



A novel human-centered methodology for assessing manual-to-collaborative safe conversion of workstations

André Cardoso^{a,b,*}, Ana Colim^b, Estela Bicho^{a,d}, Ana Cristina Braga^{a,c}, Pedro Arezes^{a,c}

^a Algoritmi Research Centre LASI, University of Minho, Guimarães, Portugal

^b DTx Digital Transformation Colab

^c Department of Production and Systems, Portugal

^d Department of Industrial Electronics, Portugal

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ABSTRACT

The Industry 5.0 paradigm places workers' well-being and safety at the core of the production processes. Despite its objectives, the current industry still faces several challenges. Examples of these challenges include global market pressures for customized products, along with the significant occurrence of Work-Related Musculoskeletal Disorders and the ageing workforce. These challenges underscore the persistent need for human-centered solutions, allowing adaptations that align with humans' physical and cognitive constraints. Collaborative robots offer a promising solution, with the potential to enhance workers' well-being, while maintaining safety, productivity, and production process flexibility. This study introduces a novel methodology designed to assess the feasibility of converting manual tasks into collaborative ones. During the development of the methodology, a focus group approach was used, comprising 6 experts in the field of Ergonomics & Human Factors and Robotics. The proposed methodology is suitable for the identification of tasks appropriate for joint execution by humans and robots, thereby augmenting the effectiveness of the robotic solution. This methodology incorporates a set of indicators (physical and cognitive ergonomics, health and safety, and operational efficiency) and technical requirements. The results of the focus group allowed the improvement of the suggested methodology. For its testing, we applied across 13 manual workstations in 5 companies from different manufacturing sectors (civil construction, cutlery, furniture, and automotive fabric manufacturing). Results show that it is possible to comprehensively identify manual workstations/tasks with good and high potential to convert into collaborative systems. This methodology seems to constitute a relevant approach to support the conceptualization of collaborative workstations.

1. Introduction

In what concerns about technological advancements, robots have emerged as transformative entities, remodeling industries, and the nature of work itself. Among these technologies, collaborative robots, commonly called cobots, represent a groundbreaking innovation to combine the potential of humans and robots. They are having an interesting diffusion because of the distinct advantages they offer (Calzavara et al., 2023). Among the advantages, this novel category of robots can provide a blend of productivity, typical of automated machines, and adaptability, characteristic of manual systems (Faccio et al., 2019). In fact, the cobots do not specialize in a singular product

reference, as traditional robots do. Instead, they can be readily adjusted to accommodate various product attributes (Calzavara et al., 2023). Additionally, they are designed to work harmoniously with human workers to achieve shared objectives (Oztemel and Gursev, 2020; Panchetti et al., 2023). Especially because they can work directly alongside humans, without barriers, sharing both space and time with the workers (Calzavara et al., 2023). Cobots are expected to reduce physical and cognitive workloads, while also enhancing safety and quality (Pauliková et al., 2021). Their potential influence extends to diverse organizational aspects, including productivity, flexibility, and precision (Cherubini et al., 2016; Panchetti et al., 2023; Villani Valeria et al., 2017).

The current paper explores the multifaceted landscape of cobots,

* Corresponding author.

E-mail addresses: andre.cardoso@dps.uminho.pt (A. Cardoso), ana.colim@dtx-colab.pt (A. Colim), estela.bicho@dei.uminho.pt (E. Bicho), parezes@dps.uminho.pt (P. Arezes).

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investigating their potential application in addressing challenges posed by contemporary industrial scenarios. A central aspect of the exploration revolves around the evolution from Industry 4.0 to 5.0, wherein assistive technologies, such as cobots play a major role. The Industry 5.0 paradigm, characterized by a human-centered approach, emphasizes sustainable and resilient industry practices that prioritize the safety and well-being of workers (Romero and Stahre, 2021). This shift underscores the significance of incorporating Ergonomic & Human Factors (E&HF) considerations into manufacturing processes and workspaces, with cobots acting as enablers for this transition (Faccio et al., 2023).

Despite their promising benefits, the contemporary industrial scenario struggles with persistent challenges, including globalization, rapid technological developments, increased customer requirements for customized products, and the shorter life cycle of products (Caputo et al., 2018; Kolus et al., 2022). In addition, considerable emphasis has been placed on sustainable products and processes, primarily directed toward environmental and economic considerations to mitigate expenses and resource utilization (Peruzzini et al., 2017). On top of that, also Work-Related musculoskeletal disorders (WMSD) that stem from physically demanding work conditions (Chiasson et al., 2012), impose more challenges to industries. These disorders, highly prevalent also in modern workstations (Chen and Luo, 2023; Roberts et al., 2023), in addition to human costs, have far-reaching economic and societal implications, due to economic losses resulting from lost or reduced productivity, medical treatments, and compensation costs (Kolus et al., 2022). Moreover, another challenge pertains to the ageing of the labor force and the concurrent increase in the retirement age. The challenge at hand stems from the fact that individuals' capacity to execute tasks demanding both physical and mental exertion tends to decline with age (Calzavara et al., 2020). These challenges coupled with the advances in industrial automation and the need for safe, flexible, and adaptable production systems lead to closer collaboration between humans and robots in several industrial fields (Pizzagalli et al., 2021). For example, the advancements in robotics allow for safer human-robot collaboration (HRC) through features like sensors and algorithms powered by artificial intelligence, while also enabling more adaptable production systems that can respond to changing demands in real-time (Ajoudani et al., 2018). This makes evident the importance of human-centered design in the integration of cobots (Caputo et al., 2018; Gualtieri et al., 2020b), to accommodate the physical and cognitive constraints of the workforce. However, HRC can frequently lead to increased workload and a decrease in human performance if the implementation of HRC fails to account for the consequential effects of automation on the worker (Hopko et al., 2022).

