; ■ Avoid in any case potential contacts with head and face;
Limit velocities of moving parts to prevent the trap of human body parts into the robot systems	EH.S. 12	Lev. 2	■ Set robot speed so that its motion is predictable; ■ Set robot speed in such a way as to make moving robot systems visible to the operator;
Limit velocities of moving parts to prevent the trap of human body parts between the robot systems and the workstation elements	EH.S. 13	Lev. 2	■ Set robot speed so that its motion is predictable; ■ Set robot speed in such a way as to make moving robot systems visible to the operator;

Legend for the code: EH = Entrampment of Human Partes; CH = Collision with Human Parts; PF = Parts Falling; TH = Transversal Hazards; S = Safety;

guidelines for the design of a soft collaborative gripper and realized it.

There is no doubt that collaborative robotics has stimulated interest from industry and research. In that regard, also according to the analyzed literature, hardware and software advancements are continuously growing, especially in the field of safety. Considering the novelty of the topic, the implementation of safe and state-of-the-art solutions for HRI should take into account the latest technical and organizational developments, also considering the preliminary results coming from the research.

According to this analysis, it is evident that a large part of the scientific researches deals with specific aspects of safety in HRC (e.g.

Table 2
Guidelines for the design of CASs considering safety requirements (main objective: minimize specific mechanical hazards related to collisions of human body parts).

Objective: Minimize specific mechanical hazards related to collisions of human body parts

Guideline	Code	Priority level	Example of application
Design the workstation elements to protect from contacts (manage energy absorption, enlarge energy transfer time or reduce impact forces)	CH. S.1	Lev. 1	▪ Increase the contact surface area of workstation elements; ▪ Round the edges of supports or equipment in the work area; ▪ Use smooth or compliant surfaces for supports or equipment in the work area; ▪ Introduce intermediate contact elements (e.g. covers) to be placed between the operator and the supports or equipment that allow a cushioning effect
Design the robot systems to protect from contacts (manage energy absorption, enlarge energy transfer time or reduce impact forces)	CH. S.2	Lev. 1	▪ Transforms a quasi-static contact into a transient contact (e.g. by using padding, cushioning, or deformable components); ▪ Use external mechanical smooth or compliance elements for robot systems to reduce contact force or pressure (e.g. springs, dampers, viscoelastic coverings, absorption elastic systems, lightweight structures, underactuated compliant hands, etc.); ▪ Round the edges of robot systems; ▪ Use deformable trunks as absorption elastic system to reduce contact Force or Pressure (e.g. springs and dampers located between a fixed base and the robotic arm);
Prevent contacts with the robot systems	CH. S.3	Lev. 1	▪ Use workstation layout to limit the reach of the robot beyond the robotic workspace; ▪ Use fences (physical or optical) to constrain the operator's movement to eliminate the risk of entering a hazardous zone; ▪ If it is necessary to introduce a part of the body (e.g. fingers) into a work area or support, provide an entry/exit point that allows a rapid extraction; ▪ Promote devices that bring body parts away from danger zones to be used (e.g. tools, storage areas, two-hands commands, etc.);
Use sensing to anticipate contacts with the robot systems (e.g. proximity detection to reduce quasi-static forces)	CH. S.4	Lev. 2	▪ Define the performance level of the safety functions (e.g. sensor systems) according to the risk assessment results (software and hardware); ▪ Limit the monitored safety area to the smallest possible; ▪ Control the fulfillment of sensors parameters according to the requirements of the specific application (e.g. resolution, reaction time, accuracy, etc.); ▪ Find the safest sensors configuration and arrangement (if multiple configurations are permitted - e.g. different positions of contact sensors); ▪ Use sensor-fusion techniques for the integration of the information coming from different safety sensors (e.g. fixed and wearable);
Use sensing to detect contacts with the robot systems (e.g. contact detection to reduce quasi-static forces)	CH. S.5	Lev. 2	▪ Define the performance level of the safety functions (e.g. sensor systems) according to the risk assessment results (software and hardware); ▪ Limit the monitored safety area to the smallest possible; ▪ Control the fulfillment of sensors parameters according to the requirements of the specific application (e.g. resolution, reaction time, accuracy, etc.); ▪ Find the safest sensors configuration and arrangement (if multiple configurations are permitted - e.g. different positions of contact sensors); ▪ Use compliance control algorithm for force management (e.g. variable impedance or admittance); ▪ Implement suitable methodologies for contact management via software (e.g. the robot stops at the time when the collision is detected, the robot behaves in a very compliant way with zero-gravity torque reaction, the robot moves away from the impact point, etc.);

(continued on next page)

Table 2 (*continued*)

Objective: Minimize specific mechanical hazards related to collisions of human body parts

Guideline	Code	Priority level	Example of application
			■ Limit forces or torques of robot systems (including the end-effector) via software; ■ Use sensor-fusion techniques for the integration of the information coming from different safety sensors (e.g. fixed and wearable);
Limit the robot to work in a defined volume to prevent human's contacts with robot systems	CH. S.6	Lev. 2	■ Limit the work volume of the robot systems so that it is as small as possible within the workstation; ■ Use task-based constraints for motion planning; ■ Set safe virtual-plane-systems or space limiting functions (considering that the usually safety plans only limit the motion of the tool center point without considering the configuration of the robot, e.g. without limiting the motion of the other joints); ■ Use safety-rated soft axis (implemented via software); ■ Limit one or more axis by using mechanical stops to ensure that even under manual mode, the robot reach is limited;
Set trajectories and configurations in such a way human body parts will not be easily hit by the robot systems	CH. S.7	Lev. 2	■ Avoid trajectories and robot configurations such as creating obstructions to free movements of the operator in the working areas and between the supports; ■ Define the robot trajectories so that its motion is predictable; ■ Define robot trajectories in such a way as to make moving robot systems visible to the operator; ■ Eliminate unintentional robot motion; ■ Avoid trajectories and robot configurations such as colliding with fixtures, tools and structures which can fall and hurt human body parts;
Limit momentum, mechanical power or energy as a function of masses and velocities	CH. S.8	Lev. 2	■ Limit moving masses (e.g. organizing the tasks in such a way as to reduce the handled load); ■ Use minimal robot payload with respect to the range of applications; ■ Set trajectories and configurations in such a way the energy exchange which can occur during unexpected collisions will be minimized; ■ Consider the configuration of the robot in case of possible collisions during motion planning; ■ Analyze the robot's sensitivity with respect to its operational space;
Set collaborative robot speeds limit for transient contacts	CH. S.9	Lev. 2	■ Set the speed limit values for quasi-static contacts in consideration of the risk assessment and ISO TS 15,066 (note that the speed limit which is possible to set into the robot controller is usually referred to TCP only); ■ Limit and prevent the potential quasi-static contacts by considering the involved body parts; ■ Avoid in any case potential contacts with head and face;
Limit velocities of moving parts to prevent contacts with human body parts into the robot systems	CH. S.10	Lev. 2	■ Set robot speed so that its motion is predictable; ■ Set robot speed in such a way as to make moving robot systems visible to the operator;

Legend for the code: EH = Entrampment of Human Partes; CH = Collision with Human Parts; PF = Parts Falling; TH = Transversal Hazards; S = Safety;

frameworks, risk assessment, devices, etc.) by losing a wider and integrated vision of related challenges. Although these studies are of high scientific relevance, they are very focused by omitting a comprehensive and systemic approach. Also, practical design principles that are oriented to main safety standards and deliverables as well as to scientific advancements for helping the system's designer without (or with limited) knowledge about safety in collaborative robotics are missing.

Therefore, this work aims at closing this gap by developing a set of design guidelines for the integration of safety requirements in CAS, focusing on mechanical hazards. The main assumption to be demonstrated is that it is possible to improve the operator's safety while collaborating with an industrial robot in assembly settings by differently designing the features characterizing the CAS. This should be possible by applying the principles provided by the guidelines proposed in this work. According to this hypothesis, the following research questions are introduced:

> RQ1: What are the main design principles to be satisfied when designing a CAS according to safety requirements and, in particular, to the prevention of mechanical hazards related to HRC?
> RQ2: What is the effectiveness of such guidelines if they are used by non-safety experts?

Table 3
Guidelines for the design of CASs considering safety requirements (main objective: minimize specific mechanical hazards related to robot system parts falling).

