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Published online: 28 Sep 2022.

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A human-oriented design process for collaborative robotics

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ABSTRACT

The potential of collaborative robotics often does not materialize in an efficient design of the human-robot collaboration. Technology-oriented approaches are no longer enough in the Industry 4.0 era. This work proposes a set of methods to support manufacturing engineers in the human-oriented design process of integrated production systems to obtain satisfactory performance in the mass customization paradigm, without impacting the safety and health of workers. It founds the design criteria definition on five main pillars (safety, ergonomics, effectiveness, flexibility, and costs), favors the consideration of different design alternatives, and leads their selection. The dynamic impact of the design choices on the various elements of the system prevails over the static design constraints. The method has been experimented in collaboration with the major kitchen manufacturer in Italy, which introduced a collaborative robotics cell in the drawers' assembly line. It resulted in a more balanced production line (10% more), a verified risk minimization (RULA score reduced from 5 to 3 and OCRA score from 13.30 to 5.70), and a greater allocation of operators to high added value activities.

1. Introduction

Collaborative robotics successfully responds to all the principles of Industry 4.0, confirming itself as one of the main enabling technologies, well-integrated with the others (machine learning, industrial internet of things, etc.), of the new industrial paradigm. The central role is played by the interconnection between man, machine, and digitization. Significant efforts have been made by the research and the industrial communities to extend the collaboration between humans and robots in industrial robotics toward a more integrated and safer environment. Industrial robotics have adopted new methodologies, pervasive sensing, and control strategies able to create a cooperative freely shared workspace (Pedrocchi et al. 2013).

Collaborative robots make it easier to commission and program them, as well as easing the operators' workload. There are operations in which the precision and reliability of the robot cannot be matched by humans and vice versa that are operations too complex to be performed by the robot. Cobots are the best candidates for strenuous, non-ergonomically, repetitive, and monotonous tasks, leading to an improvement in the ergonomics of

workplaces and working conditions in general. In fact, awkward posture, repetitive work, and heavy physical work are among the main causes of work-related musculoskeletal disorders (WMSDs), the most common health problem affecting roughly three out of every five workers in the EU-28 (EU-OSHA, 2019). WMSDs can potentially lead to pain, functional limitations, impairment, and absence, as well as a significant socio-economic impact (Korhan et al., 2019), and because of workforce aging, the incidence of WMSDs is rapidly increasing. Cobots could also contribute to the reduction of work-related stress, considering that its hazards are mainly related to work content and organization such as monotony, tasks meaningless, inadequate workload, fast work pace, lack of participation in decision-making, and lack of control over work processes (Houtman, Jettinghoff, and Cedillo 2007). However, a two-way trust is mandatory to reach a satisfactory human-robot collaboration (HRC) and assembly performance (Rahman and Wang 2018), making human factors even more important in HRC design. Trust can be achieved with predictive and reactive models capable of increasing mutual knowledge, awareness, and adaptability. For

example, Psarakis, Nathanael, and Marmaras (2022) aimed to investigate the benefits of fostering anticipatory behavior of the human operator in HRC and robot adaptiveness to human actions, using appropriate communicative means. Research is making robots increasingly able to respond in real-time to human behaviors and events in the surrounding environment. As shown by Liu and Wang (2017), an efficient HRC system should be able to understand a human worker's intention and assist him during the task execution.

The transition from a mass production model to a mass customization model, with a high number of variants and a short product life cycle, entails significant challenges for the manufacturing industry, which must necessarily resort to flexible production solutions. In this regard, HRC allows combining the advantages of double flexibility, the material one of the robots and the intellectual one of the humans. Recent advancements in lightweight low-cost flexible robots have extended these opportunities to Small and Medium-sized Enterprises (SMEs); however, there is still a need for support in the evaluation and design of a collaborative robotics cell. It is important for the company to introduce the cobot to determine what the objectives are and how to strategically allocate the tasks. In fact, the companies' advantages deriving from the introduction of a cobot do not lie in the simple automation of an operation or workspace sharing with humans, but in the flexibility and productivity gained by allocating man to value-added activities.

Role assignments and the effects of human tasks are however often implemented as a further layer of integration, on top of the selection of general-purpose suitable hardware and after having determined some safety constraints (Vicentini 2021). It results in a poor design that does not take into account the effects that equipment, layout, workflows, and task allocation have on each other and above all on the assessment of ergonomic and safety risks. The technology-driven design must progress towards a human-driven one, which is not based only on static constraints but consider the correlations between different drivers and features, preserving human health first of all. Costing and managing conflicting goals are other important issues to address. Weckenborg, Thies, and Spengler (2022) deal with the trade-offs between ergonomic and economic objectives in assembly line balancing, using collaborative robots to harmonize the conflicting objectives.

In this context, the present work aims to give a further contribution to the state of the art by proposing a method for the human-oriented design of HRC. It aims to address the following issues: (i) provide a structured and multi-criteria HRC design method; (ii) give priority to human health and safety by considering these aspects in the design criteria definition and the evaluation of design alternatives; (iii) support engineers in the consideration and evaluation of all alternatives; (iv) investigate the method applicability in a real industrial context.

The rest of the paper is organized as follows. Section 2 provides a critical analysis of the most relevant scientific literature on design methods for HRC. Section 3 presents the definition of the design criteria that should be considered for the HRC design. Section 4 describes the proposed method for the human-oriented design of HRC. In Section 5 the industrial case study is reported; it consists of the application of the proposed method for the design of collaborative robotics cell in the drawers' assembly line of a kitchen manufacturing industry. Section 6 presents the virtual simulation of the designed collaborative workstation and outlines the preliminary results. Section 7 shows the main results and Section 8 critically reviews the work, and highlights both its strengths and limitations; it also encloses suggestions for future research.

2. State of the art

The HRC becomes the new frontier in industrial robotics and plays a crucial role for manufacturing companies to be competitive. However, the implementation of collaborative robotics in industrial processes involves various challenges to be addressed. This paper aims at defining a human-oriented method for the HRC design, which represents one of these open issues (Villani et al. 2018). The introduction of a cobot is not limited to a simple installation procedure, but it involves a radical change in the working paradigm. Stadnicka and Antonelli (2019) see lean philosophy as a valid support for this transition and suggested the systematic implementation of lean tools for the collaborative work cell design. Beyond the production paradigm, several aspects (safety,

ergonomics, productivity, flexibility, etc.) need to be considered for the HRC design process. However, there is a lack of comprehensive methodologies that support the HRC design at the early phases and existing approaches mainly face the task allocation issue (Ore, Hansson, and Wiktorsson 2017). Scheduling is certainly a key aspect of HRC as it significantly determines its performance and affects the operator's well-being. Several research works are including human factors in the definition of sequence planning, considering human characteristics and fatigue (Li et al. 2019), human functional overload (Costa Mateus et al. 2019), or safety implications (Malik et al., 2019). However, the task allocation is often treated after the introduction of a cobot in the production process and is not considered in the design phase to support the choice between different design alternatives. Raatz et al. (2020), which proposed a genetic algorithm to find an eligible division of tasks between human and robot, suggested optimizing their approach by correlating it with the layout and product design. Combining design and scheduling issues would reduce cycle time, as well as support the implementation of HRC work cells.

Gjeldum et al. (2021) pointed out the necessity to integrate criteria interdependence, specific criteria requirements, and decision-makers preferences in the HRC design methodology. However, they addressed only the task allocation aspect proposing a goal-oriented procedure for HRC work cell implementation. Even Berg, Gebauer, and Reinhart (2019) proposed a multicriteria approach, but it is used for the evaluation and the comparison of different layouts for assembly activities to guarantee an efficient collaboration. Tsarouchi et al. (2017) proposed a tool to automatically generate a workcell layout and task planning between human and robot. From the ergonomics point of view, they only estimate the average human muscles strain percentage when comparing design alternatives in the simulation environment.

Although several studies addressed the HRC design process, few works proposed comprehensive methods that consider multiple criteria to support industries in the design and the implementation of collaborative robotics in their production processes. Rega et al. (2021) pointed out the complexity of HRC design due to several related relevant factors (safety, ergonomics, productivity, etc.) and presented an interesting knowledge-based approach that

considers them, although focused on layout design. The methodology proposed by Mateus et al. (2019) exploits the information overlap between product CAD model, workplace design, ergonomics, and safety but it is aimed at the definition of possible collaborative assembly sequences. A promising work is proposed by Gualtieri et al. (2019) that developed a multicriteria methodology for a preliminary feasibility analysis of the conversion of a manual assembly workstation into a collaborative one. The proposed work considers the aspects and indices proposed by Gualtieri et al. to elaborate a more structured multicriteria method.

2.1 Challenges for HRC industrial applications

The implementation of collaborative robotics in an industrial process increases its flexibility and reconfigurability, which are two crucial aspects in the mass customization context. The growing demand for individual products is increasing the variety and complexity of production making the transition to the mass personalization paradigm necessary. The challenge is the personalization of products tailored to individual consumer needs, producing them in a resource-efficient way (Lanza, Peukert, and Steier 2021). In this context, the key-enabling technologies of Industry 4.0 offer new opportunities for scheduling production resources, allowing the workforce to remain competitive and profitable (Wang and Gao 2021).

