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Inclusion of Disabled Workers in Production Environments through Industrial Collaborative Robots: a Company Case Study

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Abstract

The inclusion of workers with disabilities in industrial scenarios is a relevant challenge for the research community, both for ethical as well as for economic reasons. To fully integrate such workers, it is necessary to make them proficient in the execution of a large variety of activities, also the more complex ones. To solve this challenge, the adoption of assistive technologies which can enhance and/or complement the abilities of a disabled worker has proven to be particularly effective. In this regard, while cognitive assistance systems, e.g. augmented reality, have been widely explored, collaborative robots received a limited attention. However, such cobots are particularly promising when considering the inclusion of workers with disabilities, thanks to their capability of supporting a user in the physical execution of a task. To fill this gap, this paper presents a use case where an assembly process has been re-designed including a collaborative robot to support a disabled worker. The contributions of the paper are the development of a human-robot task allocation strategy to effectively include disabled workers and its validation in a long-term industrial experiment. The use case also led to the key finding that a correct enhancement of a disabled worker allows him/her to execute even complex manufacturing operations with better performances compared to those of a non-disabled worker.

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Keywords: Human Robot Collaboration; Inclusion; Workers with Disabilities; Industrial Collaborative Robots

1. Introduction

An effective inclusion of workers with disabilities in industrial settings is one of the most relevant challenges for the research community [1]. This is motivated both by ethical as well as by economic reasons. Developing an inclusive society is one of the Sustainable Development Goals (SDGs) presented in the 2030 Agenda for Sustainable Development, which defines universal requests for action to end poverty, protect the planet, and ensure people's peace

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and prosperity [2]. Social sustainability is also one of the cornerstones of Industry 5.0, which is trying to develop smart production lines with a human-centric approach to maximize the resilience of industries [3, 4].

From an economic perspective, an effective inclusion of workers with disabilities can compensate for the lack of workforce which is affecting the European labour market due to ageing of population [5]. In fact, only in the EU, out of the 87 million people living with some kind of disabilities, only around 50% of them could find employment [6]. However, such disabilities often act as a barrier and prevent such workers in the execution of several tasks, thus leading to their involvement only in simpler tasks.

A full integration of such categories of workers requires the adoption of smart strategies capable of maximizing and/or enhancing their capabilities, so as to become fully proficient in a large set of industrial tasks. Such a challenge has, in first place, been addressed exploiting an 'organizational' approach, e.g. exploiting scheduling models [7] or assigning the tasks so that the abilities/disabilities of a worker affect the process as little as possible [8]. A different approach, instead, consists of enhancing the capabilities of such workers by exploiting technological solutions. Among different assistance systems, it is worth mentioning (i) cognitive and (ii) physical/sensorial assistance systems [27]. The former, i.e. cognitive assistance systems, consist of those devices which can support the operator in the decision process or provide additional information, e.g. projection based assistance systems. Such systems have shown their effectiveness in reducing the cognitive workload of the operator [10] and in enhancing the skills of a disabled person, in some cases leading to a productivity even higher compared to the one of a non-disabled worker [11]. The latter, i.e. physical/sensorial system, instead, consist of all the devices which are related with the physical execution of a task and/or with the physical state of the human, e.g. collaborative robots. Among these devices, industrial collaborative robots are particularly promising thanks to their capability to act both as physical [12, 13] as well as cognitive assistance system [14, 15].

However, while the implementation of effective collaborative robotic applications is widely investigated by the research community, from work-cell design to task allocation and trajectory planning and execution (see for example [16, 17]), there are still a limited number of contributions addressing the development and/or adaptation of an industrial robotic work-cell with the goal of including workers with disabilities in manufacturing processes [18]. In [19], a software tool to determine the level of assistance required to the robotic system by a specific person is developed. This work has then been complemented in [20], where, according to the required level of assistance, a methodology to select devices/tools required to effectively include a disabled worker in assembly operation is presented. In a first pilot [21], the design requirements for a work-cell deployed for workers with cognitive disabilities are derived considering the impairments of the group of users. A general pipeline to design/develop an inclusive workcell has then been defined in [22]. In [23], a first task allocation technique which considers both the capabilities of the worker as well as the process requirements is presented. Such a technique has then been extended in [24] through an ontology-based approach, which can adapt the task allocation in situ, considering the response of the worker in terms of fast (e.g. fatigue) and slow mental processes (e.g. illnesses).