Objective: Minimize specific mechanical hazards related to robot system parts falling			
Guideline	Code	Priority level	Example of application
Design the robot systems to protect from parts falling associated with the workpiece	PF.S.1	Lev. 1	■ Design end-effectors in such a way to properly and safely handle the workpiece; ■ Design end-effectors in such a way that to block an accidental part falling; ■ Design end-effectors in such a way that to attenuate the effects of an accidental part falling (e.g. by limiting the falling velocity or trajectory);
Limit momentum, mechanical power or energy as a function of masses and velocities	PF.S.2	Lev. 2	■ Limit moving masses (e.g. organizing the tasks in such a way as to reduce the handled load); ■ Use minimal robot payload with respect to the range of applications; ■ Limit velocities of moving parts to prevent parts falling;
Set trajectories and configurations in such a way potential parts falling will limit the collision damages	PF.S.3	Lev. 2	■ Set trajectories and configurations in such a way the possibility to lose the workpiece during handling operations will be minimized; ■ Set trajectories in such a way to guide the possible falling of a part in a safe or empty area; ■ Avoid trajectories and robot configurations such as colliding with fixtures, tools and structures which can fall and hurt human body parts; ■ Eliminate unintentional robot motion;
Limit the robot to work in a defined volume to prevent contacts with robot systems	PF.S.4	Lev. 2	■ Limit the work volume of the robot systems so that it is as small as possible within the workstation; ■ Use task-based constraints for motion planning; ■ Set safe virtual-plane-systems or space limiting functions (considering that the usually safety plans only limit the motion of the tool center point without considering the configuration of the robot, e.g. without limiting the motion of the other joints);

Legend for the code: EH = Entrampment of Human Partes; CH = Collision with Human Parts; PF = Parts Falling; TH = Transversal Hazards; S = Safety;

Table 4
Guidelines for the design of CASs considering safety requirements (main objective: transversal to all mechanical hazards).

Objective: Transversal to all mechanical hazards			
Guideline	Code	Priority level	Example of application
Set access routes to prevent contacts or entrapment due to the robot systems	TH.S.1	Lev. 3	■ Restrict access to the collaborative station to authorized personnel only; ■ Protect the interaction with the workstation using passwords or authentication mechanisms; ■ Provide for flows of people and/or material outside the workstation at an appropriate distance from the operating volume of the robot;
Monitor robot systems performance	TH.S.2	Lev. 2	■ Allow command and control of the work cycle to the operator (if this is necessary for safety reasons); ■ Use the safety features of the robot to monitor and, if necessary, intervene if safety limits are exceeded; ■ Implement a suitable level of robot adaptivity related to safety-related unexpected situations (e.g. enter in free-drive mode if a certain condition is detected); ■ Provide a suitable number of well-positioned emergency stop devices for every operator working in the work area;
Signal/highlight robot systems motion and status	TH.S.3	Lev. 2	■ Inform the operator about systems motion and status (promote situational awareness) (e.g. by using auditory aids, on-screen notifications, external lights, onboard lights, augmented reality technologies, etc.); ■ Promote the most natural man–machine communication according to specific applications (e.g. displays, cameras, virtual reality, augmented reality technologies, speakers, microphones, etc.) ■ Use a proper feedback interface and HMI in terms of number, type and position of communication elements; ■ Use feedback interfaces that do not interfere with the operator's tasks and that make the operator feel in control of their work environment; ■ Signal the transition between collaborative and not-collaborative behaviors of the robot; ■ Use standard and recognizable signals/

(*continued on next page*)

Table 4 (*continued*)

Objective: Transversal to all mechanical hazards			
Guideline	Code	Priority level	Example of application
			communication media/ information as those of more “traditional” machines;
Train the operator about nominal use, extraordinary situations and safety procedures	TH. S.4	Lev. 3	■ Train the operator about the safety measures and systems of the robot; ■ Train operator about safety procedures; ■ Train operators on how to deal with erroneous situations; ■ Train operators on how to deal with emergencies; ■ Use methodologies and technologies for advanced and interactive training (e.g. simulations, Virtual Reality, etc.) ■ Attest the skills of the operator according to the level of safety required by the application;
Define specific safety procedures and behaviors	TH. S.5	Lev. 3	■ Develop standardized working procedures that are simple, clear, understandable and effectively usable by the operator; ■ Promote the use of visual instructions such as diagrams, photos, videos, etc. or Augmented Reality/Virtual Reality technologies; ■ Keep collaborative work area clear, clean and visible at all times; ■ Wear the right size and properly adjusted clothing and wearable devices and gather long hair;
Consider safety strategy during the concurrent workstation design	TH. S.6	Lev. 3	■ Identify in the design phase the main risk management strategy intend to be implemented according to the assembly cycle (preventive, mitigating, blended); ■ Identify the most suitable collaborative operation according to ISO TS 15,066 (Safety Rated Monitored Stop, Power and Force Limiting, Hand Guiding, Speed and Separation Monitoring or a combination of them); ■ Design the application by iteratively considering the results of the risk assessment; ■ Validate safety measures through standardized tests (e.g. by using biofidel measurements); ■ Define the proper level of safety responsibility between operator and control systems according to the specific application; ■ Perform risk analysis during workstation design in cooperation with the users; ■ Implement a task-oriented design of workstation; ■ Divide the workspaces into different risk compartments and provide for a proportionate safety measure; ■ Adapt safety systems according to the collaboration needs (partially active/ deactivated depending on the collaborative mode); ■ Avoid the introduction of new risks while changing the workstation design; ■ Differentiate the possibilities to access/ modify the workstation according to the role of the operator (worker, maintainer, programmer, etc.); ■ Use simulation software to support decisions and safety strategies; ■ Consider possible interdependences between safety and cyber-security in the design of connected systems;
Provide an adequate and constant workstation maintenance	TH. S.7	Lev. 3	■ The workstation may only be accessed in perfect technical condition; ■ Define a periodic maintenance plan for the workstation components; ■ Prevent robot failures after the controller has been switched off and locked out (e.g. overload, brake defect, etc.); ■ Protect cables from unintentional disconnection when the robot is running;
Consider cognitive aspects in the design of the workstation	TH. S.8	Lev. 3	■ Consider conditions that can affect safety such as fatigue, cognitive overload, stress, etc.; ■ Limit as much as possible operational errors (e.g. implement “poka-yoke” technique for workstation design); ■ Inform operators about possible assembly errors in real-time;

Legend for the code: EH = Entrampment of Human Partes; CH = Collision with Human Parts; PF = Parts Falling; TH = Transversal Hazards; S = Safety;

2. Materials and methods

2.1. Guidelines development and classification

According to the analysis of the contents provided in the previous section, the following general guidelines were developed and summarized in Table 1 to Table 4:

Table 5
Classification of safety guidelines according to main interaction variables.

Guideline Code	Workstation Layout and Elements			Robot System Features				Robot Systems Performance		Organizational Measures					
	Fixtures / Jiggs	Equipment / Tools	Structures	End-Effector	Robot Arm	External Devices and Sensors	Cables	Trajectories and Configurations	Motion Performance	Training	Procedures	Visual Management	Assembly Cycle	Strategy	Environment
EH.S.1	x	x	x												
EH.S.2				x	x	x	x								
EH.S.3	x	x	x												
EH.S.4	x	x	x												
EH.S.5				x	x	x									
EH.S.6	x	x	x									x			
EH.S.7								x							
EH.S.8								x							
EH.S.9								x					x		
EH.S.10								x							
EH.S.11								x	x				x		
EH.S.12									x				x		
EH.S.13									x				x		
CH.S.1	x	x	x												
CH.S.2				x	x	x									
CH.S.3	x	x	x												
CH.S.4				x	x	x									
CH.S.5				x	x	x									
CH.S.6								x	x				x		
CH.S.7								x							
CH.S.8				x	x	x		x					x		
CH.S.9								x	x				x		
CH.S.10									x				x		
PF.S.1				x											
PF.S.2				x	x	x		x					x		
PF.S.3								x							
PF.S.4								x	x				x		
TH.S.1			x												x
TH.S.2				x	x	x								x	
TH.S.3				x	x	x						x			
TH.S.4										x	x				
TH.S.5										x		x			
TH.S.6													x	x	
TH.S.7	x	x	x	x	x	x	x							x	
TH.S.8	x	x	x	x	x	x	x							x	