By considering E&HF aspects in the workstation design process, the collaboration between humans and cobots can be more efficient, effective, and safe (Adriaensen et al., 2023; Cardoso et al., 2021; Hopko et al., 2022). The role of E&HF includes investigating aspects related to human-robot interfaces, formulating guidelines and standards for safe HRC, and conducting evaluations of systems involving interactions between humans and robots (Kolus et al., 2022). Some studies addressed the importance of considering E&HF in the design of HRC. Pearce et al., (2018) introduced a framework that addresses the allocation of co-workers (whether human or robot) based on factors such as task completion time and the physical strain experienced by humans. Kühnlenz et al. (2018) investigated the impacts of various trajectory patterns an industrial cobot performs on human subjects. They assessed these effects by analyzing heart rate variability (HRV) and electrodermal activity (EDA). Zanchettin et al. (2019) created a motion control algorithm designed for a robotic manipulator, enabling it to handle most of the movement. This approach restricts the workers' motion to a defined amplitude and range, ensuring precise execution of the intended task. Liao and Ryu (2020) created and validated a framework designed for task allocation within a workstation that involves one human and two cobots. Colim et al. (2021) introduced an ergonomic intervention utilizing robotic solutions for assisting manual assembly tasks, aiming to

reduce the risk of WMSD. The authors considered both physical ergonomics and productivity considerations in the design phase.

However, there are situations in which (re)designing workstation process from '*tabula rasa*' is not commendable, e.g., due to spatial constraints or because an adaptive solution is warranted to address the prevailing issues within manual tasks. Hence, a restricted body of research has engaged in the challenge of converting an existing manual workstation into a collaborative one, encompassing a holistic approach that considers the various domains (such as physical and cognitive ergonomics, safety, and productivity) in which the implementation of a cobot could be an aid. In particular, Gualtieri et al. (2020a), introduced a methodology aimed at evaluating the viability of integrating cobots. This approach encompasses diverse criteria, with each criterion being characterized by a constrained set of statements. However, as a limitation, it should be noted that the E&HF aspects were assessed by a subjective approach based on generalist questions. This could impact the accuracy and comprehensive understanding of the integration's ergonomic implications. More recently, Calzavara et al. (2023) proposed a multi-objective methodology for evaluating task allocation in human-centered collaborative systems. The primary objective centers on enhancing productivity while concurrently addressing the operator's well-being. The researchers introduce a saturation constraint to harmonize task distribution, thereby reducing the workers' exertion. This endeavor results in heightened makespan efficiency and improved utilization of resources. However, as a limitation, it is notable that the consideration of human safety and well-being was not prioritized, potentially impacting the overall effectiveness of the proposed methodology.

Given the above, the principal aim of the current study revolves around developing and applying an innovative assessment methodology designed to overcome the limitations posed by previous methodologies. This new methodology primarily concentrates on human factors and integrates multiple validated techniques/methods to the parameters it encompasses.

Our integrated assessment methodology offers a more precise understanding of the issues in manual workstations, addressing ergonomics, occupational safety, operational efficiency and technical concerns. Importantly, it underscores the feasibility and potential benefits of cobot adoption in these domains, which could lead to significant improvements in productivity and worker well-being. This highlights the practical relevance of our research and its potential to shape the future of HRC in industrial automation. Moreover, the meticulous identification and acknowledgment of these issues serve as a guide for implementing cobots, ultimately resolving these identified problems upon their introduction into the workstations. Hence, the fundamental objective of this assessment methodology lies in identifying tasks within manual workstations with constraints not solved by traditional redesign approaches and that hold promise for collaborative execution alongside cobots. This methodological framework adopts a comprehensive perspective encompassing diverse indicators, including physical and cognitive ergonomics, health and safety considerations, as well as operational efficiency. Furthermore, it considers cobots' technical requirements. By conducting a comprehensive assessment, companies can make informed decisions about implementing cobots into manual workstations, thereby optimizing productivity while ensuring the well-being and safety of workers.

2. Materials and methods

The current study consists of two research phases, each aimed at addressing specific objectives, as follows: (i) development of the proposed methodology, and (ii) application of the methodology in real-industry scenarios to select tasks with high potential for collaborative systems.

The proposed methodology results from prior research stages presented in Cardoso et al., (2024). In our previous work, a careful analysis

of the current literature, industry best practices, and expert insights were considered to propose the prior version of the methodology to assess the potentiality of HRC implementation. The aim was to integrate a wide range of factors such as task complexity, E&HF considerations, workflow analysis, and technological integration. Following the formulation of the prior version methodology, a real-world application was carried out. It was applied to one manual workstation to assess its practicality and identify potential problems. This first version paved the way defining a more robust methodology. Based on this, a focus group session was organized with experts in the fields of E&HF and Robotics. As a result of this focus group, several modifications were made to refine the novel methodology proposed in the current study. Fig. 1 represents the main stages adopted to develop the proposed methodology.

2.1. Focus group session

The focus group comprised six experts selected based on specific criteria: a minimum of 10 years of experience in E&HF or Robotics, availability for in-person sessions, effective communication skills, and proficiency in Portuguese and English. The focus group technique was crucial for improving the methodology's effectiveness (McLafferty, 2004). The focus group session occurred on a single day for 6 h.

At the beginning of the session, an overview of the methodology's prior version was presented. Then, each one of the variables and techniques used for the assessment was explained. The relevance of each variable for inclusion in the methodology was discussed. At this stage, the following questions were posed: "In your opinion, is the inclusion of this variable relevant for assessing the potential transformation from manual tasks to collaborative tasks?" and "In your opinion, is the metric/technique used suitable for evaluating the presented variable?". The discussion was centered on these questions until reaching a unanimous consensus. Finally, the group discussed the last step of the methodology – the final score quantification.

2.2. Description of the novel methodology

The novel methodology encompasses two main steps, namely: (i) real-world data acquisition, and (ii) assessment of the potentiality for implementation of a cobot system. This second step involves a holistic assessment that considers two sets of variables: indicators of potential concerns that can evidence the need for improvement of the workstation and requirements for the cobot technology implementation. This methodology was designed based on a multi-technique approach to address multiple insights and, consequently, a comprehensive assessment (Salmon and Read, 2019). Related to the indicators, we included Physical Ergonomics (PE), Cognitive Ergonomics (CE), Health and Safety (HS), and Operational Efficiency (OE). The requirements only include Technical Requirements (TR). For each of these five variables, a score between 0 and 3 points is attributed. The delineation of this score range stemmed from the uniformity across all techniques employed to evaluate each of the considered variables, rendering their integration into this methodology more practicable. All techniques selected respect the following criteria: scientific validation for the respective variable assessment, having an objective descriptor for each score level, ease of application only based on direct observation, and a final score 4-level

categorized. The utilization of a 4-level score is commonplace in methodologies within the E&HF domain (Ahonen et al., 1989; McA-tamney and Nigel Corlett, 1993). A larger score assigned to each variable (indicators or requirements) represents a greater potential for a HRC implementation. An overview of the steps of this methodology is presented in Fig. 2.