Contrary to traditional robotics, collaborative robots and humans can share the same place and work alongside each other in collaboration without barriers. In this way, the worker's productivity is enhanced, and his/her workload is reduced. Cobots guarantee precision, repeatability, and accuracy, while humans provide creativity, problem-solving, and know-how. This combination of these skills represents one of the greatest advantages of the HRC. However, HRC industrial applications still present too many challenges to face with. There is a mismatch between the HRC opportunities and the actual implementations of collaborative work cells in the industry. Indeed, in most cases, the robot and human share the same space but they do not cooperate or collaborate. Fetcher et al. (Fechter, Seeber, and Chen 2018) attach this mismatch to missing planning and design tools for

collaborative workplaces. Ore et al. (2020) claim that one of the main reasons for the shortage of HRC industrial applications is related to the lack of detailed guidelines and structured methods that lead engineers in each step of the collaborative work cell design. Land et al. (2020) also pointed out the lack of guidelines and proposed a framework for the HRC development based on virtual simulation. Malik, Masood, and Bilberg (2020) went beyond by developing a unified framework to integrate human-robot simulation with virtual reality. Although these approaches offer a valid and safe environment to test the human-robot interaction and validate the conceptual solution they do not guide the design phase. To support companies in the implementation of a real symbiotic collaboration between human and robot, methods to easily identify potential workplaces for HRC should be developed (Blankemeyer et al. 2018). Especially SMEs, which do not have special experts, need to be guided in finding collaborative solutions fitting their specific requirements (Delang et al. 2018). However, attempts to address the problem of identifying HRC-suited workplaces are limited to multi-layer approaches for the business process modelling (Vitolo et al. 2020) or the calculation of capability indicators (Schröter et al. 2016). The review of Simões et al. (2022) highlights how emergent future research topics should focus on methods and tools for understanding the sustainability of HRC, which requires a human-centered approach.

2.2 Human-Robot interaction and safety issues

The first industrial revolutions were characterized by a cold coexistence of machines and men, who worked independently, and the introduction of industrial robots required physical barriers to separate the workspaces. Collaborative robots not only led to the first forms of human-machine cooperation and collaboration but also changed the safety paradigms. In collaborative applications, contact may be allowed, and traditional measures are no longer applicable. Therefore, managing health and safety aspects in HRC is much more challenging (Benos, Bechar, and Bochtis 2020). For example, Karagiannis et al. (2022) proposed dynamic safety zones to reduce the cycle time, increase flexibility, and leave more space for the operator to work. Safety-related information can also

be visualized to the operator, increasing his/her safety feeling in the cell (Makris et al. 2016).

Lu et al. (2022) described the human-machine relationship as a 5C journey: coexistence, cooperation, collaboration, compassion, and coevolution. To arrive at a scenario where empathic machines provide situational assistance to humans and both learn from each other, a human-centric HRC needs to be designed. Design concepts must deal with adaptation. HRC needs to be adapted to worker's profile and transient worker's state changes, optimizing the interaction and communication channels accordingly. Within the context of symbiotic HRC, where human and robot act as a team, the design of such systems must cross over the limits between categories (work equipment, environment, human factors, tasks, etc.) toward an integrated perspective (Wang et al. 2019). Gualtieri, Rauch, and Vidoni (2021), in their review, state that future developments should focus on the alignment of Human-Robot Interaction (HRI) safety and human factors research themes, especially in terms of sustainability, operator well-being, and psychophysical aspects of collaboration. A human-centred design would enable the implementation of safe, ergonomic, trustworthy, and efficient collaborative production systems.

2.3 Design methods for HRC

The analysis of the existing literature shows that technology-driven design methods prevail for the HRC (Hashemi-Petroodi et al. 2020). However, it is crucial to consider also human factors in the HRC design process. The robot presence in a collaborative workstation necessarily influences human performance and cognitive workload. Indeed, cobots can often cause stress to the operator, instead of reducing his/her physical and mental demand (Arai, Kato, and Fujita 2010). Therefore, it is necessary to consider multiple criteria and several aspects in the HRC design.

El Makrini et al. (2019) proposed a framework for human-robot assembly applications that merged ergonomics considerations by assessing human body posture, but they only focused on task allocation. Gualtieri et al. (2020) stressed the necessity to include safety, ergonomics, and efficiency in the design of collaborative assembly workstations. However, they only collect and classify design

guidelines and prerequisites according to standards, research works, and real use cases, rather than develop a structured design method. Other existing methods deal with the adaptation of the robot's movements to improve the operator's ergonomic condition (Van Den Broek and Moeslund 2020) or reduce human fatigue (Peternel et al. 2018).

Although several studies tried to include human factors in the HRC design, there is a lack of comprehensive HRC design methods. They should help engineers and companies to implement safe and ergonomic collaborative workstations without neglecting productivity and flexibility. This paper aims to overcome this limitation by proposing a human-oriented HRC design method that merges the concepts of ergonomics, safety, effectiveness, flexibility, and costs. The main novelty of the proposed work lies in the concretization of the human-oriented design process in a comprehensive systematic method that allows the identification of alternative design solutions and the selection of the best one based on heterogeneous drivers. Its application in a real industrial scenario also overcomes the following limitations of the approaches found in the published literature: (i) the works that consider multiple criteria are usually high-level approaches and mainly offer design guidelines; (ii) the works that concretely support a more detailed design usually focus on a specific design problem (e.g. task allocation, layout).

3. Design criteria definition

The primary concern of the shop floor automation has usually been the improvement of the performance of the equipment alone. Little consideration is given to the cooperation between humans and machines, and the potential that would arise from it. Consequently, many industrial workstations are poorly designed, resulting in lower overall productivity and unnecessary risks. In this context, expanding the boundaries of the HRC design criteria toward a 'human-oriented design', as opposed to the technologically directed, is essential. Design criteria are the explicit objectives that the HRC must achieve in order to be successful; therefore, it must consider both performance and workers' experience. Design criteria form the principles and benchmarks of the innovation that is being made.

As shown in Figure 1, everything starts from a business goal to be translated into qualitative and/or quantitative indicators. For example, 'the company aims to reduce human errors and improve quality' means that the expected number of compliant products for the HRC workstation is greater than that of the current workstation. The goal leads the design criteria elaboration, which is based on five main pillars: safety, ergonomics, effectiveness, flexibility, and costs.

Since robots and humans can work alongside and share their workspace without fences, it is essential to guarantee their safety. The objective of the safety pillar is not to expose the operator to unnecessary risks and/or to mitigate existing ones. It can mean providing robots with adaptive skills, implementing advanced safety strategies, installing adequate sensors, etc. An intelligent task allocation, which delegates dangerous tasks to the robot and leaves the safer ones to the operator, is also included. In this field, the ISO/TS 15,066:2016 specifies safety requirements for collaborative industrial robot systems and the work environment and supplements the existing industrial robot safety standards (EN ISO 10,218-
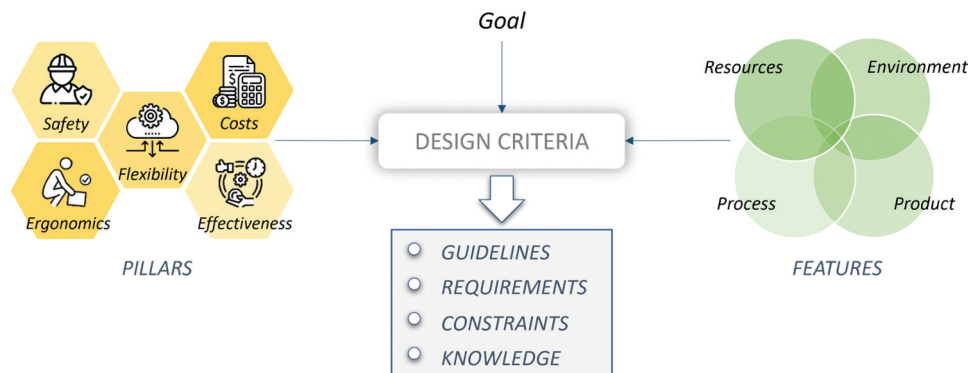

Figure 1. Design criteria definition.

1:2011 and EN ISO 10,218-2:2011). This Technical Specification provides guidelines for collaborative robot operation where a robot and a human share the same workplace. In this context, the safety system's integrity is one of the most important aspects, especially when process parameters such as speed and force are controlled. It also provides comprehensive guidance on conducting risk analysis for a collaborative robotic application based on the principle that contact between the robot and humans is allowed but must not cause pain or injury to the human. These aspects enable different design scenarios, requiring dedicated pre-collision and post-collision control systems (Lasota, Song, and Shah 2014; Villani et al. 2018):

- safety monitored stop, which timely detects imminent collisions between humans and robots by proximity sensors, vision systems, etc., and stops the operation in a controlled way.
- speed and separation monitoring, which implies that the robot adjusts the speed according to the area where the man was detected by scanners or a vision system.
- power and force limiting that ensure only safe and controlled collisions among robots, humans, and obstacles. Dedicated control systems must be provided to manage collisions between the robot and man without harmful consequences for humans.
- hand guiding that allows the operator to teach the robot positions by moving the robot, whose weight is compensated, without the need for an intermediate interface.

The ergonomics pillar leads the HRC design toward the creation of a healthy, comfortable, and task-efficient collaboration, as well as safe. It aims to reduce the risks to human health, both physical (e.g. WMSDs) and mental (e.g. work-related stress). It implies the matching of the workforce anthropometry with the various components of the HRC workstation. The ergonomic HRC design determines the physical accessibility as well; therefore, if it fits better to the human reach envelopes the discomfort can be reduced. Consideration must be given to workers' physical characteristics, positions and movements, work rhythms, expected performance, and any aid or support needed. These factors combined

determine the employee's perception, satisfaction, and quality of work. The allocation and balancing of tasks also play a fundamental role with a twofold objective: (i) to delegate non-ergonomic tasks to the robot and leave the safer ones to the operator, and (ii) to generate an adequate temporal demand or modulate the work pace according to human-related parameters. The goal of the collaboration is to emphasize the complementarity and synergy between human skills (perception, flexibility, experience, etc.) and robot skills (endurance, precision, repeatability, etc.), and not to generate new stressors.