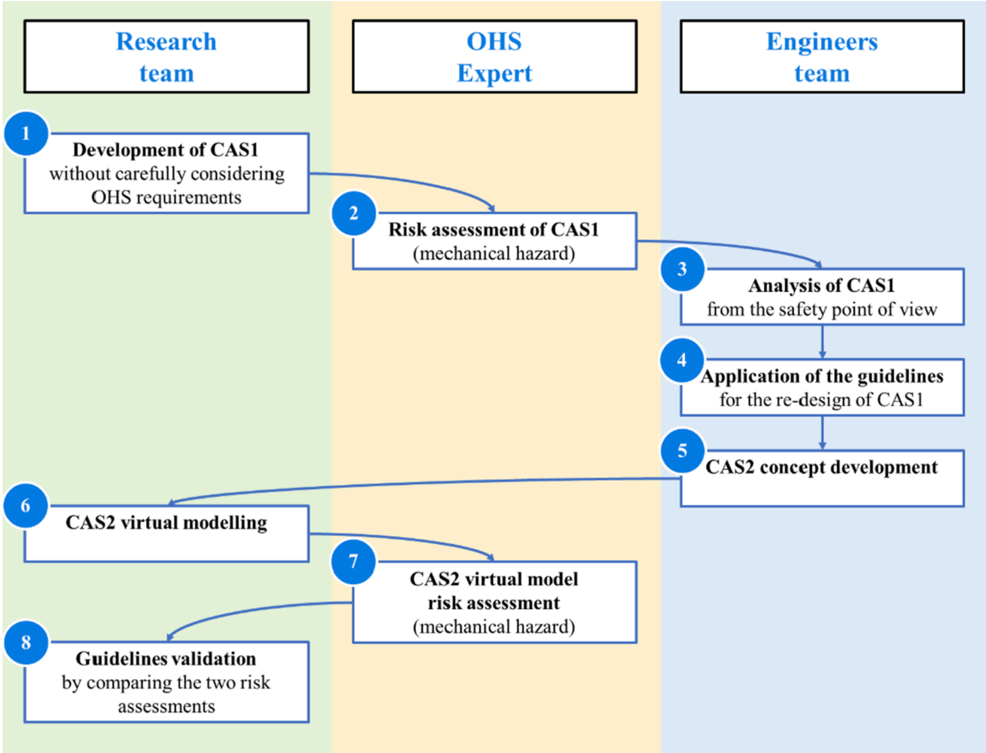


Fig. 1. Description of the validation process.

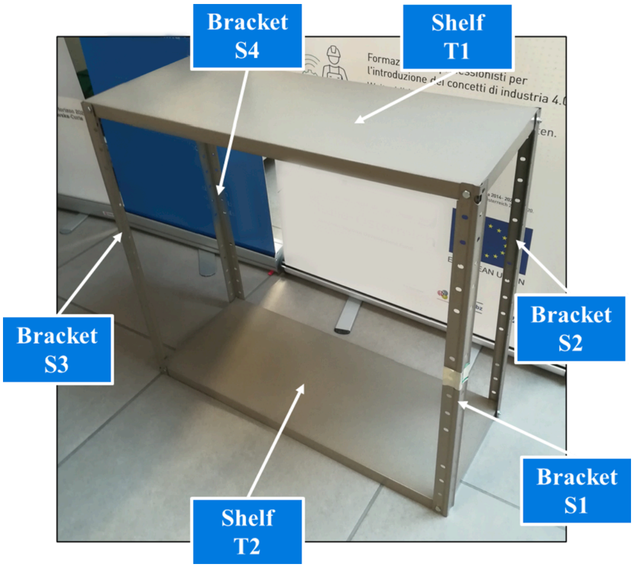


Fig. 2. Medium-sized metal furniture for collaborative assembly.

1. Entrapment of human body parts (see Table 1)
2. Collision of human body parts (see Table 2)
3. Robot system parts falling (see Table 3)
4. Transversal to all mechanical hazards (see Table 4)

These are classified by using multiple interaction variables that characterize a CAS (workstation layout and elements, robot system features, robot system performance and, organizational measures - see Table 5 for details) and according to the objectives to be satisfied in terms of prevention of mechanical hazards. In addition, a priority level for the classification of such guidelines is suggested according to the logic introduced by ISO 12100 (International Organization for Standardization, 2010):

- Lev.1 allows providing safety by system design;
- Lev.2 allows providing safety by using additional protection measures;
- Lev.3 allows providing safety by information.

Therefore, during a CAS design, the proposed guidelines should be applied by considering the following hierarchy: Lev. 1 as first, Lev. 2 as second and, Lev. 3 as third.

It is important to underline that the proposed guidelines refer to HRC in assembly. Nevertheless, since the guidelines are general and objective-oriented, it is possible to argue that these can be easily adapt to various industrial applications of HRI, and not only to the design of CAS.

3. Validation process and experimental setup

3.1. Validation process

The effectiveness of the guidelines has been validated through a laboratory case study performed in the Smart Mini Factory (SMF) laboratory of the Free University of Bolzano-Bozen. The validation process involved three main actors: (i) the research team that developed the guidelines and managed the experiment, (ii) a certified expert in OHS and collaborative robotics for the assessment of mechanical risks and, (iii) a team of three manufacturing engineers with expertise in robotics and manufacturing systems but not in OHS. The validation is based on the assumption that the team of manufacturing engineers should autonomously and gradually apply the guidelines to reduce the mechanical risks in a CAS.

To this end, a CAS for the assembly of metal furniture has been developed (named CAS1) by the research team without considering OHS requirements. This condition should reflect what normally happens in companies (especially SMEs) during the implementation of a collaborative solution: technicians often develop a potential human-robot collaborative application without considering safety requirements at

Table 6
Summary of the tasks of the collaborative assembly cycle.

Human		Task time (s)	Robot system		Task time (s)
H1	Gives a command to the robot system, picks the screws (2x) and inserts them in the rear jiggs (C and D) (2x).	19	R1	Wait for command and picks up the first bracket (S1) from the robot's picking area.	14
H2	Gives a command to the robot system, picks the screws (2x) and inserts them in the frontal jiggs (A and B) (2x)	15	R2	Wait for command and inserts the first bracket (S1) into A-B jiggs.	10
H3	Picks the upper shelf (T1).	7	R3	Picks up the second bracket (S2) from the robot's picking area and inserts it into C-D jiggs.	29
H4	Places upper shelf (T1) into A-C jiggs.	8	R4	Wait for command and holds the upper shelf (T1) in position.	53
H5	Gives a command to the robot system and picks nuts (2x).	6	R5	Wait for command and move to the position for holding the lower shelf (T2).	4
H6	Screws (manually) and tightens (by using the socket wrench) the lower screws-nuts of the upper shelf (T1) (4x).	47	R6	Wait for command and holds the lower shelf (T2) in position.	47
H7	Gives a command to the robot system and picks the lower shelf (T2).	6	R7	Wait for command and picks up the third bracket (S3) from the robot's picking area;	17
H8	Places the lower shelf (T2) into B-D jiggs.	8	R8	Wait for command and places it on the upper shelf (T1) and the lower shelf (T2) (outside).	12
H9	Gives a command to the robot system and picks nuts (2x).	6	R9	Holds the third bracket (S3) in position.	77
*H*10	Screws (manually) and tighten (by using the socket wrench) the lower screws-nuts of the lower shelf (T2) (4x).	41	R10	Wait for command and picks up the fourth bracket (S4) from the robot's picking area	19
*H*11	Gives a command to the robot system and picks screws and nuts (4x + 4x). (Wait for the robot system and gives it a command when ready to continue)	8	R11	Wait for command and places it on the upper shelf (T1) and the lower shelf (T2) (outside).	12
H12	Screws (manually) the upper screws-nuts of the upper shelf (T1) and lower shelf (T2) (4x).	77	R12	Holds the fourth bracket (S4) in position;	51
H13	Gives a command to the robot system and tightens (by using the socket wrench) the upper screws-nuts of the upper shelf (T1) and lower shelf (T2) (4x). (Gives the robot system command when ready to continue)	35	R13	Wait for command and move to the initial position.	11
H14	Picks screws and nuts (4x + 4x).	5			
H15	Screws (manually) the lower screws-nuts of the upper shelf (T1) and the lower shelf (T2) (4x).	47			
H14	Gives a command to the robot system and tightens (by using the socket wrench) the lower screws-nuts of the upper shelf (T1) and the lower shelf (T2) (4x).	84			

an early design stage. Subsequently, a first risk assessment for the analysis of mechanical hazards related to HRC in CAS1 and based on the hybrid method described in ISO TR 14121-2 (ISO/TR 14121-2, 2012) has been performed by the expert in the field. This is one of the methods for risk estimation presented in this technical report. It quantifies qualitative parameters by using numerical scoring and a risk matrix. Annex 1 provides the details about this method and an example of its application for the assessment of mechanical risks in HRC is provided in (Palomba et al., 2021). It is important to notice that this preliminary risk assessment refers only to mechanical hazards and to the operator involved in the assembly activities. Other operators who can potentially be subjected to mechanical hazards related to the presence of the robot system in their workspace (e.g. maintenance workers) are not considered in this study.