2.2.1. Real-world data collection

As mentioned, the methodology starts with comprehensive data collection from real-world manual workstations, including site visits, an ergonomic screening method, documentation analysis, and worker interviews. During this step, a participatory ergonomic approach was adopted, promoting the workers' involvement and foreseeing a deeper understanding of the complex dynamic interactions between workload, safety, and efficiency in working settings (as defended by Ibrahim Shire et al. (2020).

Relatively to the ergonomic screening method, the EWA (Ahonen et al., 1989) was selected since it is a well-known method for systematically and comprehensively analysing workstations (Colim et al., 2020). It encompasses 14 topics, namely: workspace; general physical activity; lifting tasks; work postures and of accident; work content; restrictiveness; workers' communication; decision-making; movements; risk of accident; work content; restrictiveness; workers' communication; work repetitiveness; level of required attention; lighting; thermal conditions; and noise. The method incorporates both worker and expert evaluations. Workers subjectively assess their workstations on a 4-level scale for each topic, while experts use a 4 or 5-level scale. In this method, a score of 5 (or 4 in specific topics) indicates the highest risk for the worker in the given topic. Moreover, the collected data not only include information necessary for assessing all topics but also encompass valuable additional details, such as manual tools used, task function variety, complementarity, and shift duration (Chiasson et al., 2015). Each topic was clearly explained to the workers to ensure their understanding of the evaluation criteria.

2.2.2. Assessment of the indicators

Related to the assessment of PE indicator, it is carried out using a checklist created by the Occupational Safety and Health Administration (OSHA, n.d.). This tool is shown in Fig. A1 from appendix A. The rationale behind incorporating this indicator into the current methodology stems from the fact that robots aid in enhancing workplace ergonomics and alleviate humans from very laborious and often repetitive work (Makrini et al., 2019). Therefore, the existence of WMSD risk factors in manual workstations may be a contributing factor to the need for implementing collaborative systems. The tool considered to assess this indicator presents 18 issues related to well-known physical WMSD risk factors. According to the authors of this tool, only the first 15 issues contribute to the risk final score. Examples of these WMSD risk factors are awkward body postures, repetitive movements, application of force, and vibrations (Kolus et al., 2022). The inclusion of all these factors shows its suitability as a tool for easily assessing this parameter. In addition, this surveillance method is a straightforward tool, aiding in the timely detection of discomfort related to WMSD (Lin et al., 2013). The choice of this tool stems from its simplicity in identifying WMSD risk factors and enabling the calculation of a final risk score, making it easily

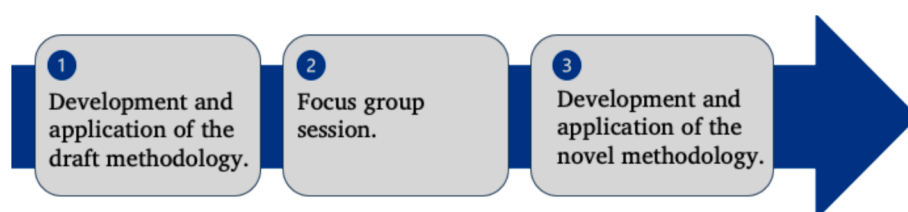


Fig. 1. Stages of development of the proposed methodology.

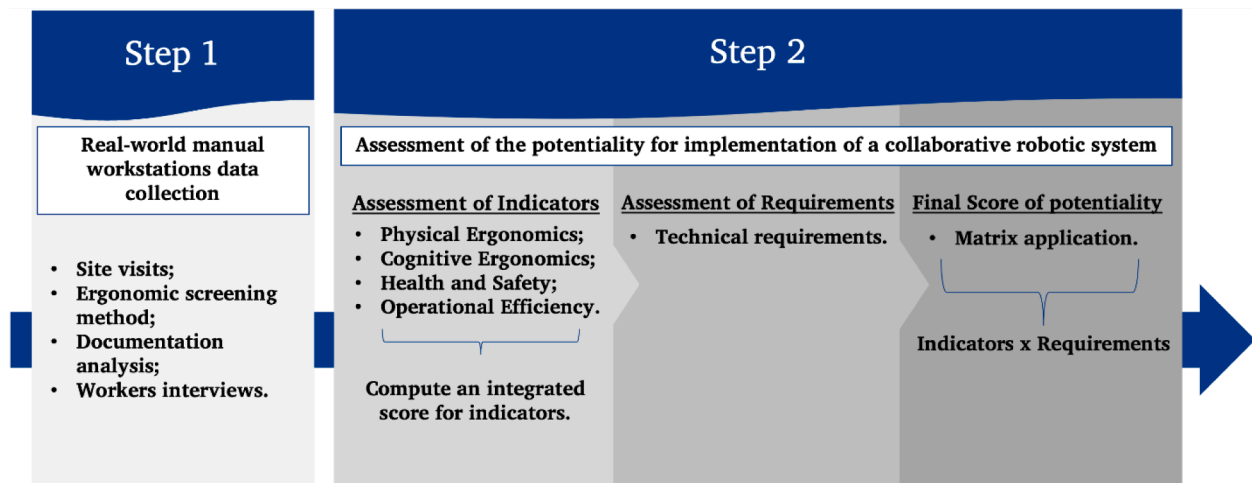


Fig. 2. Methodology approach to assess the potentiality for conversion of a manual workstation into a cobot system.

usable by individuals not specialized in ergonomics. This facilitates the widespread adoption of the current methodology in the long run. The proposed method considers three risk levels – Low, Medium and High. The conversion of these risk levels, for a scale ranging from 0 to 3, is shown in Table 1. Note that we consider a PE score of 0 when no issue is found.