In this paper, a comprehensive task scheduling methodology is developed and validated with the goal of enhancing the capabilities of workers with cognitive disabilities through collaborative robotics, enabling them to proficiently execute even complex manufacturing operations. The developed technique builds on and extends the Human Robot Activity Allocation algorithm (HRAA) [25]. In particular, it considers as inputs the process requirements, individual human capabilities, physical and cognitive ergonomics, safety and quality of the manufacturing operation. The algorithm is then based on the evaluation of several indices, each of them evaluating one of the aforementioned criteria. The outcome consists then on the automatic allocation of tasks between the human and the collaborative robot to support adaptable and inclusive robotic-assisted workplaces. The method can be applied, in general, to any kind of disability, leading, possibly, to different task allocation for different disabilities.

The contributions of the paper are (i) the development of a comprehensive task scheduling algorithm to integrate workers with disabilities in production lines, thus reducing inequalities between workers with and without disabilities (SDG 10), (ii) application and preliminary validation of such an approach on an industrial use-case and (iii) the analysis on the long term (i.e. more than one year) of the effects of enhancing the capabilities of a group of workers with disabilities with a collaborative assistive system. Results show that, exploiting such an enhancement of their capabilities, the productivity and the quality of the process as well as the well-being of the worker could be systematically improved.

The remainder of this paper is structured as follows: in Section 2 the developed methodology to effectively include workers with disabilities in production lines is presented and detailed, while its application in an industrial use case is described in Section 3. The validation of the effectiveness of the method as well as of the relevance of enhancing workers with disabilities with assistive technologies is reported in Section 4. Finally, in Section 5, conclusions are drawn.

2. Methodology

In this Section, the developed Human Robot Activity Allocation for Inclusion (HRAA4I) algorithm is introduced and detailed. The developed method extends and complements the Human Robot Activity Allocation algorithm (HRAA) [25], an established methodology for the redesign of manual assembly workstations into collaborative ones, to account for the capabilities of workers with disabilities and for the possibilities to enhance their skills.

The HRAA algorithm is based on the decomposition of a process into single tasks, where every task is then analyzed exploiting a sequential combination of hierarchical indices which are evaluated for every single task i:

- Technical Evaluation Index $TEI(i)$, which aims at evaluating whether a certain activity can be executed by a cobot by considering the technical requirements given by the process and the technical capabilities of the machine.
- Safety and Ergonomics Evaluation Index $SEEI(i)$, which determines if a task might compromise the safety and/or the ergonomics (both physical as well as cognitive) of the operator.
- Quality Evaluation Index $QEI(i)$, which evaluates if the task requires an improvement in terms of production quality (e.g. production errors, product variability and so on).
- Economics Evaluation Index $EEI(i)$, which defines whether a task provides added value to the product or not.

Each index can assume value 'H' if the activity is compatible only with the human operator, 'R' if the activity is compatible only with the robot and 'H' or 'R' if it can be executed by both entities. The results of the evaluation of the aforementioned indices are then used to compute the Final Evaluation Index $FEI(i)$, which determines if an activity has to be executed by the operator, by the collaborative robot or if it can be executed by both of them. For more details on the different indices as well as on the methods developed to compute them, the readers can refer to [25].

This paper extends such an approach with the goal of developing a methodology to adapt a workstation designed for non-disabled workers to be effectively operated by disabled ones. The methodology can be deployed with any kind of disabilities, even if it might lead to different task allocations when different kinds of disabilities are considered. Moreover, the method can recognize whether a specific disability of an operator is not compatible with a given process and precludes its involvement.

To do so, a new additional index is introduced: Human Capabilities Evaluation Index $HCEI(i)$, which aims at evaluating whether a given worker can effectively execute this task. In fact, it is crucial to determine if a set of tasks is compatible with the abilities of a given worker. To evaluate it, it is necessary to consider not only the execution of one single activity, but also the long-term effects. As an example, a worker with certain disabilities might correctly execute a mentally demanding task for a short period of time, but would probably not be able to maintain the same level of focus over a longer period. The outcome of such an index can be 'True' or 'False' depending on whether the given worker can or not execute the task. Further details on the evaluation of the HCEI can be found in Section 2.1.

The novel algorithm is graphically represented in Fig. 1. The principle guiding the algorithm is that, if an operation can be executed by the operator and can not be executed by the robot, it has to be assigned to the human operator. If, on the contrary, the operation could be executed from a technical standpoint by both of them but it might compromise safety or ergonomics of the operator and/or it is not a value adding activity, it must be executed by the robot. Another possible case is the one in which only the robot can perform such a task due to safety or ergonomics, quality, or production efficiency reasons. Instead, whether an activity can not be executed neither by a worker with disabilities nor by the robot, the overall process is not suitable for the inclusion of this specific operator.