In a second step, the team of manufacturing engineers was involved in the experiment: after a brief presentation and introduction in the safety design guidelines for HRC proposed in Section 2, the team had to analyze the existing situation (CAS1) and to autonomously propose a new solution (named CAS2) by interpreting and applying the presented guidelines according to the priority level (note that the group was not aware of the results of the first risk assessment). After the conception of the new solution (CAS2), a digital twin model was created by the research team using “Tecnomatix Process Simulate” from Siemens as a simulation tool (Tecnomatix, 2020) and discussed with the team of manufacturing engineers. Subsequently, the risk assessment was repeated by the OHS expert validating the solutions proposed in the digital twin model. The difference in terms of residual risk values between CAS1 and CAS2 was used to demonstrate the effectiveness of the use of such guidelines. This validation process is illustrated in Fig. 1.

3.2. *Experimental set-up*

The experiment involved light and medium-sized metal furniture as an assembly workpiece (see Fig. 2 for details). This is composed of six parts (four brackets and two shelves) and 16 couples of small-sized screws/nuts. The overall dimension of this assembly is about: 750 mm height; 700 mm width; 300 mm depth.

The experimental setup is represented in Fig. 4. The collaborative assembly cycle involved a Universal Robots model UR10 (highlighted with the number (1) in Fig. 4) to be used as a robotic assistance system and equipped with a Robotiq collaborative gripper (2). This was mounted on a dedicated pedestal (3) designated for the robot's high motion performances and anchored to a standard aluminum workbench (4). The collaborative workspace is defined on the top of such a table. Four jigs (A, B, C, D) mounted on the corners of the table were 3D-printed and used as supports for the clamping of the brackets in the right position. The performances of the robot system were set by partially considering ISO TS 15066 requirements (International Organization for Standardization, 2016). Button commands and an emergency stop (5) are located on the frontal side of the workbench. The boxes for the screws and nuts (6) are freely placed on the table according to the operator's needs. The role of the robot system was to pick (from a dedicated area (7)) and position the brackets in the jiggs as well as to support the operator during the fixing of the shelves. The manual activities referred to the pick and positioning of the shelves and the fix of the screws and nuts. The tasks of the collaborative assembly cycle are summarized in Table 6. The related human-robot chart is presented in Fig. 3. This is a graphical representation of the simultaneous activities of the worker and the collaborative robot system that emphasizes the periods of cooperative work, independent work, and idle time along a time scale (Orzes et al., 2018). The data related to the human's tasks are highlighted in blue, while the ones related to the robot system are highlighted in green. The red areas represent the resource's lead time while the yellow arrows represent the commands given by the operator to enable the robotic tasks.

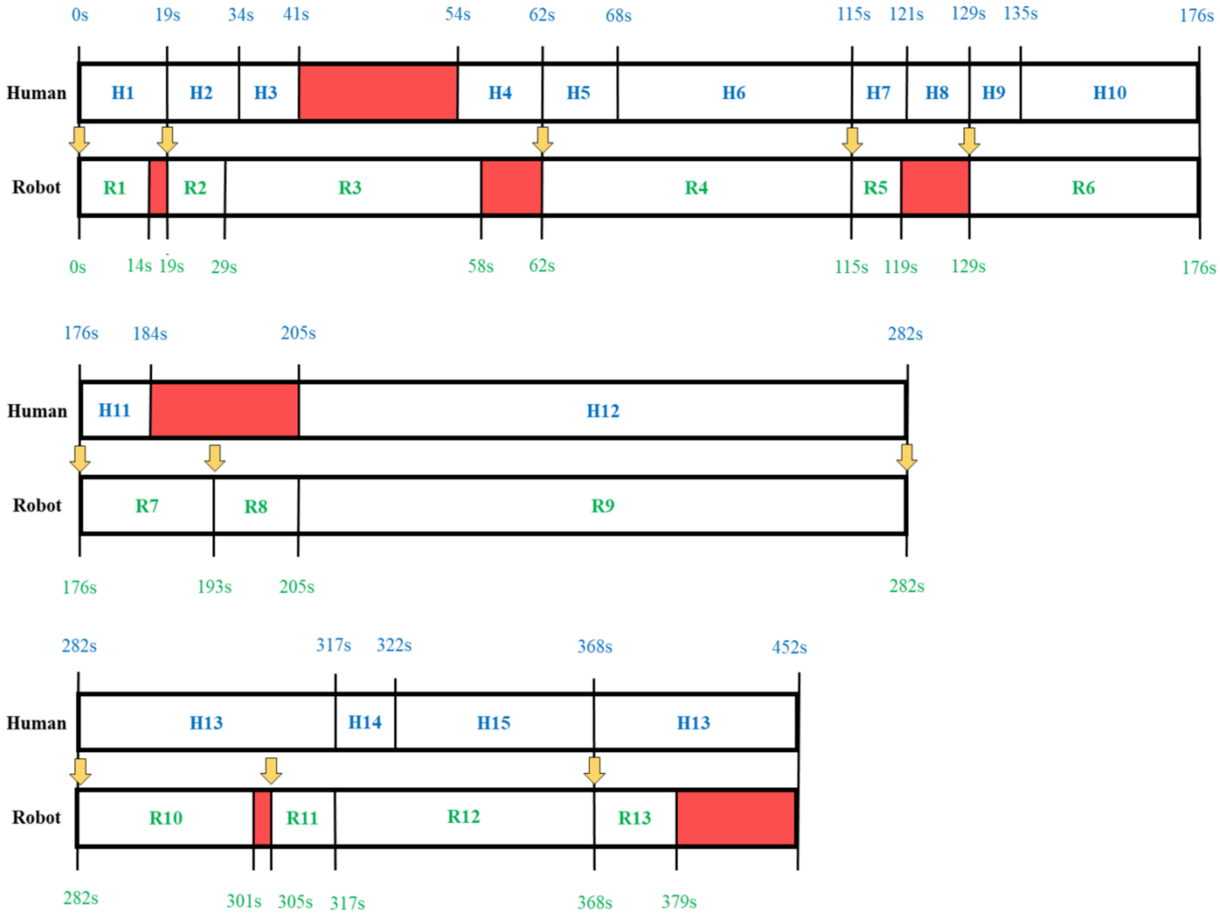


Fig. 3. Human-robot chart according to to the tasks summarized in Table 6.

Table 7
Guidelines implementation (proposed solutions) in the experimental case study.

Implemented guideline	Proposed solution
EH.S.9, EH.S.10, CH.S.6, CH.S.9, PF.S.4, TH.S.6	Separation of the operator's and robot system's workspace by using a dedicated roundtable that moves the assembly from the operator to the robot system and vice-versa. This will allow maintaining always a safe distance for all the time by properly synchronizing the assembly activities;
EH.S.1, CH.S.1	Round of the edges of the roundtable and the workbench. This will limit the possibility to be trapped as well as the severity in case of collisions or crushings.
EH.S.3, CH.S.3	Use of the picking area (shelves) and storage area (final products) as layout elements to restrict access to the robot system's workspace. This will limit the possibility of entering into the robot system's workspace.
EH.S.6	Identification of the workspaces of the robot system and the operator using special colored tapes placed on the floor. This will provide the operator a greater awareness of limits and workspaces.
EH.S.7, EH.S.8, CH.S.7	Implementation of smoother and more predictable trajectories of the robot arm. This will allow the operator to better understand the motions and predict dangerous situations.
TH.S.1	Restriction of access to the CAS to authorized personnel only by using a password. Displacement of the boxes for the screws and nuts and related tools in a fixed location outside the workbench area. These solutions will force the operator to stay close to the robot system only for the time which is strictly necessary for assembly purposes.
TH.S.2	Integration of a command (gesture-based or based on a wearable device) that allows the operator to stop the motion of the robot arm at any time. This will allow the operator to have more control over the assembly cycle and on the robot system operations.
TH.S.4	Development of dedicated safety and operative procedure. This will allow the operator to be informed and trained to deal with unexpected and/or dangerous situations.
TH.S.3, TH.S.5	Integration of a dedicated HMI based on an LCD screen by using a dynamic digital-twin representation. This will allow the operator to understand in advance the robot system's behavior and to prevent dangerous situations.
EH.S.2, CH.S.2, CH.S.5	Inherently applied (use of collaborative robot systems, e.g. the collaborative robot arm and collaborative gripper).