Concerning CE, this indicator was included since it is of major importance for the design of human-centered workstations (Faccio et al., 2023). Cognitive workload is defined as the sum of all characteristics (both cognitive and emotional) associated with task complexity, limited resources, and feelings at work (Rosen et al., 2019). In addition, a high mental workload can affect productivity, safety, and quality of work (Van Acker et al., 2018). The rationale behind the inclusion of this indicator stems from the acknowledgement that manual tasks imposing a high cognitive workload on workers could be improved through the deployment of collaborative robots. By handling repetitive and monotonous tasks, cobots can liberate workers to focus on more complex assignments, leading to a more balanced and fulfilling work environment (Javaid et al., 2022). The evaluation of this indicator can be conducted by utilizing the CLAM methodology (Thorvald et al., 2019). This tool is shown in Fig. A2 from appendix A. This tool combines different factors that enable the estimation of the mental workload of each task (Calzavara et al., 2023). It assesses the mental workload of the worker by employing five task-related factors and six workstation-related factors. A specific combination of them results in the final cognitive load score, which is categorized into four levels, ranging from very low to high (Lorenzini et al., 2023). It is important to highlight that the choice of employing this particular tool for evaluating this metric is grounded in the distinction that, unlike alternative tools within this field, it does not depend on self-reported evaluations provided by workers. Instead, it

relies on the observation of task execution conditions. This enables external observers to assess operators' cognitive workload with a diverse range of factors. In Table 2, the ranges of the CLAM index with their respective meanings and CE scores are shown.

The indicator HS was included since it is well-established that robotics can improve the working conditions of workers by avoiding exposure to hazardous tasks (Cunha et al., 2020; Gualtieri et al., 2019; Mercader Uguina and Muñoz Ruiz, 2019). Therefore, the inclusion of this variable is supported by the fact that if a workstation has a high level of risk of injury, then it may have the potential implementing a cobot. On this topic, we considered the topic 5 – 'risk of accident' from the Ergonomic Workplace Analysis (EWA) method (Ahonen et al., 1989). This tool is shown in Fig. A3 from appendix A. The tool not only aids in identifying hazardous conditions but also assesses the level of risk based on the likelihood and severity of the identified hazards. The score for this variable related to the assessment of the method is shown in Table 3. It is important to note that, within this indicator, only the issues with the highest scores contribute to the final score. To illustrate, in situations with two issues related to HS issues, if one issue is assigned a score of 3 while the other obtains a score of 4, the factor influencing the overall HS score is the issue with the highest score.

The indicator OE holds significant importance in enhancing performance and building competitive advantage among companies, therefore is of utmost importance (Liu et al., 2020). Its objective is to minimize waste in terms of time, effort, and materials, while maintaining the production of high-quality products (Shahriar et al., 2022). The promotional claims surrounding cobots emphasize their potential to enhance the productivity of manual workstations (Colim et al., 2021). Consequently, workstations exhibiting suboptimal operational efficiency represent promising opportunities for introducing cobot solutions. In evaluating OE indicator, we employed the statements provided by Gualtieri et al. (2020b) concerning product and process quality, as well as economic considerations. This tool is shown in Fig. A4 from appendix A. For scoring, we adopted the identical scoring system provided by these authors (as shown in Table 4). It is essential to emphasize that the highest obtained score contributes solely to the overall score of the indicator.

Table 1
Scoring for PE indicator.

Risk Level	Number of issues	PE Score
No risk	No issues were found.	0
Low	No issues were found in numbers 1, 2, or 3, and fewer than 3 issues were found in numbers 4 through 15.	1
Medium	Issue number 1 was found (and changes have been made in the workplace) along with issues number 2 or 3 and another issue in numbers 4 through 15 / three to five issues were found in numbers 4 through 15.	2
High	Issue number 1 was found (and changes have not been made in the workplace to fix it) along with issues number 2 or 3, and two other issues in numbers 4 through 15 / six or more issues were found in numbers 4 through 15.	3

Table 2
Scoring for CE indicator.

Risk level	Interval of CLAM	CE Score
Very Low	0–2	0
Low	2–4	1
Moderate	4–6	2
High	> 6	3

Table 3
Scoring for HS indicator.

Risk of accident Score in EWA	HS Score
1	0
2	1
3	2
4 or 5	3

Table 4
Scoring for OE indicator.

Scoring system	OE Score
Improvements are not required for that activity/ the problem does not exist.	0
The achievable improvements could be moderate for that activity	1
The achievable improvements could be good for that activity	2
The improvements could be very significant for that activity.	3

To conclude the step concerning indicator scoring, it is necessary to obtain a composite score for this set of indicators. For this purpose, the information from Table 5 is used. It should be noted that greater importance has been assigned to the PE, CE, and HS indicators, at the expense of OE. This design choice aligns with the paradigm of Industry 5.0, where worker well-being and safety are placed at the center of the production process (Xu et al., 2021). In other words, if issues related to these three indicators are identified, it signifies that the workstation is more likely to benefit from implementing a cobot to minimize occupational risks. For instance, if a score of 3 is assigned to both PE and CE, 2 for HS (totaling 8), and 2 for OE in the manual task, the final score for the indicators will be 6. Conversely, if a score of 2 is assigned to PE, CE, and HS (totaling 6), and 2 for OE, the final score for the indicators will be 4.

2.2.3. Assessment of the requirements

Regarding requirements, as previously mentioned, we only considered the TR. This variable plays a pivotal role in system implementation since it ensures compatible and efficient integration of robots into existing processes. The central objective of a production system is to achieve timely, budget-conscious, high-quality, and flexible product delivery (Chrysosolouris et al., 2013). Consequently, the TR for a collaborative work cell encompasses factors related to this, namely handling, process, and production aspects (Malik and Bilberg, 2017). In a work developed by Gualtieri et al., (2019) a list of critical issues related these TR is delineated. We have extended this list to include the case where the component weight exceeds the payload capacity of the cobot or gripper. This inclusion is attributed to the limitation imposed on the range of cobot activities by its payload (Cohen et al., 2022). This tool is shown in Fig. A5 from appendix A. Meeting these technical prerequisites may ease the cobot deployment, and further enhance productivity, minimize risks, and optimize the collaborative interaction between robots and human workers. Additionally, it is essential to notice that a score equal to 0 in this category leads to the implementation of a cobot in a specific manual workstation unfeasible, since that means that the

Table 5
Final score for indicators variables.