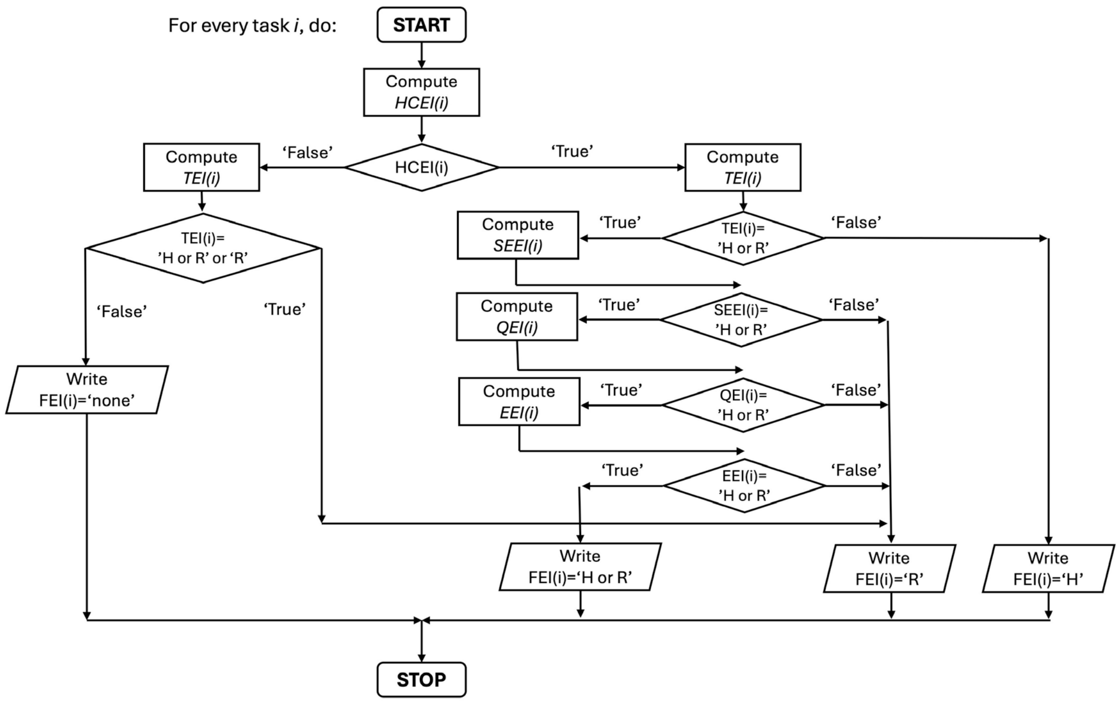


Fig. 1: Graphical representation of the HRAA4I algorithm.

2.1. Human Capabilities Evaluation Index (HCEI)

To determine the capability of an operator with disabilities to execute a given task, it is necessary to consider both the physical as well as the cognitive functional characteristics that may be involved in a task.

The authors propose the following guidelines to evaluate if the abilities of a worker are compatible with the functional requirements associated with a given task. First of all, to evaluate the outcome of an index, among the following questions, the ones which are relevant with respect to the execution of the specific task are to be selected. If the answer to the selected questions is 'yes', i.e. the operator has the abilities required to execute that task, the value of the index is 'True'. If, instead, the operator does not have all the abilities required to execute that task, i.e. if the answer to even one of the selected questions is 'no', then the index assumes a 'False' value.

Physical Capabilities [26, 27]:

- Fine physical coordination: can the worker execute motions with the required precision?
- Force physical exertion: is the worker able to generate the forces required to execute the task without overloading him/her?
- Physical speed: does the worker have the ability to perform movements with the speed required by the task?
- Bilateral coordination: if required, can the worker use both hands together in a coordinated way?
- Manual dexterity: does the worker have the overall hand skill and agility in performing the task?
- Postural control and balance: can the worker maintain stable posture during the task execution?
- Physical endurance: can the operator execute the task over time?
- Reaction time: does the speed of the operator guarantee him an adequate capability of responding to stimuli?

Cognitive Capabilities [27, 28, 29]:

- Attention regulation: does the worker have the ability to stay focused on the task?
- Sustained attention: can the worker maintain focus over a prolonged period?