4. Results of the validation in the laboratory case study

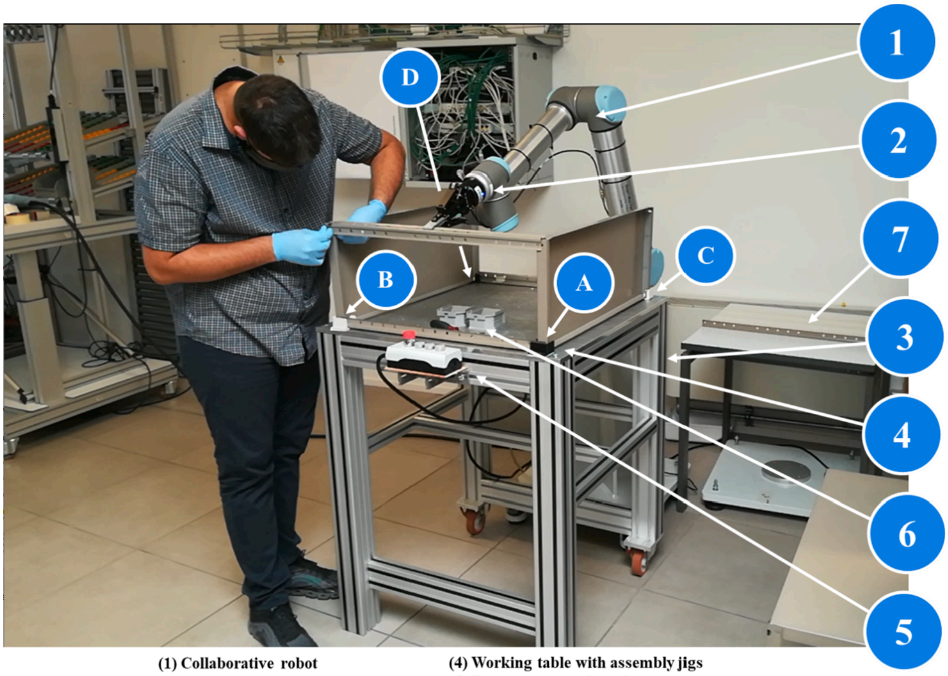
The first risk assessment (performed on CAS1 and based on the hybrid method described in ISO TR 14121-2 (ISO/TR 14121-2, 2012) reveals some hazardous situations characterized by the following values (worst case), which means a "high-risk":

- *Severity (Se)* = 3,
- *Frequency* (*Fr)* = 6,
- *Avoidance* (*Av)* = 3,
- *Probability* (*Pr)* = 3,
- *CI* = *Fr* + *Av* + *Pr* = 12

In particular, this was the situation in which the robot arm (part of link 3, wrist and end-effector) potentially collides with the operator's head/neck/shoulders and/or chest at a limited speed during the

Table 8
Risk assessment based on the hybrid method (ISO/TR 14121-2, 2012) (see Appendix 1) and potential improvements between CAS1 and CAS2 in terms of reduction of mechanical hazards.

Parameter	Risk assessment			Potential improvementand related guidelines
Se	**CAS1**	- The robot arm (part of link 3, wrist and end-effector) potentially collides with the operator's head, neck, shoulders, and/or chest at a limited speed; - The robot arm is massive; - The robot system is collaborative and a Power and Force Limiting safety function (International Organization for Standardization, 2016) is inherently applied.	- $Se = 3$ Normally irreversible injury; it will be slightly difficult to continue work after healing.	$\Delta Se = -1$ (−33%) EH.S.1, CH.S.1, EH.S.9, EH.S.10, CH.S.6, CH.S.9, PF.S.4, TH.S.6, TH.S.4, EH.S.2, CH.S.2, CH.S.5
	CAS2	- The round of the edges of the roundtable and the workbench allows limiting the severity in case of collisions or crushings; - The development of dedicated safety and operative procedure allows the operator to be informed and trained to deal with unexpected and/or dangerous situations; - The robot system is collaborative and a Power and Force Limiting safety function (International Organization for Standardization, 2016) is inherently applied.	- $Se = 2$ More severe scratches, bruises, stabbing, which require medical attention from professionals.	
Fr	**CAS1**	- According to the organization of the assembly cycle and layout, the robot system and operator are simultaneously sharing the workspace for most of the time; - The boxes for the screws and nuts are freely placed on the table forcing the operator to stay in the shared workspace longer than the necessary time.	- $Fr = 6$ Interval less than or equal to an hour	$\Delta Fr = -2$ (−33%) EH.S.9, EH.S.10, CH.S.6, CH.S.9, PF.S.4, TH.S.6, TH.S.1, TH.S.4
	CAS2	- The separation of the operator's and the robot system's workspace by using a dedicated roundtable allows the synchronization of the assembly activities by avoiding the simultaneous sharing of the workspace; - A restriction of access to the CAS to authorized personnel only by using a password is proposed. Furthermore, the boxes for the screws and nuts and related tools are supposed to be displayed in a fixed location outside the workbench area. These solutions will force the operator to stay close to the robot system only for the time which is strictly necessary for assembly purposes; - The development of dedicated safety and operative procedure allows the operator to be informed and trained to deal with unexpected and/or dangerous situations.	- $Fr = 4$ Interval between exposure is more than a day but less than or equal to two weeks;	
Av	**CAS1**	- The robot arm speed is low and the motions are always the same for every assembly cycle; - There are no measures to inform the operator about the motions of the robot arm.	- $Av = 3$ Possible: for example, it is possible to avoid an entanglement hazard where the speed is slow.	$\Delta Av = -2$ (-67%) EH.S.6, EH.S.7, EH.S.8, CH.S.7, TH.S.4, TH.S.3, TH.S.5
	CAS2	- The robot arm speed is low and the motions are always the same for every assembly cycle; - Special colored tapes placed on the floor allows the identification of the workspaces of the robot system and the operator by providing a greater awareness of limits and workspaces; - Smoother and more predictable trajectories of the robot arm allow the operator to better understand the motion and to predict dangerous situations; - The integration of a dedicated HMI based on an LCD screen by using a dynamic digital-twin representation allows the operator to understand in advance the robot system's behavior and to prevent dangerous situations; - The development of dedicated safety and operative procedure allows the operator to be informed and trained to deal with unexpected and/or dangerous situations.	- $Av = 1$ Likely: for example, it is likely that contact with moving parts behind an interlocked guard will be avoided in most cases should the interlocking fail and the movements continue.	
Pr	**CAS1**	- During the robotic tasks, the operator is focused on performing manual operations (in parallel) and cannot pay attention to the robot system's motions and activities; - There are several points in the collaborative workspace where the operator may become accidentally entangled with clothing or devices in use.	- $Pr = 3$ Possible: for example, this kind of component can fail so a hazardous event occurs. Human error is possible.	$\Delta Pr = -2$ (-67%) EH.S.1, CH.S.1, EH.S.3, CH.S.3, TH.S.4,
	CAS2	- The round of the edges of the roundtable and the workbench allows limiting the possibility to be trapped in case of collisions or crushings; - The use of the picking area (for shelves) and storage area (for final products) as layout elements to restrict access to the robot system's workspace will limit the possibility for the operator to enter into the robot system's workspace; - The development of dedicated safety and operative procedure allows the operator to be informed and trained to deal with unexpected and/or dangerous situations.	- $Pr = 1$ Negligible: for example, this kind of component never fails so that a hazardous event occurs. No possibility of human error	
CI and risk class	**CAS1**	$CI = 12$ ($Se = 3$); High risk		$\Delta CI = -6$
	CAS2	$CI = 6$ ($Se = 2$); Risk is under control		



(1) Collaborative robot
(2) Collaborative gripper
(3) Robot pedestal
(4) Working table with assembly jigs
(5) Button commands and emergency stop
(6) Boxes for assembly parts
(7) Robot's picking area

Fig. 4. Experimental set-up: a researcher plays the role of the operator during the collaborative assembly in CAS1.

automatic positioning of the brackets in the shared workspace. In the meantime, the operator is focused on performing manual operations (in parallel) and cannot pay attention to the robot's motions and tasks. Since the assembly lasts about 7.5 min, this situation is (theoretically) repeated many times during a typical 8-hours work shift, making this kind of collision probable. Furthermore, there are no additional safety measures in the CAS with respect to the inherent ones of the robotic arm (power and force limiting functions (International Organization for Standardization, 2016) for further safeguarding the operator (e.g. audio/visual information about the robot system's status or a vision system for the implementation of speed and separation monitoring (International Organization for Standardization, 2016). As indicated, the residual risk values were not adequate and further improvements were needed urgently (see Table 8 for details about the risk assessment).