Scoring system	Indicators final score
If the Sum of PE, CE, HS = 0 and OE = 0	0
If $1 \leq \text{Sum of PE, CE, HS} \leq 4$ and $0 \leq \text{OE} \leq 1$	1
If $1 \leq \text{Sum of PE, CE, HS} \leq 4$ and $2 \leq \text{OE} \leq 3$	2
If $5 \leq \text{Sum of PE, CE, HS} \leq 7$ and $0 \leq \text{OE} \leq 1$	3
If $5 \leq \text{Sum of PE, CE, HS} \leq 7$ and $2 \leq \text{OE} \leq 3$	4
If the Sum of PE, CE, HS ≥ 8 and $0 \leq \text{OE} \leq 1$	5
If the Sum of PE, CE, HS ≥ 8 and $2 \leq \text{OE} \leq 3$	6

technical requirements have not been met and, therefore, it is impossible to implement a cobot on that workstation. The scoring system for this topic is provided in Table 6. Note that in the specific case of this indicator, only the issues with the lowest scores contribute to the final score. This is to ensure that if at least one problem makes the implementation of the robot unfeasible, the potentiality must be lower.

2.2.4. Final score of potentiality

Finally, to obtain a final potentiality score, the matrix highlighted in Fig. 3a is utilized. This matrix allows obtaining a potentiality score for transforming a manual task/workstation into a collaborative one based on indicator scores (0–6) and requirements (0–3). This potentiality score ranges from 0 to 4. Where 0 signifies 'no potential'; 1 signifies 'low potential'; 2 signifies 'moderate potential'; 3 signifies 'good potential,' and 4 signifies 'high potential' (See Fig. 3b).

When assessing the transformation potential for collaborative robot implementation, specific conditions dictate the rating. A null potential signifies that without indicator issues or unmet requirements, there's no impetus for deployment. A low potential (score 1) indicates minimal issues solvable with costly or slightly less costly conversion costs. Moderate potential (score 2) is evident either there are low problems at the indicator level, but requirements are favorable for cobot implementation, or there are serious problems at the indicator level, but the requirements are not favorable for robot implementation as they require high costs for the conversion. Good potential (score 3) signifies medium to high indicator issues solvable at varying costs. Good potential (score 3) signifies that problems in the indicators range from medium to high (3 to 5) and the requirements can be solved at different levels of complexity and cost. Finally, high potential (score 4) suggests that when serious problems are identified in the indicators and the requirements can be met with low costs or without significant changes.

2.3. Application of the proposed methodology

We assessed 13 distinct workstations provided by four different companies operating in Portugal. Companies' managers selected these workstations due to workers' complaints. The companies were categorized into distinct sectors, namely civil construction, cutlery, furniture, and automotive fabric manufacturing industries. The enrolled individuals provided their consent by endorsing an Informed Consent Document, in alignment with the Research Ethics Committee for Social and Human Sciences at the University of Minho (approval reference: CEICSH 038/2020), thereby adhering to the principles outlined in the Declaration of Helsinki.

As proposed in the current study, for the application of the potentiality methodology, first data collection from the different workstations was carried out, including the analysis through the application of EWA method (Ahonen et al., 1989). Second, building upon the dataset gathered, the methodology for assessing the potential of conversion was applied to the identified tasks of manual workstations. The different tools for assessing each of the indicators and requirements are presented in Appendix A.

Table 6
Scoring for TR variable.

Scoring system	TR Score
The issues found are impossible to solve.	0
The issues found can be solved with costly and time-consuming solutions.	1
The issues found can be solved with simple and low-cost solutions.	2
No issues were found.	3

		Requirements score					
		0	1	2	3	Final score	Meaning
Indicators final score	0	0	0	0	0		
	1	0	1	1	2	4	High potential
	2	0	1	2	2	3	Good potential
	3	0	1	3	3	2	Moderate potential
	4	0	2	3	4	1	Low potential
	5	0	2	3	4	0	No potential
	6	0	2	4	4		

Fig. 3. a. Matrix for scoring the potentiality for conversion of a manual workstation into a collaborative one. b. Final score of potentiality with the respective meaning.

3. Results

3.1. Results of the focus group session

The feedback from the focus group significantly influenced the refinement of the methodology's initial version (Cardoso et al., 2024). Several modifications were introduced, including refining the indicators assessment and creating an assessment matrix to support the quantification of the final score.

Specifically, significant modifications were made to the CE indicator. Previously, a self-reported method (Roscoe, 1984) was used to assess this indicator. This method only allowed for workers' perceived

assessment of cognitive workload and is more related to airplane pilots. The focus group discussions highlighted the need to replace this evaluation method with another one suitable for manufacturing that academic or industrial practitioners could implement without relying on the workers' self-reports. For this purpose, the Cognitive Load Assessment for Manufacturing (CLAM) methodology (Thorvald et al., 2019) was selected. The CLAM methodology was devised for application within manufacturing contexts. In addition to assessing the human subject's cognitive status, it also considers their interaction with the environment and tools.

Regarding the HS indicator, some modifications were implemented based on the outcomes of the focus group session. Initially, when assessing this indicator, our focus was solely on identifying hazards. It was modified to incorporate risk quantification, considering probability and severity through the guidelines of the EWA method (Ahonen et al., 1989).

Related to product and process quality (PPQ) and economics (EC) indicators from the methodology prior version, major changes resulted from the focus group. Those two indicators were merged into a single indicator – OE. This consolidation was deemed essential since operational efficiency is of major importance for enhancing performance and fostering competitive advantage (Liu et al., 2020).