The flexibility pillar pushes the HRC design to make it easier to reconfigure or relocate the robotic cell. Fenceless is an important opportunity for flexibility. The design should favor versatile, modular, and flexible work cell that easily adapts to new products, tasks, equipment, or people. It makes the collaborative system dynamic to timely respond to changing demands and conditions in the factory, supply chain, or market. This aspect is increasingly stressed by the mass customization paradigm, which implies small lot sizes and high product variants.

The effectiveness pillar focuses on performance. Most likely it is the simplest to pursue because it coincides with the most common driver that companies follow when they innovate or invest. However, it is important to be aware of which key performance indicators (KPIs) could be influenced by the implementation of the collaborative system and how to track and measure them. Only in this way, it will be possible to estimate the potential benefits and benchmarks different alternatives. It is equally important to consider the extent of the possible change and the possible impact on other indicators or criteria.

The design choices and compliance with the requirements of the aforementioned pillars give rise to costs that must necessarily be evaluated and compared with the company's propensity to invest. The

Table 1. Main topics related to the five pillars.

Pillar	Main topics
Safety	Speed, force, hazard-related aspects (nature, duration, frequency, probability, preventability, human body parts involved, etc.)
Ergonomics	Posture, reachability, manual material handling, force, steps, skills, workload, repetitiveness, recovery times
Flexibility	Volume changes, product variants, set-up, reprogramming
Effectiveness	Times, scraps, rework
Costs	Investments, labor, operating costs

direct and indirect economic impact must be considered, as well as the potential benefits generated.

Table 1 summarizes the main aspects to be considered in relation to the five pillars.

The level of accomplishment in pillars fields is affected by the company reality, so the integration into existing scenarios. Products, processes, resources, environment, and their interactions need to be analyzed in detail. In the HRC design, the equipment selection is necessarily affected by product features such as shape, dimensions, weight, material, complexity, bill of materials, and modularity. The context and function of the product could give rise to specific requirements (e.g. food industry). The product-equipment interaction requires the analysis of additional aspects such as point and modalities for handling or point and orientation for feeding. Product specifications also determine the process-related requirements (e.g. tolerance, accuracy, precision). Processes also include the task analysis (e.g. elementary operations, precedence constraints, times, complexity) and the production analysis (e.g. volume, schedule), which determine the degree of automation and the tasks allocation. Resources involved in the current processes provide an overview of man-hours and skills required and the anthropometric characteristics variability. These factors are essential for the benefit-cost ratio evaluation, task allocation, and system adaptability. The environment analysis mainly leads the layout definition according to available space, constraints, flows, existing equipment arrangement, and the need for specific microclimate or hygienic conditions (e.g. controlled room temperature, cleanroom).

Implementing one criterion could make the implementation of another infeasible or costly. For this aim, different weights can be assigned to pillars by the company managers according to the business goal. It could mean scarify secondary criteria, which are highly desirable but not essential, in favor of primary criteria. From all these considerations derive guidelines, requirements, constraints, and knowledge needed for the conceptual HRC design.

4. Human-Robot collaboration design

The proposed method aims to support the human-oriented HRC design by merging the concepts of ergonomics, safety, and technological innovation with the need for efficiency, flexibility, and quality of the industrial process. Pursuing the evolution of interaction between humans and robots, from cooperation to coevolution, passing through collaboration, man is increasingly placed at the center of the design process (Figure 2). Intelligent robots work with humans in a shared workplace in a symbiotic way, with mutual adaptation to increase performance and trust. Robot capabilities, such as flexibility, high-performance, and reconfigurability, need to be considered as a support to improve well-being, ensure safety, guarantee health and enhance the skills of the operator.

As shown in Figure 3, the HRC design starts from the conceptual design of the HRC workstation, after the identification of all the design criteria. In general, conceptual design can be described as the phase of the design process in which the functional structure
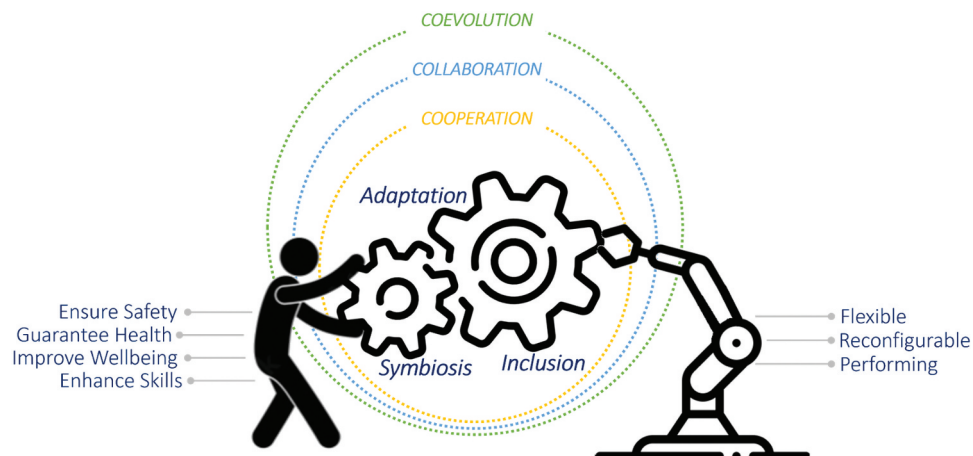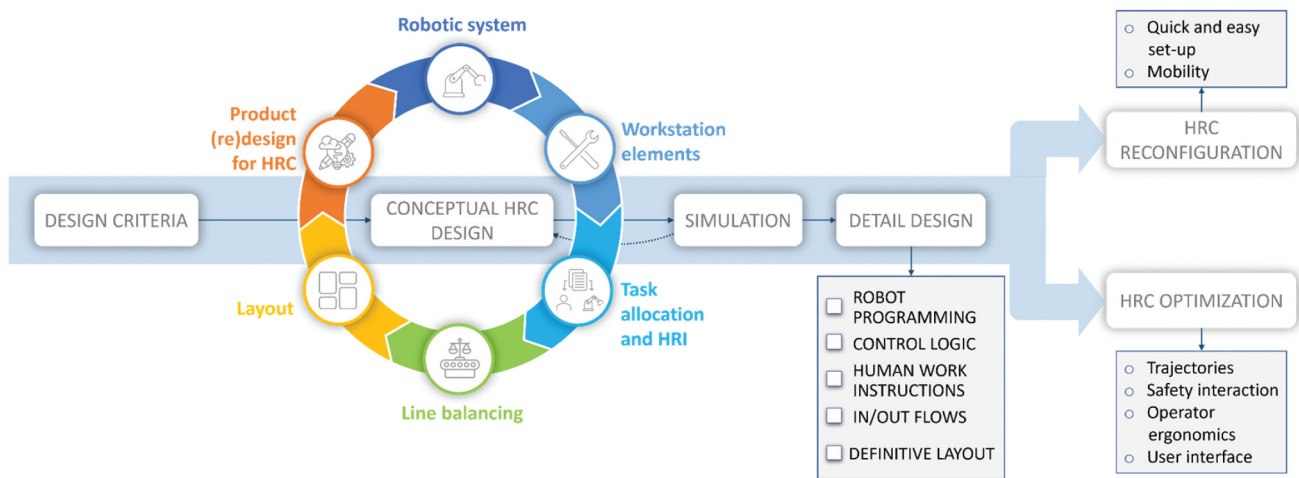

Figure 2. Human-Oriented HRC.

Figure 3. HRC design process.

and the appropriate solution principles are defined (Pahl et al. 2007). In the context of HRC, based on the defined design criteria and requirements, in the conceptual design phase, a suitable concept solution for the HRC work cell has to be identified. In the proposed method, the conceptual HRC design consists of six consecutive steps with an iterative approach. In this phase, the following items and aspects need to be defined:

- Possible redesign of the product for HRC. Evaluate if materials, gripping modality, and shape of the product or its components could be modified to make more feasible the implementation of the cobot in the considered workstation. For example, the following strategies could be considered: to lighten the product, to standardize the components, to simplify the features recognition, to favour the gripping by the robot, etc.
- Definition of the robotic system: cobot, end-effectors (considering the shape and size of the workpiece, payload limits, target cycle time, and actuators), dispensers, hardware for safety systems (i.e. vision-based systems, sensors, laser sensors, etc.), software control systems, and devices for HRI.
- Definition of workstation elements: workbench, support structure for the robot, fences, storage boxes for components and small parts, tools (i.e. screwdriver, wrenches), and equipment (i.e. low-cost automation).
- Task allocation and HRI: each task has to be assigned to human, robot, or human and robot

according to its characteristics and constraints. For example, the operator should only focus on tasks that enhance human skills, leaving to robots all tasks that can be automated, such as lifting and moving. Quantitative skill assessment methodologies can be used to support the task distribution problem (Mourtzis et al. 2021). They allow classifying the level of expertise of an operator on a specific activity and also personalize the information to be provided. Indeed, also the interaction modality needs to be defined to ensure a safe collaboration. Various systems (buttons, multimedia interfaces, extended reality, etc.) can be used to manage the tasks' sequence and the product variants guaranteeing the workstation flexibility.
- Line balancing: the entire production line needs to be re-balanced after the design of the new workstation in order to guarantee productivity and efficiency.
- Definition of the new workstation layout: the position of the robot and the operator, the type of material and resources supply, nearby workstations, corridors for internal logistic transports, etc., must be determined. The workstation layout can be determined according to standard ergonomic guidelines (e.g. golden and strike zone) to minimize movement to reduce fatigue and ergonomic risks. The robot's position has to be defined in order to reach all the necessary points, avoiding the robot's configurations with singularities. Different layouts can be hypothesized and then evaluated to choose the best one. For this

aim, the method proposed by Berg, Gebauer, and Reinhart (2019) could be exploited.

All the described aspects are strictly related to each other and the modification of one item can significantly influence other aspects as well. Thus, an iterative approach is essential to comply with all the defined requirements.