- Selective attention: is the worker able to distinguish between relevant and irrelevant stimuli?
- Cognitive flexibility: can the worker shift between moltiple tasks within the same work-cycle?
- Memory: does the worker have the ability to retain information for the required amount of time?
- Planning capability: can the worker mentally organize this step, in combination with the others required to complete a task?
- Problem-solving: is the worker able to respond or find solutions to unexpected situations?
- Responsiveness: is the worker quick enough to understand and react to stimuli?
- Instruction comprehension: can the worker understand written or verbal directions?

3. Use Case

In this Section it is firstly outlined the original industrial process which has been redesigned and complemented with a collaborative robot with the goal of enhancing the capabilities of workers with disabilities (Section 3.1). Subsequently, the application of the proposed methodology is detailed (Section 3.2).

3.1. Industrial Process

The process considered in this use case consists on the production of a component for the electric car industry. The process was carried out entirely manually and the methodology has been applied, leading to a semi-automatic, i.e. collaborative one to include a group of two workers with cognitive disabilities. Please note that several details cannot be revealed due to trade secrets and confidentiality agreements.

The main steps of the assembly process are the following:

- the molding machine, starting from raw material, produces a plastic element. The pieces are released (in a non-ordered way) on a conveyor belt, where they cool down.
- assembly steps: all other components composing the final product are assembled on the plastic element. Even if such operations cannot be detailed due to trade secrets, they require a high precision and dexterity for placing/joining all the different pieces.
- quality check: all pieces have to be singularly inspected (100% check) to ensure that all the assembly steps have been properly executed. Such a control can be executed in two ways: either (i) visually, observing the component, or (ii) electronically, analysing the physical properties of the final assembly. In fact, if the workpiece has been properly assembled, it exhibits a peculiar magnetic property which can be electronically detected.
- the products, once checked, must be packed in a box for shipment.

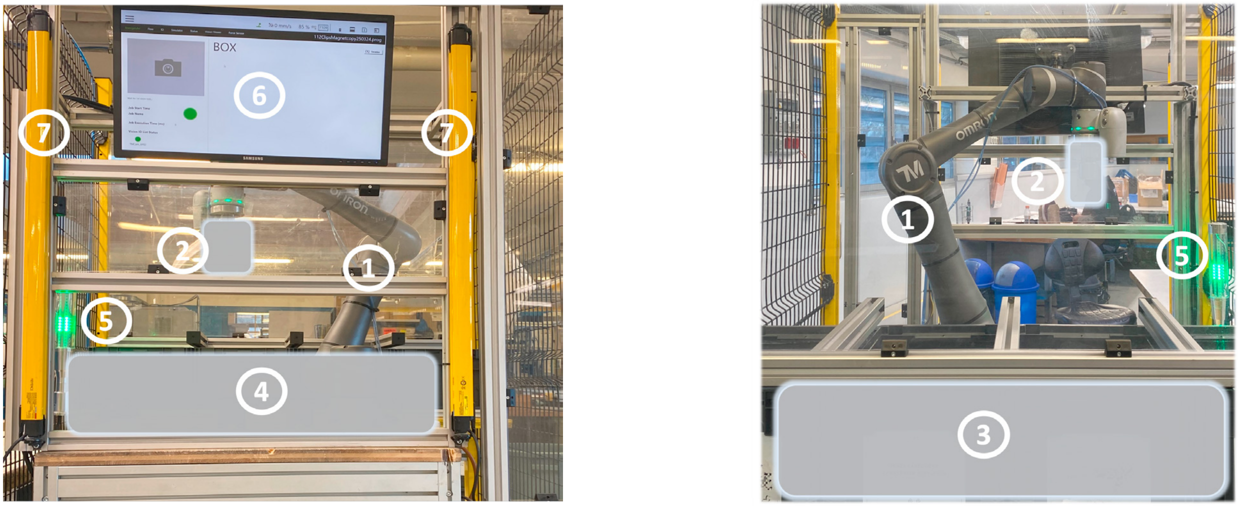
3.2. Process Redesign

Application of the Human Robot Activity Allocation 4 Inclusion Algorithm

The application of the proposed approach with respect to two workers sharing the same cognitive disability is summarized in Table 1. Since the particular kind of disability is not required to understand the use case, the authors preferred not to mention it due to privacy concerns. The task allocation algorithm led to the assignment of the assembly operations requiring high dexterity to the human operator, while the quality check and the packaging operations, where it is desired to reduce the variability and improve the quality of the process, to the collaborative robot. Please note that the workers considered in this validation were affected by a cognitive and not by a physical disability, which does not compromise their ability in the execution of manual operations.