Following, Table 7 summarizes the main solutions proposed by the team of manufacturing engineers for the system re-design (CAS2). These were developed by applying the safety guidelines according to the priority level. Fig. 5 represents the digital twin model of CAS2. This virtual model was developed according to the solutions provided by the team of engineers. The model was also discussed with the research team and approved before proceeding with the second assessment of mechanical risks.

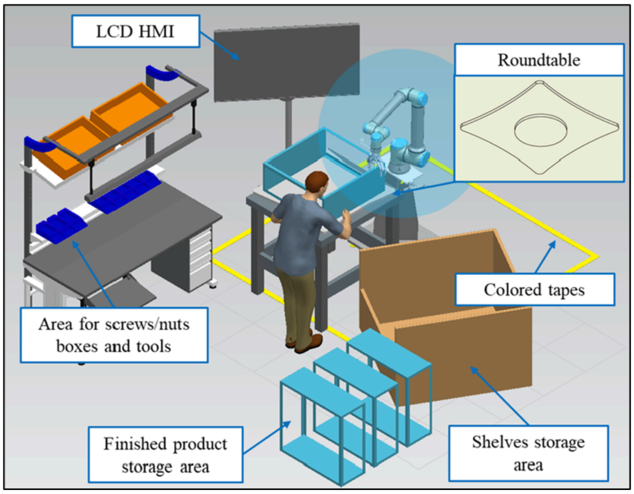


Fig. 5. Digital twin model of CAS2 (the robot system's workspace is highlighted by the blue sphere).

The proposed solutions allowed a potential general improvement of the operator's safety from the point of view of the mechanical hazards. In particular, the new risk assessment reveals the following values for CAS2 (from originally "high-risk" with $Se = 3$ and $CI = 12$ to "risk under control" with $Se = 2$ and $CI = 6$):

- *Severity (Se)* = 2 (originally 3),
- *Frequency (Fr)* = 4 (originally 6),
- *Avoidance (Av)* = 1 (originally 3),
- *Probability (Pr)* = 1 (originally 3),
- $CI = Fr + Av + Pr = 6$ (originally 12).

Following, Table 8 and Fig. 6 summarize the achieved reduction of mechanical risk levels between CAS1 (no guidelines applied) and CAS2 (guidelines applied).

5. Discussion and conclusions

5.1. Discussions of results

Considering the (mechanical) risk assessment of CAS2, the residual risk value results under control (estimated $Se = 2$ and $CI = 6$). In particular, all the parameters reduced significantly and strongly contributed to the reduction of the risk class: −33% for *Se*, −33% for *Fr*, −67% for *Av* and −67% for *Pr*. Main improvements are related to the separation of the operator's and robot system's workspaces by using the roundtable (synchronization of activities) and to the new layout which limits the operator's movements outside the robot system's workspace. All these conditions positively reduced the frequency and duration of

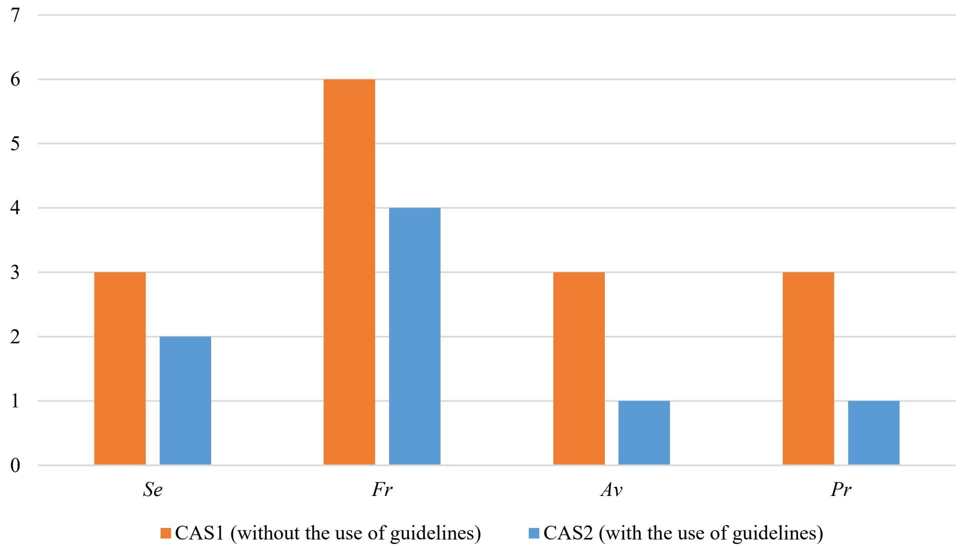


Fig. 6. Final results in terms of reduction of mechanical risks between CAS1 and CAS2.

exposure to hazardous events as well as the likelihood of occurrence of dangerous situations. In addition, even though these are non-stimulable measures, the possibility to have more control on the cycle, the round of the edges, the use of more predictable robot arm trajectories, the integration of the HMI based on the digital-twin, the restriction of the access to the CAS only to authorized operators, the development of dedicated operational and safety procedures may have a further (but not directly quantifiable) positive effect on the mitigation of mechanical hazards.

5.2. Limitations of the work

The proposed work presents some limitations. Nevertheless, the achieved results can be considered satisfying and the proposed approach promising, especially for the preliminary development of safety solutions in CASs. Following, the main limitations are briefly discussed.

Due to the difficulties and time required for the realization of a real CAS, the proposed validation process is based on a virtual model. Even if state-of-the-art software for simulation are very effective in approximating reality, this simplification may affect the reliability of the results. To minimize such a risk the research team used also Virtual Reality equipment (Occulus Rift headset) for the second risk assessment by the OHS expert. Considering the importance of safety in HRC, future advancements should provide a more reliable risk assessment by integrating the results of the virtual model with the ones obtainable by analyzing a real CAS located in a relevant industrial environment.

The validation was based on only one test case which involved three manufacturing engineers. The risk assessment is preliminary and refers only to the operator involved in the assembly. Future works should enlarge the number of case studies to be tested as well as the number of people involved in the validation phase. Furthermore, the risk assessment should be comprehensive and consider the role of other operators who can potentially be subjected to mechanical hazards related to the presence of the robot system in their workspace (e.g. maintenance workers).

This work presents a first classification of the guidelines according to the objective to be satisfied by proposing a “priority level” and considering the various interaction variables that characterize a CAS. This classification should preliminarily guide the designer into the selection of the most suitable set of guidelines according to the specific design problems/requirements. Among the guidelines that refer to the same classification (e.g. all the lev.1 guidelines), this work did not analyze the hierarchical relationships between the various guidelines, as well as possible inconsistencies in their implementation. Future works should focus more also on this aspect.

Finally, there can be possible barriers to the implementation of such guidelines in an industrial environment. Also, according to the feedback provided by the team of engineers involved in the experiment, these are discussed in the following.

- The guidelines involved an extra effort for their implementation. This can be considered in terms of costs and/or time for the development of related solutions (e.g. the purchase, installation, and configuration of an additional safety system);
- Even if one of the main goals of such work is the development of design principles that can be used by non-experts in the field, the judgment of an expert in the field of safety of machinery/collaborative robotics to support the decisions of the system designers remains necessary (e.g., for a proper evaluation of the results by using the “hybrid method” (ISO/TR 14121-2, 2012) for mechanical risk assessment);
- As for other manufacturing systems design, designers should consider the technical resources of the company while defining the solutions according to the guidelines (e.g. the availability of an internal programmer able to set the trajectories of the robot in a certain way).

Such barriers can be partially overtaken by preliminary explaining the content of the guidelines (also providing some relevant examples of application) through a dedicated training session for the CAS designers provided by experts in the field. An additional solution might be to integrate the guidelines into smart and computer-aided tools to further support unskilled designers in their decisions.