The next step is the virtual simulation of the designed HRC workstation. The objective is to simulate the conceptual design of the cell evaluating preliminary performance, ergonomics, safety, layout, and interaction between human and robot. In this way, it is possible to find out some possible errors made in the conceptual design phase or risks for the operator not detected before. At this point, if necessary, the concept design of the workstation can be reviewed and modified to achieve a better solution.

The detail design is the final step of the standard design process. Starting from the concept of the solution, the design is developed considering all the technical and economic aspects to be ready for production. In this phase, the design of the HRC workstation is finalized by the definition of the robot programming algorithm, the implementation of control logic, the analysis of all workflows from/to the considered production area, the definition of human work instruction, the integration of the workstation with the production line components (conveyors, feeders, etc.) and the choice of definitive layout. Another important activity to be completed in the detail design phase is the elaboration of production documents, including the detailed drawing of the workstation's components and assembly.

At this point, two different activities can be executed on the HRC system: reconfiguration and optimization. The HRC system can be easily reconfigurable and flexible if properly designed. By implementing HRC stations instead of completely automated ones, companies are able to reconfigure a hybrid line when it is necessary, for example, to deal with production picks (Calitz, Poisat, and Cullen 2017). The installation of collaborative robots implicates a relevant economic investment for the company; however, the system reconfigurability can decrease the costs, because it can be moved among the line instead of adding a new robot. Furthermore, the great variability of collaborative robotics' applications (e.g. pick and place, screwing, inspection, assembly,

disassembly, etc.), the quick and easy set-up, and mobility, make its use very attractive for industries (Weckenborg et al. 2019). However, few studies addressed the reconfigurability of HRC proposing a design method to enhance it (Hashemi-Petroodi et al. 2020).

In this context, the optimization of all aspects of the HRC system becomes fundamental. The use of smooth and predictable motions of the robot allows for making the application not only faster but also more ergonomic for the operator (Lasota and Shah 2015). Rojas et al. (2021) identified a set of possible robot trajectories that satisfy the operator's psychological wellbeing and the process performance by complying with the safety requirements in terms of safety risk prevention. By actively predicting the human's actions and motions, a robot can produce safe motions proactively by a motion planning approach, instead of relying on frequent replanning (Lasota, Song, and Shah 2014). Automatic and adaptive human-centered solutions also allow optimizing ergonomics by reducing worker effort and improving their skills (Rauch, Linder, and Dallasega 2020). For example, the robot can place objects at the most comfortable height for humans or adapt the physical assistance as soon as the fatigue of humans exceeds a certain threshold (Peternel et al. 2018; Lorenzini et al. 2019). To better support collaborative activities and make HRI quick and easy, it is useful to adopt a user-friendly interface. The interface design is fundamental, the interface needs to be intuitive so that the operator can easily program and interact with the robot. The operator enjoys assistance and can receive information on the completion status of the activity, any postural corrections, or manage dangerous or unexpected situations (Villani et al. 2018).

4.1 Conceptual HRC design

The need for a comprehensive multicriteria structured method for the HRC design is addressed by the workflow proposed in Figure 4. It supports the conceptual phase by considering as many hypotheses as possible and discarding from time to time those that are not feasible or not convenient from different perspectives (i.e. safety, ergonomics, costs, performance).

The first step is the creation of the Product Task Resource (PTR) sheet, which summarizes the HRC design features related to task j that is performed on
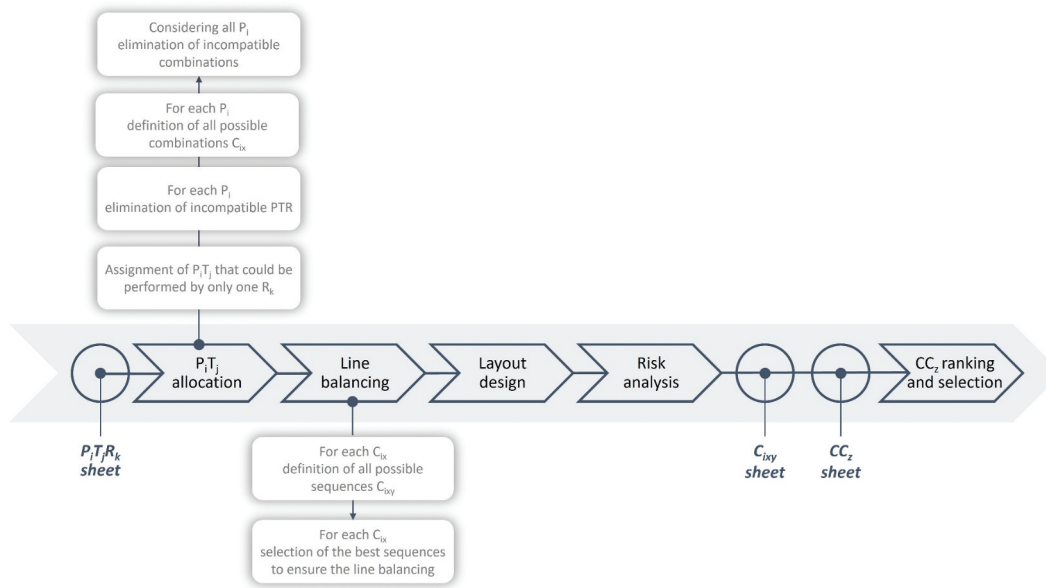
Figure 4. Conceptual HRC design workflow (P: product; T: task; R: resource; C: combination).

product i by the resource k (human, robot, human + robot).

As shown in Figure 5, PTR rows are all items and sub-items functional to the HRC design according to the design criteria. The last column classifies the (sub)item impact level according to a 3-classes value (9- red/high, 3-yellow/medium, 1-green/low). A high impact can mean economic unsustainability of the solution, an ergonomic risk that would require immediate changes, production performance worse than the current one, etc. A medium impact implies a potentially acceptable economic
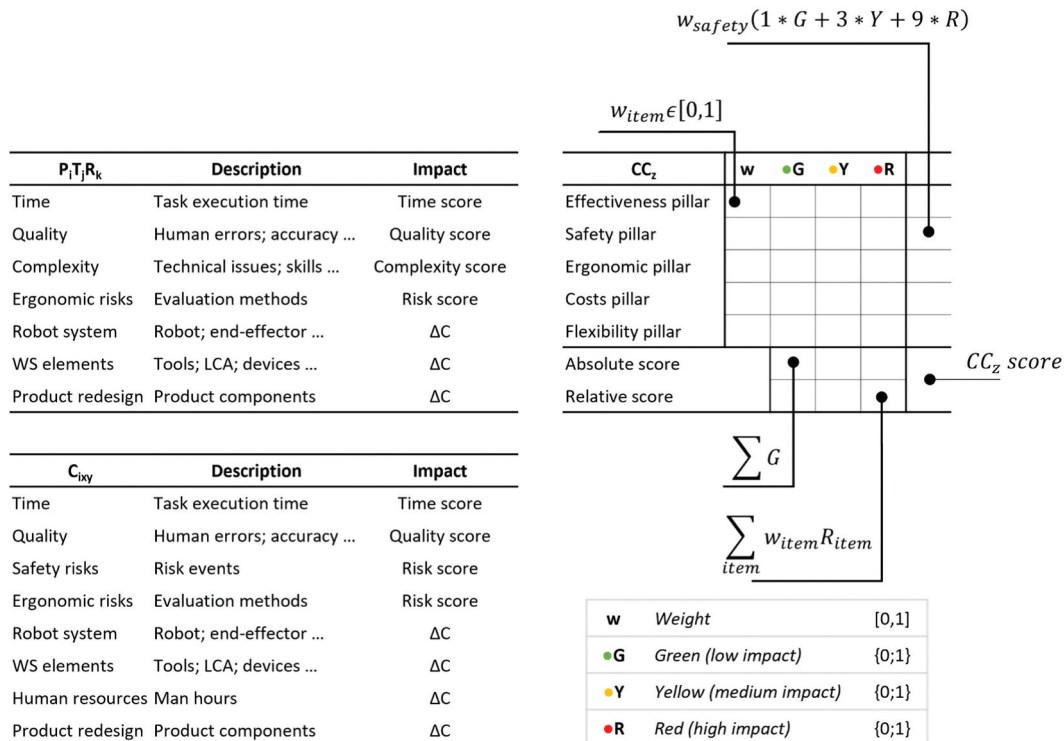

Figure 5. PTR sheet, C sheet, and CC sheet.

investment, an ergonomic risk that could require improved actions, production performance comparable to current ones, etc. A low impact mainly means economic and productive benefits and the absence of risks. Time refers to the time taken by the resource to perform the task. It can be known (e.g. the task is currently performed by a human) or estimated (e.g. new task, cobot time). The impact evaluation is based on company thresholds related to the current execution time or the desired cycle time (e.g. red if time is greater than the current one, yellow if time is equally or 5% less than the current one, green if time is at least 5% less of the current one).

Quality considers defects, scraps, reworks, and errors. It can consider known (e.g. current human errors rate) or estimated (e.g. cobot accuracy) parameters. The impact evaluation is based on company thresholds related to the current or desired ratio of compliant parts to total parts produced.

Complexity refers to both the technical criticalities that must be faced in the design, construction, and implementation of the robotic work cell and the pressure exerted on man in physical, mental, temporal, and performance terms. Due to the heterogeneity of the factors and the difficulty of providing a quantitative estimate, in this case, the classification of the impact is qualitative. Checklists or score sheets can support engineers in this evaluation (Malik and Bilberg 2019). Information exchanged between all actors of the manufacturing system also contributes to the definition of complexity. A quantitative approach to evaluate the complexity of digitalized manufacturing systems is proposed by Mourtzis et al. (2019). According to the information theory, the authors consider the information content, the entropy, and the channel capacity in the communication human-human, human-machine, and machine-machine.