Operation	*HCEI*	*TEI*	*SEEI*	*QEI*	*EEI*	*FEI*
Assembly	'True'	'H'	-	-	-	'H'
Quality Check	'True'	'H or R'	'H or R'	'R'	-	'R'
Packaging	'True'	'H or R'	'H or R'	'R'	-	'R'

Table 1: results of the application of the HRAA4I algorithm to the use case.



(a)

(b)

Fig. 2: Picture of the developed workstation: (a) front and (b) back. Some details are hidden on purpose to protect trade secrets.

Implementation

To implement the outcome of the HRAA4I algorithm, the workstation shown in Fig. 2 has been developed. In particular, the workstation consists of an Omron TM5 collaborative robot (Fig. 2 - Item 1) equipped with a custom made end-effector (Fig. 2 - Item 2), which is used both to grasp the pieces as well as to execute the quality check operation by analyzing the magnetic properties of the assembled pieces. The workstation is characterized by an area where the boxes used to store the assembled and checked products are placed (Fig. 2b - Item 3) and an area used to manually assemble the product (Fig. 2a - Item 4). A tower light (Fig. 2 - Item 5) and a screen (Fig. 2a - Item 6) are used as interfaces with the operator. Two laser barriers (Fig. 2a - Item 7) have been placed to monitor possible intrusions of the operator in the robot's workspace.

This solution has been adopted for the following reason: the ISO/TS 15066 [30] defines a maximum admissible speed at which a human operator and a collaborative robot can physically interact, based on the idea that, even if a collision would happen, the speed would be slow enough not to cause an injury to the operator. However, such a speed would result in overly slow motions, which do not meet the process requirements, i.e. cycle time. For this reason, the robot movement is supervised by a safety controller inspired by [31], which modulates the speed of the robot depending on the position of the human operator:

- if the human is working on the same workspace of the manipulator, i.e. when a human-robot collision might occur, the speed of the manipulator is reduced to the 'safe' one as required by [30].
- if, on the other hand, the human is not working in the same workspace of the manipulator, the robot operates at higher speeds.

The placement of the barriers has been chosen so as to make sure that the minimum separation distance from the robot and the operator, combined with the deceleration time of the robot, ensures that the robot has enough time to decelerate to the 'safe' speed before a collision might happen.

As prescribed by the [30], the maximum safe speed $v_{PFL} = \frac{F_{max}}{\sqrt{\mu k}} = \frac{p_{max} A}{\sqrt{\mu k}}$, where F_{max} and p_{max} are, respectively, the maximum allowable contact force and the maximum allowable pressure, k is the effective spring constant for a specific body region (reference values in [30]), A is the contact area, while μ is the reduced mass of the two body system. The value of v_{PFL} has been computed considering a possible transient collision between the human hand, wrist, forearm, elbow and upper arm, an end effector mass of $1kg$ and an estimated contact area $A = 0.75cm^2$, resulting in a worstcase, maximum allowable speed equal to $1.01m/s$. Adopting a conservative approach, it has been decided to limit the robot speed, when operating in PFL mode, to $0.9m/s$.

To determine a safe distance of the laser scanners, the time required by the robot to decelerate from its nominal speed to the 'safe' one by moving along the nominal path T_d can be determined solving the following problem:

$$\min \quad T_d \tag{1}$$

$$\text{s.t.} \quad |\tau(\ddot{\mathbf{q}}(t), \dot{\mathbf{q}}(t), \mathbf{q}(t), \tau_{ext})| \leq \tau_{max} \tag{2}$$

$$|v_r| \leq v_{PFL} \tag{3}$$

The problem consists of finding the minimum deceleration time (eq. 1) which satisfies the torque limits of the manipulator (eq. 2) and allows the robot to achieve a speed lower than the maximum one (eq. 3). Rounding the results also in this case with a conservative approach resulted in the definition of a deceleration time $T_d = 150ms$.

The minimum separation distance between the laser scanners, i.e. the border of the collaborative area, and the robot's trajectory s_d can then be computed as:

$$s_d = T_d \cdot (v_{HR}) \tag{4}$$

where v_{HR} is the relative human-robot velocity. An evaluation of the process allowed to determine that the maximum value of v_{HR} can be assumed to be $1.6m/s$, thus resulting in a separation distance $s_d = 0.24m$.