5.3. Conclusions

This work refers to the prevention of mechanical hazards in industrial HRC and aims at simplifying the development of CAS. In particular, a set of guidelines for the design of the features characterizing the final system are developed and validated. According to the existing literature, the use of international standards and deliverables related to safety in industrial robotics may be complex and time-consuming for designers (Gualtieri et al., 2018). Furthermore, companies often struggle with their use since requirements are perceived as overly complex and demanding in terms of documentation and investment, a challenge that is aggravated when production processes start involving dynamically planned workflows (Shafei, Hodges, & Mayer, 2018).

On the other hand, many scientific works focus on specific aspects of safety in HRC (see Section 1.2 for a detailed discussion). Although these studies are of high scientific relevance, they usually do not consider a systemic view. Therefore, the guidelines proposed in this work have been set to be more general and to propose different solutions and safety measures useful for the whole CAS. Furthermore, they consider both the indications provided by the state-of-the-art standards/deliverables and robotic manufacturers as well as the latest scientific advancements.

The proposed design guidelines have been validated by means of a laboratory case study and a virtual model based on a digital twin. According to the results, it is possible to argue that the proposed guidelines effectively helped non-expert users in the development/improvement of the preliminary CAS concept from the safety point of view. Nonetheless, expert judgment to support the decisions of the system designers remains necessary.

According to these considerations, the proposed research questions have been addressed since the proposed design guidelines will support companies (especially SMEs) in standardizing their implementation of CAS from the safety perspective. This will allow the following main advantages:

- improving the safety of the operators working in a collaborative workspace;
- reducing the subjectivity involved in the design of safety solutions;
- reducing the time needed for the integration of the safety measures and related risk assessment.

Furthermore, the guidelines should help technicians and non-experts in fulfilling their (possible) lack of knowledge and skills by overcoming the technology barrier associated with safety in collaborative robotics.

CRediT authorship contribution statement

Luca Gualtieri: Conceptualization, Methodology, Writing – original draft. **Erwin Rauch:** Methodology, Validation, Supervision, Writing – review & editing. **Renato Vidoni:** Supervision, Writing – review & editing.

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.

Acknowledgment

This work was supported by the Open Access Publishing Fund of the Free University of Bozen-Bolzano.

Appendix A. Hybrid method for risk assessment according to ISO TR 14121-2

In the following, the so-called "hybrid method" for risk assessment for the safety of machinery is introduced according to ISO TR 14121-2 (ISO/TR 14121-2, 2012). In general, this document gives practical guidance on conducting a risk assessment for machinery in accordance with ISO 12100 (International Organization for Standardization, 2010) and describes various methods and tools for each step in the process. In particular, the hybrid method is the most effective approach for risk estimation presented in this technical report. It quantifies qualitative parameters by using numerical scoring and a risk matrix. In practice, the risk is estimated by using the combination of four parameters: Severity (Se), Frequency (Fr), Probability (Pr) and, Avoidance (Av). Table 9 explains how it is possible to define a value for such parameters. The risk is estimated through the calculation of the risk class ($CI = Fr + Pr + Av$) in accordance with the Se value and results in three different risk classes: low, medium and, high (which are respectively represented by the color green, yellow and red in Table 10).

Table 9

Estimation of Severity (Se), Frequency (Fr), Probability (Pr) and Avoidance (Av) according to the hybrid method (ISO TR 14121-2 (ISO/TR 14121-2, 2012).

Parameter description and associated values
Severity (Se) Se is the severity of possible harm as an outcome from the identified hazard. The severity is scored as follows: 1 = scratches, bruises that are cured by first aid or similar; 2 = more severe scratches, bruises, stabbing, which require medical attention from professionals; 3 = normally irreversible injury; it will be slightly difficult to continue work after healing; 4 = irreversible injury in such a way that it will be very difficult to continue work after healing, if possible at all.
Frequency (Fr) Fr is the average interval between frequency of exposure and its duration. The frequency is scored as follows: 2 = interval between exposure is more than a year; 3 = interval between exposure is more than two weeks but less than or equal to a year; 4 = interval between exposure is more than a day but less than or equal to two weeks; 5 = interval between exposure is more than an hour but less than or equal to a day. Where the duration is shorter than 10 min, the above values may be decreased to the next level. 6 = interval less than or equal to an hour. This value is not to be decreased at any time.
Probability (Pr) Pr is the probability of occurrence of a hazardous event. Consider, for example, human behavior, reliability of components, accident history and the nature of the component or system (e.g. a knife is always sharp, a pipe in a dairy environment is hot, electricity is dangerous by its nature) to determine the level of probability. The probability is scored as follows: 1 = Negligible: for example, this kind of component never fails so that a hazardous event occurs. No possibility of human error. 2 = Rarely: for example, it is unlikely that this kind of component will fail so that a hazardous event occurs. Human error is unlikely. 3 = Possible: for example, this kind of component can fail so a hazardous event occurs. Human error is possible. 4 = Likely: for example, this kind of component will probably fail so a hazardous event occurs. Human error is likely. 5 = Very high: for example, this kind of component is not made for this application. It will fail so that a hazardous event occurs. Human behavior is such that the likelihood of error is very high.
Avoidance (Av) Av is the possibility of avoiding or limiting harm. Consider, for example, whether the machine is to be operated by skilled or unskilled persons, how quickly a hazardous situation can lead to harm, and the awareness of risk by means of general information, direct observation or through warning signs, so as to determine the level of avoidance. The possibility of avoidance is scored as follows: 1 = Likely: for example, it is likely that contact with moving parts behind an interlocked guard will be avoided in most cases should the interlocking fail and the movements continue. 3 = Possible: for example, it is possible to avoid an entanglement hazard where the speed is slow. 5 = Impossible: for example, it is impossible to avoid the sudden appearance

Table 10
Risk matrix according to the hybrid method (ISO TR 14121-2 (Robla-Gomez et al., 2017).

Se	***CI***				
	3-4	**5-7**	**8-10**	**11-13**	**14-15**
4	🟨	🟥	🟥	🟥	🟥
3	🟩	🟨	🟥	🟥	🟥
2	🟩	🟩	🟨	🟥	🟥
1	🟩	🟩	🟩	🟨	🟥

References

Antonelli, D., & Stadnicka, D. (2019). Predicting and preventing mistakes in human-robot collaborative assembly. *IFAC-PapersOnLine, 52*(13), 743–748.

Askarpour, M., Mandrioli, D., Rossi, M., & Vicentini, F. (2019). Formal model of human erroneous behavior for safety analysis in collaborative robotics. *Robotics and Computer-Integrated Manufacturing, 57*, 465–476.

Awad, R., Fechter, M., & van Heerden, J. (2017). Integrated risk assessment and safety consideration during design of HRC workplaces. In *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 1–10). IEEE.

Beluško, M., Hegedüš, M., & Fedorko, G. (2016). Creating Visual Work Instructions to Ensure Safe and Fluent Operation of the Semi-automatic Production Lines. *Open Engineering, 1*(open-issue).

Chemweno, P., Pintelon, L., & Decre, W. (2020). Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems. *Safety Science, 129*, 104832. https://doi.org/10.1016/j.ssci.2020.104832

Cimini, C., Pezzotta, G., Pinto, R., & Cavalieri, S. (2018). Industry 4.0 technologies impacts in the manufacturing and supply chain Landscape: an overview. In *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing* (pp. 109–120). Cham: Springer.

Cimini, C., Pirola, F., Pinto, R., & Cavalieri, S. (2020). A human-in-the-loop manufacturing control architecture for the next generation of production systems. *Journal of Manufacturing Systems, 54*, 258–271.

Gervasi, R., Mastrogiacomo, L., & Franceschini, F. (2020). A conceptual framework to evaluate human-robot collaboration. *The International Journal of Advanced Manufacturing Technology, 108*(3), 841–865.

Gopinath, V., & Johansen, K. (2016). Risk assessment process for collaborative assembly–a job safety analysis approach. *Procedia CIRP, 44*, 199–203.

Gopinath, V., Johansen, K., & Derelöv, M. (2018). Demonstrators to support research in Industrial safety–A Methodology. *Procedia Manufacturing, 17*, 246–253.

Gopinath, V., Ore, F., & Johansen, K. (2017). Safe assembly cell layout through risk assessment–an application with hand guided industrial robot. *Procedia CIRP, 63*, 430–435.

Gualtieri, L., Palomba, I., Wehrle, E. J., & Vidoni, R. (2020). The Opportunities and Challenges in SME Manufacturing Automation through Safety and Ergonomics in Human-Robot Collaboration. In D. T. Matt, V. Modrak, & H. Zsifkovits (Eds.), *Industry 4.0 for SMEs Challenges, Opportunities and Requirements* (pp. 105–144). Basingstoke: Palgrave Macmillan.