Ergonomic risks will have as many sub-items as the standard assessment methods (e.g. NIOSH, RULA, OCRA) applied. The output score can be directly used for the impact classification (e.g. red if NIOSH Lifting Index >3, yellow if 1 < NIOSH Lifting Index ≤3, green if NIOSH Lifting Index ≤1).

Robot systems include the main elements of the robotic system (e.g. cobot, end-effector, vision-based systems) and the impact evaluation is based on the estimated cost of these elements.

Workstation elements can include low-cost automation, tools, conveyor belt, etc., or specific interventions to rearrange the layout and the impact evaluation is based on the necessary economic investment.

The product redesign includes the product components that could be redesigned for HRC and the impact evaluation is based on the estimated Δcost (ΔC).

In these three cases, a green ΔC could be a lower investment than that accepted by the company; a yellow ΔC could be an investment that falls within the tolerance threshold defined by the company, but the benefit-cost ratio must be further investigated; a red ΔC could be that the investment exceeds the company threshold (defined in the economic criteria).

The second step is the PT allocation, which means assigning man, robot, or both to the task. Firstly, there is the assignment of the P_iT_j that could be performed by only one R_k. It occurs due to the unsuitability of a resource according to the design criteria or is suggested by too many red impacts in the $P_iT_jR_k$. For each P_i, incompatible PTR sheets are then eliminated. It could mean requirements related to cobot, end-effector, workstation configuration, skills, etc. that could give rise to technical infeasibility, excessive extra costs, or high psychophysical workload. For each P_i, all possible combinations x are generated (C_{ix}). They consist of the set of PTR necessary to make the product. Considering all products, incompatible combinations are eliminated favoring consistent choices between products (e.g. the same resource assignment for similar tasks, common elements of the robotic system or workstation). They include the estimation of the total number of resources, both humans and robots, that could give rise to excessive extra costs (e.g. three products require three different robotic systems) or high psychophysical workload (e.g. many tasks assigned to the same resource with a high number of product variants).

The third step consists of the definition of all possible sequences y (i.e. the order in which the tasks are performed respecting all precedence constraints) for each combination C_{ix}, defining all the possible C_{ixy}, and the selection of the C_{ixy} that ensures the best line balancing.

In the fourth step, preliminary layout planning is carried out. It aims to guarantee the best working conditions for the operator (e.g. golden and strike

zone), the correct functioning of the robot (e.g. robot workspace, reachable poses), the minimization of flows/movements, and the respect for existing spatial constraints (e.g. nearby workstations, AGV corridors).

The fifth step is the risk estimation which considers the combination of the following risk factors:

- The severity of the potential consequences or effects of a risk event (e.g. contact between human and robot);
- Contact nature (accidental or deliberate), duration, and human body parts involved;
- The probability and frequency of a hazard occurring;
- The possibility of hazard preventing or injury minimizing.

Considering the Pilz Hazard Rating (Jongerius, Hanco BV and Pilz 2014) technique the degree of risk can be calculated by (1):

$$\text{Pilz Hazard Rating(PHR)} = \text{DPH xPO xPA xFE} \quad (1)$$

where:

- DPH is Degree of Possible Harm
- PO is Probability of Occurrence
- PA is Possibility of Avoidance
- FE is Frequency and/or Duration of Exposure

C_{ixy} for which a high risk was found, difficult to mitigate, are eliminated. C_{ixy} sheet is then created (step 6), where the information of the relative PTR converges. A new item for the safety risks is added, instead of complexity (Figure 5). Each item's impact is updated considering the implications of PTR combining (e.g. the same robot is used for two tasks, new system elements, interventions coming from the layout planning). The item related to human resources is also added to consider a possible reduction or increase in the workforce.

Similarly, C_{ixy} sheets converge in the CC_z sheet (step 7), where the evaluation is extended to all products. In CC_z sheet the impact level refers to the five pillars (Figure 5), as follows: time and quality affect the effectiveness pillar; ergonomic and safety risks affect the relative pillars; robot system, workstation elements, product redesign, and human resource affect the costs pillar. A new row is added for the flexibility pillar, which can be evaluated according to the ability

of the proposed solution to be suitable for most of the product families considering their importance in terms of quantity or turnover (ABC Analysis/Pareto Analysis).

CC_z are then ranked, in ascending order, considering the weighted sum of all items to select the best solution. As anticipated in section 3, the company could assign different weights to the items, in this case, the CC_z score is calculated by multiplying each item's score for its corresponding weight w and by summing all contributions. In particular, the CC_z score is calculated as suggested by (2):

$$CC_z \text{score} = 1 * \sum_{item} w_{item} * G_{item} + 3 * \sum_{item} w_{item} * Y_{item} + 9 * \sum_{item} w_{item} * R_{item}$$

$$(2)$$

5. Industrial case study

The proposed method has been applied for the design of an HRC workstation in LUBE Industries, the major kitchen manufacturer in Italy. In this section, the case study, the definition of the design criteria, and the conceptual HRC design are explained.

The case study focuses on the drawers' assembly line. Figure 6 represents the complete production process. The first part of the production line is automated, a traditional robot moves the drawer's front panel on the line, and a CNC machine drills the front panel and inserts the metal accessories. Then, the drawer is manually assembled on three workstations. In the first workstation, the door is assembled on the drawer's front panel. Subsequently, the screws and the metal plate are inserted. Finally, the operator mounts the sides on the drawer and loads it into the cart near the line.

Each step of the proposed method has been followed to design the HRC workstation for drawers' assembly. The first step is goal determination, the company intends to reduce ergonomic risks for the operators preserving productivity and efficiency. This goal can be translated into quantitative constraints to be followed:

- Elimination of high (red) ergonomic risks (ergonomics pillar)
- Cycle time $\leq$ *as-is* cycle time (57 seconds) imposed by the CNC machine (effectiveness pillar)
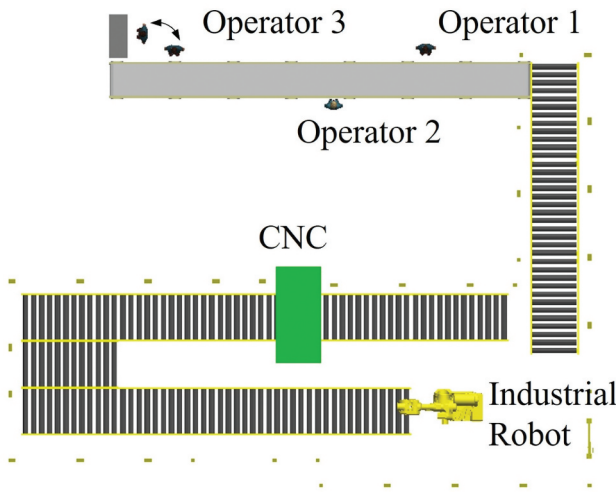
Figure 6. As-Is production line layout.

- Quality requirement is not demanded (effectiveness pillar).

The drawers produced daily are about 800 and vary in weight and size. Although almost 20 different product variants can be identified, for the HRC design it is possible to consider only the products that differ in functionality and assembly process. For this reason, 3 different drawers' models have been selected: P_A, P_B, P_C. Figure 7 shows the description of all the tasks and the production process for each product considering the average time and precedence constraints. The average time of each operation was appropriately calculated from the data collected by Time and Methods Department.

Considering the as-is production line, the current task allocation is the following: the first operator is responsible for inserting the door on the drawer's front panel; the second operator performs the screwing activities; the third operator inserts the sides and loads the drawer in the cart. However, the three

manual workstations are not perfectly balanced: the utilization rate of each workstation is lower than 70%. In particular, the second operator has a significant dead time in which performs other activities, such as the management of not standard products or the load of the front panels in the automated initial part of the line. For this reason, the objective is also to reduce manual work and assign higher value-added activities to operators.

The ergonomic analysis of the manual workstations was carried out using two standard methods: RULA (McAtamney and Corlett 1993) and OCRA (Occhipinti 1998). The analysis allowed the detection of high risk (RULA Score: 5; OCRA Score: 13.30) for the insertion of the screws in the vertical direction (T_4). The ergonomic risk scores are mainly due to excessive flexion of the upper arm and elbow, a high arm abduction, and the use of an electric screwdriver. This ergonomic risk must be mitigated to comply with the ergonomic pillar and the related goal previously defined. Ensuring the operator's safety is indispensable (safety pillar), so all the possible risks and dangerous events have been identified and then prevented. Even the flexibility pillar has to be respected, thus the solution had to be suitable for all the product variants. To complete the definition of the design criteria, the company specified the economic thresholds for the components redesign and the investment related to robot systems and workstation elements.

At this point, the conceptual HRC design started. Firstly, the PTR sheets were filled out for each product, task, and resource (robot or human) for a total of 28 PTR sheets (12 for product A, 10 for product B, and 6 for product C). As an example, Figure 8 shows the PTR sheets for product C. Theoretically, 42 PTR sheets should be created considering also the combination of the two resources (R_{H+R}); however, no combination
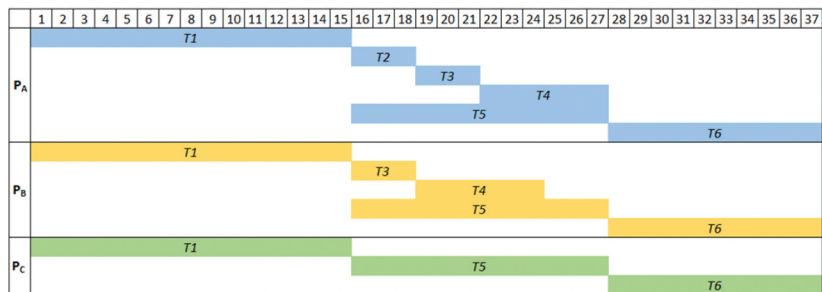

Figure 7. Tasks sequence and precedence for each product.

of product and task (P_iT_j) was complex enough to require the use of both resources.