Finally, significant adjustments were made concerning the final score. Aligned with the Industry 5.0 paradigm, which emphasizes the central role of human workers in the production process (Xu et al., 2021), a greater weight was attributed to E&HF indicators. In the prior version, the final score was obtained using a mathematical formula, however, the experts' focus group suggested a simplification, suggesting the creation of an assessment matrix that takes indicators and

Methodology for assessing the potentiality of conversion of a manual workstation into a cobot system

1. Indicators assessment

1.1. Physical Ergonomics (PE):

Risk Level	Number of issues	PE Score
No risk	No issues were found.	0
Low	No issues were found in numbers 1, 2, or 3, and fewer than 3 issues were found in numbers 4 through 15.	1
Medium	Issue number 1 was found (and changes have been made in the workplace) along with issues number 2 or 3 and another issue in numbers 4 through 15 / three to five issues were found in numbers 4 through 15.	2
High	Issue number 1 was found (and changes haven't been made in the workplace to fix it) along with issues number 2 or 3, and two other issues in numbers 4 through 15 / six or more issues were found in numbers 4 through 15.	3

1.2. Cognitive Ergonomics (CE):

Risk level	Interval of CLAM	CE Score
Very Low	0 – 2	0
Low	2 – 4	1
Moderate	4 – 6	2
High	> 6	3

1.3. Health and Safety (HS):

Risk of accident Score in EWA	HS Score
1	0
2	1
3	2
4 or 5	3

1.4. Sum of PE, CE and HS score:

PE + CE + HS Score =

1.5. Operational Efficiency (OE):

Scoring system	OE Score
Improvements are not required for that activity/ the problem does not exist.	0
The achievable improvements could be moderate for that activity.	1
The achievable improvements could be good for that activity.	2
The improvements could be very significant for that activity.	3

Highest OE Score =

2. Requirements assessment

2.1. Technical Requirements (TR):

Scoring system	TR Score
The issues found are impossible to solve.	0
The issues found can be solved with costly and time-consuming solutions.	1
The issues found can be solved with simple and low-cost solutions.	2
No issues were found.	3

3. Potentiality final score

Lowest TR score =

Indicators final score =

Requirements score =

Potentiality final score =

Indicators final score	Requirements score	Potentiality final score
0	0	0
1	0	1
2	0	1
3	0	1
4	0	2
5	0	2
6	0	2

Final score	Meaning
4	High potential
3	Good potential
2	Moderate potential
1	Low potential
0	No potential

1.6. Indicators final Score

Scoring system	Indicators final score
If the Sum of PE, CE, HS = 0 and OE = 0	0
If 1 ≤ Sum of PE, CE, HS ≤ 4 and 0 ≤ OE ≤ 1	1
If 1 ≤ Sum of PE, CE, HS ≤ 4 and 2 ≤ OE ≤ 3	2
If 5 ≤ Sum of PE, CE, HS ≤ 7 and 0 ≤ OE ≤ 1	3
If 5 ≤ Sum of PE, CE, HS ≤ 7 and 2 ≤ OE ≤ 3	4
If the Sum of PE, CE, HS ≥ 8 and 0 ≤ OE ≤ 1	5
If the Sum of PE, CE, HS ≥ 8 and 2 ≤ OE ≤ 3	6

Indicators final score =

Fig. 4. Worksheet of the proposed methodology for assessing the potentiality of conversion of a manual workstation into a cobot system.

requirements score as input, similar to other methodologies in the E&HF domain (Hignett and McAtamney, 2000; McAtamney and Nigel Corlett, 1993).

As a result of this focus group session, the novel methodology was readjusted and a worksheet to ease its real application was developed (Fig. 4). The various tools/techniques for assessing each indicator and requirement can be found in Appendix A.

3.2. Results of the novel methodology application

In this study, we examined a total of 13 workstations across four distinct companies, as mentioned earlier. The workers ($n = 13$) allocated to these workstations have the following sociodemographic characterization: an average age of 46.7 ± 13.9 years old, an average height of 174 ± 9 cm, an average seniority of 13.7 ± 16.2 years, all were right-handed, and none reported any prior WMSD. Regarding gender, there were 10 male individuals and 3 female individuals in the sample. The description of the considered workstations, along with a brief overview of the tasks assigned to each of them, is presented in Table 7. The upcoming subsections will be structured as follows: (i) EWA Results, and (ii) Potential for Conversion from Manual to Collaborative Robotic System Results.

3.2.1. EWA results

In this subsection, it is shown the findings from the EWA evaluation across the 13 included workstations. This evaluation is based on assessments provided by both perceived worker assessment (W) and the expert observational assessment (E). Table 8 displays the comprehensive assessments covering 11 topics of the method. For further insights, and detailed justifications from the expert assessments see Appendix B, specifically Tables B1 (WK.1–5), B2 (WK.6–9), and B3 (WK.10–13).

The assessments shows that some topics receive consistently positive evaluations from both workers and experts, such as “workspace” (in WK.8–10, and WK.13), ‘lifting tasks’ (in WK.2, 5,7,8, and 10–12), ‘workers’ communication’ (WK.2 – 6, and 11), lightning, thermal environment and noise (in most of the assessed workstations). While, some topics were understood more negatively by both evaluators, namely ‘work postures and movements’ (in WK. 1–7, 10,11, and 13), ‘work content’ (in WK. 1,2,4,5,8, and 10–13), ‘restrictiveness’ (in WK. 4–6,8,10, 12 and 13), ‘work repetitiveness’ (in WK. 4–13), and ‘level of required attention’ (in Wk. 1–3, 5–7, and 11–13). Those negative topics assessment indicates factors that require more concerns and, probably, corrective measures.

However, several topics reveal discrepancies between worker perceptions and expert observations. Notably, the expert assessment tends to be more negative on many topics indicating that experts might view certain aspects less favorably than the workers themselves. This could be due to a variety of factors, including differences in perspective, expertise, or the level of detail that each group focuses on. In the case of the worker, a lower level of awareness, adaptation to discomfort and potential fear of consequences also could explain these differences. Areas of concern, as indicated by the negative perceived worker assessment, are ‘general physical activity’ (in WK. 4 and 5), ‘lifting tasks’ (in WK.1, 6, and 9), ‘risk of accident’ (in WK.1 and 2), and ‘level of attention required’ (in WK. 8 and 10). These findings suggest that workers on those workstations may perceive certain conditions more negatively than experts, and these areas may require attention to improve worker satisfaction and well-being.