Gualtieri, L., Rauch, E., Rojas, R., Vidoni, R., Matt, D. T., Puik, E. C. N., Foley, J. T., Cochran, D. S., & Betasolo, M. L. (2018). Application of Axiomatic Design for the design of a safe collaborative human-robot assembly workplace. *MATEC Web of Conferences, 223*, 01003. https://doi.org/10.1051/matecconf/201822301003

Gualtieri, L., Rauch, E., & Vidoni, R. (2021). Methodology for the definition of the optimal assembly cycle and calculation of the optimized assembly cycle time in human-robot collaborative assembly. *The International Journal of Advanced Manufacturing Technology, 113*(7-8), 2369–2384.

Gualtieri, L., Rauch, E., Vidoni, R., & Matt, D. T. (2020). Safety, Ergonomics and Efficiency in Human-Robot Collaborative Assembly: Design Guidelines and Requirements. *Procedia CIRP, 91*, 367–372.

International Organization for Standardization (2010). Safety of Machinery – General Principles for Design-Risk Assessment and Risk Reduction (ISO 12100:2010). https://www.iso.org/standard/51528.html.

International Organization for Standardization (2011). Robots and Robotic Devices – Safety Requirements for Industrial Robots – Part 2: Robot Systems and Integration (ISO 10218-2:2011). https://www.iso.org/standard/41571.html.

International Organization for Standardization (2011). Robots and Robotic Devices – Safety Requirements for Industrial Robots – Part 1: Robots (ISO 10218-1:2011). https://www.iso.org/standard/51330.html.

International Organization for Standardization (2016). ISO TS 15066 – Robots and Robotic Devices – Collaborative Robots (ISO/TS 15066:2016). https://www.iso.org/standard/62996.html.

International Organization for Standardization (2018). Robotics – Safety Design for Industrial Robot Systems – Part 1: End-Effectors (ISO/TR 20218:2018). https://www.iso.org/standard/69488.html.

ISO/TR 14121-2:2012. International Organization for Standardization. 2012. Safety of machinery – Risk assessment – Part 2: Practical guidance and examples of methods. (ISO/TR 14121-2:2012). https://www.iso.org/standard/57180.html.

Jespen, T. (2016). *Risk Assessments and Safe Machinery: Ensuring Compliance with the EU Directives*. Springer.

Koch, T., & Soltani, B. (2019). Safeguarding of an automated assembly process using a Balanced Decoupling Unit and the HRC switching mode. *Procedia CIRP, 81*, 328–333.

Kuka Roboter GmbH (2016). KUKA Sunrise.OS 1.11. Operating and Programming Instructions for System Integrators.

Liu, Z., Wang, X., Cai, Y., Xu, W., Liu, Q., Zhou, Z., & Pham, D. T. (2020). Dynamic risk assessment and active response strategy for industrial human-robot collaboration. *Computers & Industrial Engineering, 141*, 106302. https://doi.org/10.1016/j.cie.2020.106302

Maeda, I., Nobuhiro, M., Shimizu, T., Okada, K., Dohi, M., Fujitani, S., … Fujita, T. (2018). New New concept of safety to realize improvement of higher productivity and safety in an environment of human-robot collaboration, and proposal of the concept of Collaboration Safety Level. In *ISR 2018; 50th International Symposium on Robotics* (pp. 1–6). VDE.

Marvel, J. A. (2017). Sensors for safe, collaborative robots in smart manufacturing. In *2017 IEEE SENSORS* (pp. 1–3). IEEE.

Michalos, G., Kousi, N., Karagiannis, P., Gkournelos, C., Dimoulas, K., Koukas, S., … Makris, S. (2018). Seamless human robot collaborative assembly–An automotive case study. *Mechatronics, 55*, 194–211.

Orzes, G., Rauch, E., Bednar, S., & Poklemba, R. (2018). Industry 4.0 implementation barriers in small and medium sized enterprises: A focus group study. In *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 1348–1352). IEEE.

Palomba, I., Gualtieri, L., Rojas, R., Rauch, E., Vidoni, R., & Ghedin, A. (2021). Mechatronic Re-Design of a Manual Assembly Workstation into a Collaborative One for Wire Harness Assemblies. *Robotics, 10*, 43.

Pinzone, M., Albè, F., Orlandelli, D., Barletta, I., Berlin, C., Johansson, B., & Taisch, M. (2020). A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems. *Computers & Industrial Engineering, 139*, 105132. https://doi.org/10.1016/j.cie.2018.03.028

Poot, L., Johansen, K., & Gopinath, V. (2018). Supporting risk assessment of human-robot collaborative production layouts: A proposed design automation framework. *Procedia Manufacturing, 25*, 543–548.

Robla-Gomez, S., Becerra, V. M., Llata, J. R., Gonzalez-Sarabia, E., Torre-Ferrero, C., & Perez-Oria, J. (2017). Working together: A review on safe human-robot collaboration in industrial environments. *IEEE Access, 5*, 26754–26773.

Saenz, J., Behrens, R., Schulenburg, E., Petersen, H., Gibaru, O., Neto, P., & Elkmann, N. (2020). Methods for considering safety in design of robotics applications featuring human-robot collaboration. *The International Journal of Advanced Manufacturing Technology, 107*(5-6), 2313–2331.

Salvietti, G., Iqbal, Z., Hussain, I., Prattichizzo, D., & Malvezzi, M. (2018). The co-gripper: a wireless cooperative gripper for safe human robot interaction. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 4576–4581). IEEE.

Schlotzhauer, A., Kaiser, L., Wachter, J., Brandstötter, M., & Hofbaur, M. (2019). On the trustability of the safety measures of collaborative robots: 2D Collision-force-map of a sensitive manipulator for safe HRC. In *2019 IEEE 15th international conference on automation science and engineering (CASE)* (pp. 1676–1683). IEEE.

Shafei, A., Hodges, J., & Mayer, S. (2018). Ensuring Workplace Safety in Goal-based Industrial Manufacturing Systems. *Procedia Computer Science, 137*, 90–101.

Tecnomatix (2020). https://www.plm.automation.siemens.com/global/en/products/tecnomatix/. Visited on February 2021.

Universal Robots (2018). UR3/CB3 Version 3.6.0 Original instructions.

Zacharaki, A., Kostavelis, I., Gasteratos, A., & Dokas, I. (2020). Safety bounds in human robot interaction: A survey. *Safety science, 127*, 104667. https://doi.org/10.1016/j.ssci.2020.104667

Luca Gualtieri is research fellow in the Smart Mani Factory lab at the Faculty of Science and Technology, Free University of Bolzano. He received his M.Sc. in Industrial Engineering (major: logistics and production) from the University of Padova, Italy, in 2016 and is a PhD candidate at the Free University of Bolzano. He is responsible for research in the field of industrial collaborative robotics focusing on human-machine interaction from the point of view of the operator's occupational health and safety, ergonomics and shared workplace organisation. ORCID https://orcid.org/0000-0002-4976-1893.

Erwin Rauch is an Assistant Professor of Manufacturing Technology and Systems at the Faculty of Science and Technology at the Free University of Bolzano. He studied at the Free University of Bolzano, at the Technical University in Munich and got his PhD at the University of Stuttgart. He was Visiting Scholar at WPI Worcester Polytechnic Institute and Chiang Mai University. His main research interests are the design of smart manufacturing systems, Industry 4.0, sustainable manufacturing, assistance systems in production and axiomatic design. He is also head of the Smart Mini Factory laboratory for Industry 4.0 in SMEs at the Free University of Bolzano. ORCID https://orcid.org/0000-0002-2033-4265.

Renato Vidoni, Full Professor, received his M.Sc. in Electronic Engineering (major: Automation) from the University of Udine, Italy, in 2005. In 2009, he obtained his Ph.D. degree in Industrial and Information Engineering from the University of Udine, Italy. Currently, he is Full Professor in Applied Mechanics, mechatronics and robotics at the Faculty of Science and Technology of the Free University of Bolzano. His research activity is in the mechatronic and robotics field with more than 100 international publications. In particular, his research interests include high-performance (energy, vibration, safety, collaborative) automatic machines with rigid and flexible links; optimal motion planning of industrial (collaborative) robotic systems; from nature / to nature robotic and mechatronic systems. ORCID https://orcid.org/0000-0002-7429-0974.