The next steps refer to the PT allocation. At first, by analyzing all the 28 PTR sheets, it was possible to assign immediately some PT to only one resource R. Table 2 indicates the PT that can be performed by only one R including the specific reason. As a result, 23 PTR sheets remained.

Subsequently, considering the possible combinations of PTR for each product, the incompatible PTR sheets were eliminated. Table 3 specifies which PTR sheets have been deleted, thus 17 PTR sheets remained.

Table 2. Assignment of PT that could be performed by only one R.

PT	Assigned Resource	Reason
P_AT_1, P_BT_1, P_CT_1	Human	The locking mechanisms for the assembly of the drawer on the door have a great variability based on the product. Thus, a robot is not suitable for the execution of this operation.
P_AT_4, P_BT_4	Robot	Ergonomic risk indicators exceed the defined threshold

For each product, starting from the remained PTR, all the possible combinations are defined:

- C_{A1}: $P_AT_1R_H + P_AT_2R_R + P_AT_3R_H + P_AT_4R_R + P_AT_5R_R + P_AT_6R_H$
- C_{A2}: $P_AT_1R_H + P_AT_2R_R + P_AT_3R_H + P_AT_4R_R + P_AT_5R_H + P_AT_6R_H$
- C_{B1}: $P_BT_1R_H + P_BT_3R_H + P_BT_4R_R + P_BT_5R_R + P_BT_6R_H$
- C_{B2}: $P_BT_1R_H + P_BT_3R_H + P_BT_4R_R + P_BT_5R_H + P_BT_6R_H$
- C_{C1}: $P_CT_1R_H + P_CT_5R_R + P_CT_6R_H$
- C_{C2}: $P_CT_1R_H + P_CT_5R_H + P_CT_6R_H$

Considering all the products, it was convenient to allocate the same resource to T_5: if it was assigned to human for product A, the same happened for the other two. In this way, the compatible combinations were reduced to 2: $C_{A1} + C_{B1} + C_{C1}$ and $C_{A2} + C_{B2} + C_{C2}$. Moreover, since the vertical and the horizontal screws are not the same, it would have been necessary to use two different end-effectors and two dispensers. However, it was possible to redesign the vertical screw head without additional costs. The use of a collaborative electric screwdriver for T_2 and T_4

PRODUCT C								
T1: Insert door			**T5: Insert sides**			**T6: Load drawer in the cart**		
$P_CT_1R_R$	Description	Impact	$P_CT_5R_R$	Description	Impact	$P_CT_6R_R$	Description	Impact
Time		●	Time		●	Time		●
Quality		●	Quality		●	Quality		●
Complexity		●	Complexity		●	Complexity		●
Ergonomics risks	-	-	Ergonomics risks	-	-	Ergonomics risks	-	-
Robot system	-	-	Robot system	UR10	●	Robot system	Industrial Robot	●
	-	-		End-effector	●		End-effector	●
	-	-		Vision system	●		-	-
WS elements	-	-	WS elements	Support structure	●	WS elements	Standard carts	●
	-	-		Fences	●		Fences	●
	-	-		Sides feeder and layout redesign	●		-	-
Product Redesign	-	-	Product Redesign	-	-	Product Redesign	-	-

$P_CT_1R_H$	Description	Impact	$P_CT_5R_H$	Description	Impact	$P_CT_6R_H$	Description	Impact
Time		●	Time		●	Time		●
Quality		●	Quality		●	Quality		●
Complexity		●	Complexity		●	Complexity		●
Ergonomics risks	RULA	●	Ergonomics risks	RULA	●	Ergonomics risks	RULA	●
	OCRA	●		OCRA	●		OCRA	●
	NIOSH	●		NIOSH	-		NIOSH	●
Robot system	-	-	Robot system	-	-	Robot system	-	-
WS elements	Door feeder	●	WS elements	-	-	WS elements	Manipulator	●
Product Redesign	-	-	Product Redesign	-	-	Product Redesign	-	-
⇩			⇩			⇩		
H			**H or R**			**H or R**		

Figure 8. $P_CT_jR_k$ sheets.

Table 3. Elimination of incompatible PTR.

PT	Assigned Resource	Reason
P_AT_2	Robot	T_4 and T_2 are screwing operations. Since T_4 has been necessarily assigned to R, it was convenient to allocate even T_2 to R.
P_AT_3, P_B T_3	Human	By using the same robot for T_4, T_2, and T_3, it would be necessary to use a double-flange as end-effector. However, this solution was not feasible due to the characteristics of the collaborative electric screwdriver. Buying another robot, the economic thresholds would not be respected any more. As a result, the plate had to be assembled by human.
P_AT_6, P_B T_6, P_C T_6	Human	There was not enough space at the end of the line to install an industrial robot with all the obligatory safety systems. Furthermore, the investment for the construction of standard carts was too high according to the defined thresholds.

required the metal plate redesign due to obstruction problems.

For each compatible combination, according to the tasks' precedence, two different sequences were determined. It was chosen the one that best balanced the line. Figure 9 shows the line balancing for the most complex product (A). The chosen sequence was the first one in which T_5 was performed in the second workstation after the screwing activities have been completed. The same was for the other two products.

At this point, a conceptual layout of the workstation was designed. In the first workstation, the operator and the robot collaborate to complete T_1, T_2, T_3, and T_4. They interact in a shared space, but if the operator is inside the robot's working area, the robot stops. The robot is fixed on a specific support frame connected to the conveyor and with two plexiglass panels to reduce the risk for the operator during the robot's movements. If T_5 was assigned to the human, the second workstation would be completely manual, and the operator will mount the sides on the drawer and load it on the cart.

Figure 9. Line balancing analysis for product A.

Otherwise, the two stations (robot and operator 2) would work in parallel.

The next step was the risk assessment according to the ISO/TS 15,066:2016 and the PHR analysis (Table 4). Considering all the activities assigned to the robot, the following potentially dangerous events were identified and classified as low risks:

- Crushing of a hand when the collaborative screwdriver moves towards the drawer for the insertion of the vertical screw
- Accidental collision between arm or upper body during robot's movements
- Accidental collision between screw and operator's face if the collaborative screwdriver cannot hold the screw
- Crushing of hand when the robot inserts the sides on the drawer
- Accidental collision between sides and upper body during robot's movements

Consequently, for each product, the C_{ixy} sheets were created for the compatible combinations based on the PTR sheets. Figure 10 shows the C sheets for product B, as an example. In the first combination (C_{B11}) T_5 was allocated to the robot, while in the second one (C_{B21}) T_5 was performed by the operator. They differed in:

- Cycle time: the use of a robot for T_5 allowed reducing operations time
- Safety risks: obviously, if T_5 was assigned to the human, potentially dangerous events related to HRC would be reduced
- Costs related to the robot system and workstation elements: the implementation of two different robots increased the overall costs. The allocation of
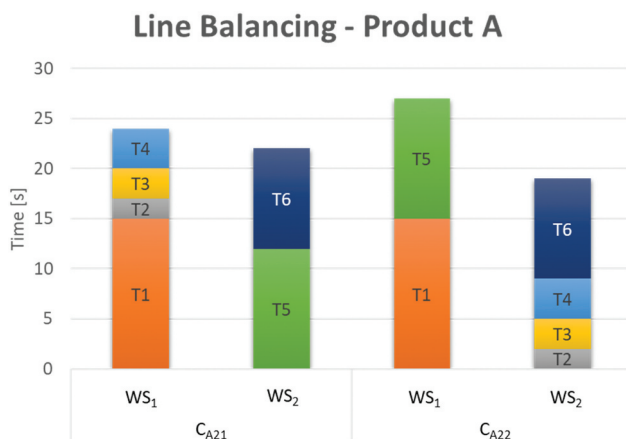
Table 4. Risks identification of the HRC workstation.

Task	Risk	Parts	Contact Category	PHR Score	Risk level
T_2, T_4	Crushing	Hand-Screwdriver	Transitory	4.96	Negligible
T_4	Crushing	Hand- Screwdriver	Quasi-static	14.06	Very Low
T_2	Crushing	Hand- Screwdriver	Quasi-static	5.63	Negligible
T_2, T_4, T_5	Collision	Robot-Forearm	Transitory	15.63	Very Low
T_2, T_4	Collision with screw	Face-Screw	Transitory	20.63	Very Low
T_5	Crushing	Hand-Sides	Transitory	28.12	Very Low
T_5	Collision	Upper body-Sides	Transitory	15.62	Very Low
T_5	Crushing	Hand-Gripper	Quasi-static	14.06	Very Low

T_5 to the robot involved the design of an appropriate sides feeder and the consequent layout redesign to introduce it. This implicated a great increment of the investment, which remained anyway under the defined tolerance threshold. Moreover, it was necessary to provide a vision system for picking the suitable sides for each specific product.

In both cases, the human resources were reduced from three operators (as-is production line) to two with a higher utilization rate. The third operator has been reallocated to higher value-added operations within the plant.

The last step is the compilation of CC sheets (CC_1 and CC_2) by considering all products. As shown in Figure 11, the CC_z scores are calculated. Firstly, the weights for each pillar were set: the company's priorities were ensuring the operator's safety and maintaining at least the same productivity. The impact levels were determined based on the C sheets previously created. The two CC sheets mainly differed in the effectiveness and costs pillar. In particular, in the CC_1 (in which T_5 was assigned to the robot) the costs exceeded the defined threshold (red score), while the effectiveness pillar had a lower impact because the cycle time was significantly reduced. In the CC_2 (in which T_5 was assigned to the human) the investments were lower than the ones defined by the company, whereas the cycle time was not improved. Ranking the CC sheets in ascending order, the CC_2 was selected and T_5 was assigned to the second operator.

As a result, the new production line is composed of two workstations: in the former cobot and human collaborate, in the latter, a second operator completes the drawer's assembly and loads it on the cart.