In summary, these findings reveal the importance of considering both worker perceptions and expert observations when evaluating workplace conditions. It highlights areas where workers’ perceptions and expert assessments align, as well as areas where differences exist. Addressing these discrepancies and acting upon worker concerns in key areas will likely contribute to overall improvements in workplace conditions, workers’ satisfaction, and productivity. In this specific case, these situations are of greater importance to consider when applying the

Table 7

Description of the tasks performed in the selected workstations.

Workstation (WK)	Company sector	Task (T)	Description
WK1. Metal parts welding	Civil construction	T1	Reorientate the part to start the process.
		T2	Weld the part.
		T3	Use the pneumatic hammer to remove surplus solder.
		T4	Use the grinder to smooth the corners of the parts.
WK2. Window assembly	Civil construction	T1	Reach components and tools for the assembly.
		T2	Apply the glue on the edge of the frame preforms.
		T3	Apply bicomponent (for adhesion and filling of voids in the metallic structures) inside the frame preforms.
		T4	Insert the squares (components needed for joint different preforms) inside of the preforms.
		T5	Assemble the window frame (jointing the preforms).
		T6	Place the metal pins to guarantee the window frame stability.
		T7	Apply again bicomponent for finishing the frame.
		T8	Clean the surplus bicomponent.
		T9	Quality control of the frame handling it in different orientations.
WK3. Furniture assembly	Civil construction	T1	Place the rails in the drawers and on the furniture.
		T2	Fix the rails with screws to the drawers and furniture.
		T3	Place the drawers in the furniture.
		T4	Place the drawer mirror.
		T5	Fix the drawer mirror with screws.
WK4. Wood sanding	Civil construction	T1	Sand the wood manually with the left hand.
		T2	Sand the wood manually with the right hand.
WK5. Cutlery molding	Cutlery manufacturing	T1	Reach metal bars.
		T2	Place the metal bars in the oven.
		T3	Remove the heated metal bars from the oven.
		T4	Place the heated metal bars in the press machine.
		T5	Reach the pressed parts from the press machine.
		T6	Deliver the pressed parts to the next workstation.
		T7	Reach the pressed parts.
		T8	Place the pressed parts in the molding press machine.
		T9	Reach the molded parts from a container in the ground.
		T10	Pour the molded parts into a bigger container.
WK6. Cutlery laser printing	Cutlery manufacturing	T1	Placing the parts in the laser machine.

(continued on next page)

Table 7 (continued)

Workstation (WK)	Company sector	Task (T)	Description
WK7. Cutlery sanding	Cutlery manufacturing	T2	Place the cutlery pieces into the laser machine (to engrave the logo).
		T3	Store engraved cutlery pieces.
		T1	Reach the cutlery pieces.
		T2	Sand the cutlery pieces in the sanding machine.
WK8. Feeding wooden slats	Furniture manufacturing	T3	Storage the polished cutlery pieces in a box.
		T1	Remove the fastening components from the wooden slats.
		T2	Reach a set of slats and feed the cutting machine.
		T3	Push a bottom to start the cutting machine.
WK9. Palletizing of cut wooden slats	Furniture manufacturing	T4	Change the cutting disc of the machine.
		T1	Pull a set of wooden slats.
		T2	Palletize the wooden strips on a pallet (Set of slats or crate).
		T3	Adjust stacker height.
WK10. Feeding of wooden boards	Furniture manufacturing	T4	Remove wood excess from the mat.
		T1	Place the stacker with the pallet next to the workstation.
		T2	Adjust the height of the stacker to the height of the conveyor belt.
		T3	Place a sticker on the wooden boards.
WK11. Packing of flat furniture	Furniture manufacturing	T4	Place the wooden board on the conveyor belt.
		T1	Place cardboard honeycombs in the box.
		T2	Place the fitting box in the box.
		T3	Place fine wood in the box.
WK12. Finishing wooden boards edges	Furniture manufacturing	T4	Place the bottom of the drawers in the box.
		T5	Place the drawer sides in the box.
		T6	Place a sticker on the wooden shelf.
		T7	Place the wooden shelf in the box.
WK13. Visual inspection of automotive fabric	Automotive fabric manufacturing	T8	Place the bottom of the drawers in the box.
		T9	Place the wooden board in the box.
		T1	Receive a piece of wood recently edged.
		T2	Rotate the piece of wood if necessary.
WK14. Feeding of wooden boards	Furniture manufacturing	T3	Use a tool to remove excess of the edge.
		T4	Clean the surplus of glue with a chemical.
		T5	Palletize the wooden piece.
		T6	Place the wooden board in the box.

Table 7 (continued)

Workstation (WK)	Company sector	Task (T)	Description
WK13. Visual inspection of automotive fabric	Automotive fabric manufacturing	T1	Feed the fabric roll into the machine.
		T2	Confirm the reference parameters on the computer.
		T3	Place the cardboard tube into the machine.
		T4	Pull fabric manually and attach it to a cardboard tube.
WK14. Feeding of wooden boards	Furniture manufacturing	T5	Use the machine interface to adjust machine speed and tension parameters.
		T6	Visual inspection of the fabric.
		T7	Manual cut of the fabric.
		T8	Remove the roll of fabric using a trolley.

potentiality methodology (whose results are presented in the following subsection). This allows for a better understanding of the working conditions and risk factors to which workers are exposed, consequently assisting in obtaining a more reliable assessment.

3.2.2. Potentiality for conversion from manual to collaborative robotic system results

This subsection presents the outcomes of the potentiality assessment for transitioning manual workstations into a collaborative robotic systems. Table 9 provides a summary of these results across the 13 workstations (WK1 to WK13). It includes the score for each indicator and requirement, as well as the final score of potentiality for HRC with the respective meaning.