4. Experimental Validation

The validation consists of a comparison between two different scenarios: from September 2022 to February 2024 the process has been executed entirely manually, while, from March 2024 to May 2025, the collaborative assistance system to include workers with cognitive disabilities has been introduced.

The effectiveness of the developed methodology has been evaluated through the metrics detailed in Section 4.1, which aim at quantifying productivity as well as operator's well-being related effects. The results of the experimental test are then presented and discussed in Section 4.2.

4.1. Metrics

To evaluate the effectiveness of the inclusion of a disabled worker, the following metrics have been defined:

- Productivity metric P_{ps}: it quantifies the production rate of the production process. It is defined as the number of pieces produced per shift (8 working hours).
- Quality metrics, which aim at measuring the production errors and their economic impact. In particular, the first metric, N_c is defined as the number of complaints of the customer per year. The second metric, C_c, is defined as the cost derived from the complaints per year. Please note that the cost is not directly associated to the number of complaints. In fact, it is also affected by the severity of the production errors and by the subsequent corrective actions required.
- Cognitive Workload metric C_{wl}, evaluated through a questionnaire aiming at evaluating the mental demand associated with a task, which has been extracted by the NASA Task Load Index, [32].
- Technology Usability metric T_u: its goal is to numerically establish the ease of use of such a technology and it is defined as the average time required by a disabled operator to become proficient at working with the new setup.

4.2. Results

In Table 2 the results of the experimental comparison are reported. As it is possible to observe, the introduction of the assistive technology, i.e. the cobot, to support the operation led to an increase in productivity (almost doubled) and to a decrease in the production errors (100% reduction of the errors). While the increase in productivity is mainly due to the parallelization of the tasks between the human operator and the robot, the improvement in the quality of the production process is achieved thanks to an efficient allocation of tasks between the worker and the robot. The robot, supporting the operator in the quality control and in the packaging phases, takes care of the activities which are more repetitive and associated with the higher cognitive workload. The operator can then focus on the tasks which are more aligned with its abilities. In fact, the operator is responsible of the assembly of the product, which requires a high dexterity that is not compatible with a robotic application. The improvement in the quality of the production process plays also a crucial role in the business plan of a product. In fact, possible complaints of the clients are associated with both re-manufacturing costs as well as costs related to the workload required to handle the complaint.

Concerning cognitive workload, the experimental validation highlighted how the deployment of the methodology to the redesign of the workstation led to a decrease in cognitive workload (-37.8%). This can be explained by the fact that the manipulator executes the set of activities which were associated with the larger mental effort for the operator.

Concerning usability, the average time required to become proficient in learning a process carried out exploiting a cobotic assistance system is larger than the one without assistance system, i.e. executing the entire process manually, by half an hour. While introducing additional systems to a production process clearly increases the duration of the training phase, the increase measured in the use case (half an hour) does not preclude or pose a barrier to the deployment of such a technology and is quickly compensated by the increase in productivity and the improvements in the process' quality.

Category	Metric	Without assistance	With assistance	Variation (in %)
Productivity	P_{ps}	$1.05 \cdot 10^3$	$2.01 \cdot 10^3$	+91.4%
Quality	N_c	3,33	0	-100%
Quality	C_c	6000€	0€	-100%
Cognitive workload	C_{wl}	82	51	-37.8%
Technology Usability	T_u	0.5 h	1 h	+50%

Table 2: table reporting the results of the validation for all the metrics introduced in Section 4.1.

5. Conclusion

This paper presents a human-robot task allocation algorithm which aims at developing industrial collaborative workstations capable of including workers with disabilities in the production lines and, consequently, reduce the inequalities between workers with and without disabilities, by exploiting collaborative robots to enhance/complement their strengths. Such a methodology considers the abilities of the single worker, the technical feasibility of possible automation, safety, physical and cognitive ergonomics, quality and the economic aspects associated with the redesign of the workstation. The approach has been preliminarily validated in an industrial use case scenario, where a workstation for the assembly of an electric car component has been revised so as to effectively include some workers with disabilities. The analysis of the outcomes of such a use case showed, first of all, the effectiveness of the developed methodology and, even more important, that, through the exploitation of such an assistive technology, the workers could achieve even higher performance with respect to those of non-disabled workers. Future works might be related with a more extensive validation of the approach when considering a larger variety of disabilities and of products, as well as with the development of methodologies to design workstations characterized by an interoperability with respect to different kinds of disabilities and that are not specific to a single operator. Another possible future work could also be related with the effective co-creation of workstation by workers, occupational experts and automation experts.

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