In addition, the Smart Robots © vision system was integrated into the workstation as an interaction modality between robot and human to manage multiple products and different tasks. By a real-time mapping of the workplace, the device guarantees a possible automatic slowing down of the robot to avoid a collision and the robot's control through gestures. Indeed, the operator can control the robot with simple gestures (e.g. 'close hand', 'open and', 'V hand sign') activating a specific task, stopping or starting the robot.

6. Virtual simulation

The new production line and the HRC workstation have been simulated by using the software Tecnomatix Process Simulate by Siemens. The simulation allowed the analysis and the evaluation of several aspects: ergonomic risks, layout optimization, time and performance analysis, technical feasibility, and the related revision of the workstation and robotic systems components. Figure 12 shows the layout of the new production line. In the first workstation, the operator and the robot collaborate to execute the screwing operations, while the second operator completes the drawer's assembly by inserting the sides and loads it on the cart by using a manipulator.

The simulation mainly focused on the HRC workstation. Figure 13 displays the tasks sequence of this workstation. The drawer moves on the conveyor and arrives at the HRC workstation, the operator inserts the door, then places the drawer in the correct position (a) and lowers a squaring system (L-shape

C_{B11} ($P_B T_5 R_R$)	Description	Impact
Time	Cycle time	🟢
Quality		🟢
Safety risks	Transitory crushing between hand and screwdriver	🟢
	Quasi-static crushing between hand and screwdriver	🟢
	Transitory collision between robot and forearm	🟢
	Transitory collision between robot and upper body	🟢
	Transitory collision with screw	🟢
	Transitory crushing between hand and sides	🟢
	Transitory collision between sides and upper body	🟢
	Quasi-static crushing between hand and gripper	🟢
Ergonomic risks	RULA	🟡
	OCRA	🟡
	NIOSH	🟢
Robot system	UR5	🟢
	Collaborative screwdriver	🟢
	Screws dispenser	🟢
	UR10	🟡
	End-effector for UR10	🟢
	Human-Robot Interface for WS1	🟢
	Vision system for WS2	🟢
WS elements	Sides feeder and layout redesign	🟡
	Structure for UR5	🟢
	Structure for UR10	🟢
	Fences WS1	🟢
	Fences WS2	🟢
	Manipulator	🟡
Human Resources	Man/Hours	🟢
	Balancing	🟢
Product redesign	Metal plate	🟢

C_{B21} ($P_B T_5 R_H$)	Description	Impact
Time	Cycle time	🟡
Quality		🟢
Safety risks	Transitory crushing between hand and screwdriver	🟢
	Quasi-static crushing between hand and screwdriver	🟢
	Transitory collision between robot and forearm	🟢
	Transitory collision between robot and upper body	🟢
	Transitory collision with screw	🟢
Ergonomic risks	RULA	🟡
	OCRA	🟡
	NIOSH	🟢
Robot system	UR5	🟢
	Collaborative screwdriver	🟢
	Screws dispenser	🟢
WS elements	Human-Robot Interface for WS1	🟢
	Structure for UR5	🟢
	Fences WS1	🟢
	Manipulator	🟡
Human Resources	Man/Hours	🟢
	Balancing	🟢
Product redesign	Metal plate	🟢

Figure 10. Comparison of C_{Bxy} sheets.

CC_1: $C_{A11}+C_{B11}+C_{C11}$	w	🟢G	🟡Y	🔴R	
Effectiveness pillar	25%	🟢			0.25
Safety pillar	30%	🟢			0.3
Ergonomic pillar	20%		🟡		0.6
Costs pillar	10%			🔴	0.9
Flexibility pillar	15%	🟢			0.15
Absolute score		2	2	1	**2.2**
Relative score		0.7	0.6	0.9	

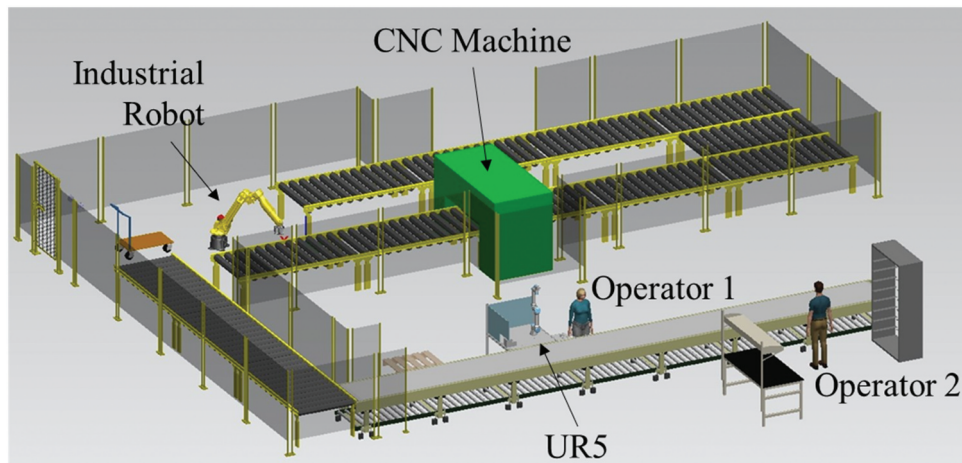| CC_2: $C_{A21}+C_{B21}+C_{C21}$	w	🟢G	🟡Y	🔴R	
Effectiveness pillar	25%		🟡		0.75
Safety pillar	30%	🟢			0.3
Ergonomic pillar	20%		🟡		0.6
Costs pillar	10%	🟢			0.1
Flexibility pillar	15%	🟢			0.15
Absolute score		4	1	0	**1.9**
Relative score		0.55	1.35	0	

Figure 11. Comparison of feasible CC_z sheets.

Figure 12. New production line for drawers assembly.

profile), specifically designed, to lock it. The robot inserts the first screw in the horizontal direction (b). The operator places the metal plate and locks it with an appropriate clamping system, specifically designed (c). The robot inserts the other two screws in the vertical direction (d). The operator unlocks the systems (e), and the drawer moves to the second workstation.

The simulation allowed verifying the absence of ergonomic risks for the operator. The RULA analysis showed a considerable reduction of ergonomic risks. In the HRC workstation, the most critical activities are the correct positioning of the drawer before robot operations (a) and the locking of the metal plate (c). Since both are short operations and do not require high strength, the associated ergonomic risks are anyway low (RULA Score: 3).

In addition, the simulation pointed out an ergonomic risk for the insertion of the door (T_1). The insertion of the door and the screwing operations should be executed respectively in the back and the front of the drawer. The combination of these two activities in the same workstation forced the operator to assemble the door on the drawer rotated on the opposite side, thus he had to assume awkward

postures to complete the activity. To reduce the ergonomic risk and let the operator mount the door with the drawer in the correct position, an idle rotating roller for the rotation of the drawer was introduced. After the operator inserted the door with the drawer correctly positioned, he turned the part of the conveyor with the rotation system so that the drawer was correctly rotated for the screwing operations. In this way, the operator correctly completed T_1 avoiding physical efforts.

The simulation allowed the analysis of the time and performance of the new production line. The HRC workstation design respected the cycle time of 57 seconds. Even if the total time of the HRC workstation increased, the line balancing improved. To reduce the time for the robot's operations, an automatic feeder was used for the screws. In this way, the time waste due to the robot's movements for each screw load was avoided. As a result, the overall time of the HRC was 47 seconds.

Finally, the simulation allowed verifying the technical feasibility of all the HRC workstation components and their integration into the workstation. In particular, it was necessary to redesign the clamping
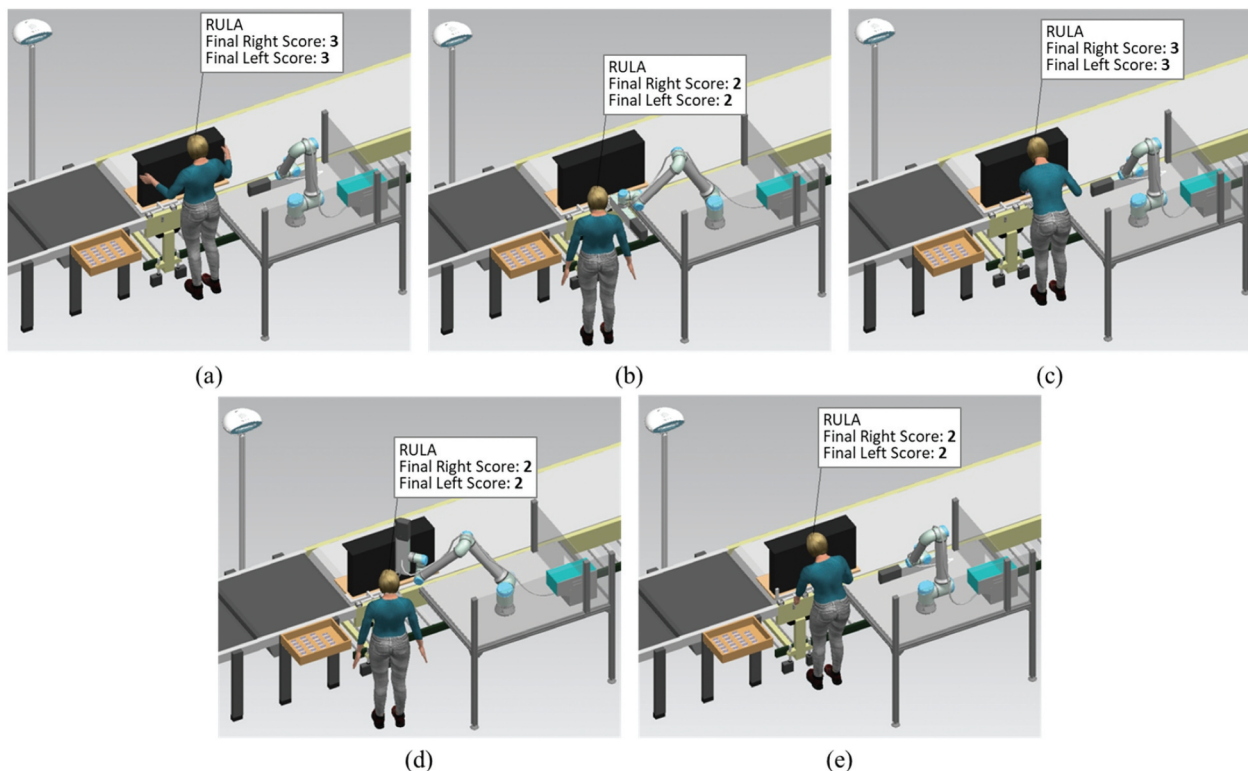

Figure 13. Simulation of the human-robot collaboration.

system for the plate's block because it obstructed the collaborative screwdriver movements due to its rotation limits.

7. Results

The virtual simulation allowed the evaluation of the conceptual design of the HRC work cell and the detection of possible errors made in the design phases and risks for the operators. In particular, the collaborative workstation was reviewed, and some components were redesigned (e.g. clamping system, automatic screws feeder, etc.). Consequently, the detail design of the collaborative workstation was completed (Figure 14). In this step, the definitive layout was defined, the robot programming and control logic were implemented in the work cell. Finally, the new HRC work cell has been realized, tested, and implemented in the production line.

The new collaborative workstation allowed mitigating ergonomic risks and the operators' activities are not hazardous. The ergonomic analysis is performed in the new production line according to RULA and OCRA methods. The obtained results confirmed the ones carried out by the simulation. By comparing the as-is and to-be scores, it can be noticed that the ergonomic risks lowered from high to low for all the activities (RULA score: 3; OCRA score: 5.70).

The new production line respects the cycle time (57 seconds) imposed by the CNC machine. Although the two stations have a higher cycle time than before, the reduction of the manual workstations (from three to two) and the introduction of a collaborative robot involve better line balancing. The utilization rate of each workstation is increased and is about 80%. Thus, the whole production line is more efficient and can guarantee a productivity increment. All the results are summarized in Table 5.

The collaborative work cell has been provided with physical and virtual barriers and the robot works in collaborative mode with low velocity. In this way, the operator and the robot can share the same workplace in a safe collaboration, and dangerous events for the operator can be avoided. In addition, the Smart Robots device ensures effective communication between human and robot. It allows the management of multiple products and related operations in a simple and fast way: the robot can be controlled
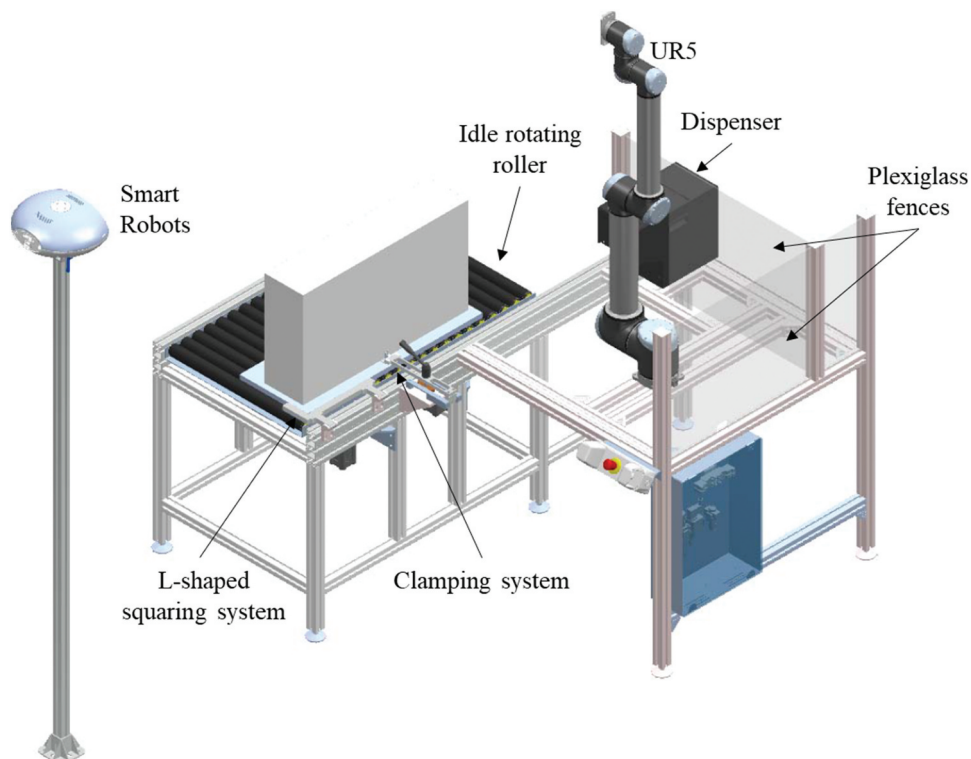

Figure 14. Prototype of the collaborative workplace.

Table 5. Comparison between as-is and HRC solution.

Indicator	AS-IS	HRC
RULA score	5 (red)	3 (yellow)
OCRA score	13,30 (red)	5,70 (green)
Workstations	3 manual	1 collaborative
		1 manual
Average utilization rate	70%	80%
Average cycle time	57 sec	47 sec

without the need for a physical interface, and the operator can interact directly with the robot to modify its activities with gestures and commands. Moreover, it can adapt and synchronize the robot's schedules with human actions. Although the Smart Robots is not recognized as a certified safety system, thanks to its real mapping of the workplace and its perception and reasoning capabilities, it is able to detect the human-robot distance in real-time and slow down the robot before the collision occurs. Finally, the risk assessment is carried out considering the implementation of all these safety systems. The safety risks identified during the first preliminary evaluation, performed in the HRC conceptual design phase, have been mitigated and all the risks are negligible.

8. Discussion and concluding remarks

The paper proposes an HRC design method that jointly considers different criteria, often conflicting, for the definition and evaluation of design alternatives. Drivers of the traditional technology-oriented approach (performance and costs) are combined with human factors and the growing need for production flexibility. The transition to human-oriented design imposes the definition of risk thresholds that eliminate the consideration of non-ergonomic or dangerous solutions and provide for an update of the risk assessment whenever the design choices generate repercussions on the human-robot interaction.

The study results reveal a high potential for HRC implementation to improve performance and flexibility without exposing the operator to risks to his health and safety while respecting an affordable cost-benefit ratio. Therefore, the proposed method is suitable to support decision-makers who hesitate or find difficulties with the implementation of collaborative robotics in their particular field of application.

8.1 Limitations and future works

The implementation of the method in a real industrial context demonstrated its potentialities, but also highlighted some limitations to be tackled. In the assembly line analyzed, the wide customization of the products had limited repercussions on the tasks to be performed, facilitating the application of the method and the achievement of flexibility requirements. In fact, the variability of the product dimensions did not affect the work area or the components to be assembled. The variability of tasks was therefore easily manageable by the operator through the interface. However, in other potential kitchen furniture assembly stations (e.g. door assembly), which will be tested in the next future, there could have been a significant growth in design solutions to consider and evaluate. If on the one hand, the consideration of all the alternatives helps not to be constrained in the design and enhances the engineers' creativity, on the other, it could make the process too time-consuming. The engineers' effort needs to be reduced by improving the usability and applicability of the method. Another criticality is the lack of knowledge to accurately estimate the impact of the various items. In this regard, it is necessary to evaluate the right compromise between a qualitative evaluation, which could be used in the PTR, and a more quantitative one to be used in the CC.

The development of a software tool would allow the automatization of some steps of the conceptual HRC design, favoring its adoption by both SMEs and no expert users. It should include a wizard procedure and a knowledge-based approach, as well as be user-friendly. It should support the requirements definition according to the five pillars and the data collection from the company's context; automatically generate all possible PTR, combinations, and sequences; provide a scoring guide, warnings, and suggestions for the design and evaluation phases. With the use of machine learning, it could then become the first step toward the HRC generative design. Future works will also deepen the HRC optimization and HRC reconfiguration modules by proposing a structured method and translating theoretical principles into quantifiable items.

8.2 Outlook and trends

The new digital transformation towards the Industry 5.0 paradigm is based on 3 main pillars:

well-being, sustainability, and resilience. If Industry 4.0 paradigm followed a technology-driven approach, Industry 5.0 moves towards a human-centric one, as proposed by this method. This new approach will let the industrial sector reach many social goals besides employment and growth, and it puts the worker's well-being at the center of the production process (Xu et al. 2021). To this aim, many Industry 4.0 technologies will be the drivers towards the achievement of this revolution (Mourtzis, Angelopoulos, and Panopoulos 2022). Recently, the COVID-19 pandemic highlighted the lack of preparation for risk and crisis management in the manufacturing sector, demanding more resilient and smarter production systems (Romero and Stahre 2021). As a consequence, multi-criteria methods to support the human-oriented design process of future cyber-physical systems are increasingly required. Human ingenuity represents the heart of this revolution since it combines flexibility, creativity, ambition, and innovation. These attitudes allow turning the adversities into opportunities. In this context, a new operator generation is emerging, which evolves from Operator 4.0. Specifically, the 'resilient operator 5.0' is defined as a clever and competent operator who uses creativity, resourcefulness, and human innovation, thanks to technology and information, in order to overcome obstacles. Therefore, it will be necessary to consider even operator cognitive aspects, such as stress, fatigue, frustration, and dissatisfaction, in the HRC design method. Finally, the evolution of the human-machine collaboration up to mutual co-evolution will make the real-time adaptability a fundamental requirement of the systems of the future. The development of methods that take this into account is encouraged.

Acknowledgments

Disclosure statement

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