According to our findings, most of the workstations present tasks with 'low potential' or 'medium potential'. Examples include WK.2 (T8, T9), WK.10 (T4), WK.13 (T1, T3, T4) – 'Low potential', and WK.1 (T2, T3, T4), WK.6 (T1, T2, T3), WK.7 (T1, T2, T3) – 'medium potential'. Several workstations demonstrate "No potential," indicating either the absence of significant issues in the indicators or the failure to meet the technical requirements for robot implementation. These include WK1 (T1), WK4 (T1, T2), WK5 (T3, T4, T5, T6, T9, T10), WK8 (T1, T4), WK.10 (T1, T3), WK11 (T6), and WK13 (T6, T8). Some workstations have tasks with 'good potential' or 'high potential' which suggest the presence of numerous issues with high scores in the domains of physical ergonomics, cognitive ergonomics, health, and safety, and/or operational efficiency, while the technical requirements encounter few or no barriers to the implementation of a collaborative robot. This situation represents a promising opportunity to enhance efficiency, ergonomics, safety, and productivity through the integration of robotic technology. The workstations with tasks that have 'good potential' are WK.3 (T2, T5), WK.5 (T7), WK.9 (T2), and WK.12 (T3). Related to 'high potential' only WK.2 presents tasks on this level, namely, T1, T4, T5, and T6.

The results not only allow the identification of tasks with the greatest potential for collaborative robotic implementation but also allow the identification of strengths and weaknesses for each of them, helping guide potential improvements and strategies to optimize overall performance and well-being during the workplace redesign process.

For instance, in the WK2 (T1) scenario, the overall assessment illustrates a final score of 4 for the indicators. Upon a closer examination of the individual indicators, it becomes apparent that PE (2), CE (2), and OE (3) contribute significantly. Consequently, with a final requirement score of 3, the utilization of cobot emerges as a potentially effective strategy to address the identified issue. Conversely, in WK4 (T1), despite the final indicator scores indicating concerns across all individual indicators (PE = 3, CE = 2, HS = 2, and OE = 2), the final requirement score suggests that implementing a cobot to solve these issues is not

Table 8
EWA Findings for 13 Workstations: Worker and Expert Assessments.

Topic	WK.1		WK.2		WK.3		WK.4		WK.5		WK.6		WK.7		WK.8		WK.9		WK.10		WK.11		WK.12		WK.13	
	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E
1. Workspace	--	2	+	3	-	2	+	3	+	4	+	4	+	4	+	2	+	2	+	1	-	3	-	3	+	2
2. General physical activity	-	3	+	3	+	2	-	2	-	2	+	3	+	4	+	2	+	3	-	3	+	2	-	3	+	3
3. Lifting tasks	--	1	+	2	-	3	-	3	+	2	-	2	+	2	+	2	-	2	+	2	+	2	+	2	--	4
4. Work postures and movements	-	3	+	4	--	4	--	3	--	4	-	3	-	4	+	5	+	5	--	4	-	4	+	4	-	4
5. Risk of accident	-	2	-	2	+	2	--	3	+	4	+	2	+	4	+	3	-	3	+	2	+	1	--	3	+	2
6. Work content	--	5	--	3	+	3	--	5	--	5	+	5	+	5	--	5	+	5	--	5	--	5	--	5	--	3
7. Restrictiveness	+	3	+	2	--	2	--	3	--	5	-	4	+	4	--	4	+	5	--	5	+	3	--	4	--	3
8. Workers' communication	-	4	+	1	+	2	+	1	+	2	+	1	-	4	+	3	+	3	+	3	+	1	+	3	+	3
9. Decision-making	+	2	-	5	--	5	+	2	--	2	+	2	-	2	+	2	+	2	+	2	--	5	-	3	+	2
10. Work repetitiveness	+	4	+	2	-	2	--	5	--	4	-	5	-	5	--	4	-	5	--	5	--	4	--	4	--	4
11. Level of required attention	--	3	--	3	--	3	+	3	--	3	-	3	-	4	3	2	+	2	--	2	-	4	--	4	--	4
12. Lighting	+	2	+	1	+	1	+	2	+	2	+	1	+	2	+	1	+	1	+	1	+	1	+	1	-	2
13. Thermal conditions	-	2	+	2	+	2	-	3	+	2	+	2	-	3	+	2	+	2	+	2	+	2	+	2	+	2
14. Noise	-	5	+	2	+	2	+	2	--	4	--	4	-	4	+	2	+	2	+	2	+	2	+	2	+	1

Worker Score (W); Expert Score (E)

Worker Score (W); Expert Score (E).

feasible, leading to an outcome marked as "no potential". In this context, the final score solely signifies that a cobot implementation is not a viable solution for rectifying the issues detected within the workstation/task. Nonetheless, this approach serves to identify existing problems and thereby directs efforts toward their resolution through alternative solutions.

4. Discussion

This study focused on developing and applying a novel methodology to evaluate the potential for transforming manual workstations into collaborative setups. During the development phase, the initial version of the methodology (Cardoso et al., 2024) was refined through feedback from a focus group, aiming to improve the assessment approach. Through iterative discussions and consensus-building processes among E&HF and Robotics experts, potential biases or oversights were mitigated, enhancing the robustness of the proposed methodology.

Regarding the application phase, as indicated in the methodology proposed, two key steps were involved: (i) real-world data collection using the EWA method; and (ii) assessing the potential for converting from manual to cobot systems (Bruseberg and Mcdonagh-Philp, 2002; Mosconi et al., 2022).

The EWA method facilitated an in-depth assessment of ergonomic considerations inherent to each workstation, aiming to improve overall conditions by mitigating WMSD risks and enhancing individual well-being and productivity (Chiasson et al., 2012, 2015; Colim et al., 2020). Results indicated positive and negative aspects for each workstation, with areas such as workspace and lifting tasks receiving positive evaluations, while work postures and movements, work content, restrictiveness, work repetitiveness, and required attention were

perceived more negatively. Differences between worker perceptions and expert observations were observed, underlining the importance of considering both perspectives for a comprehensive understanding of workplace conditions and risk factors (Chiasson et al., 2015). Addressing these differences and worker concerns in critical areas is crucial for enhancing overall conditions, worker satisfaction, and productivity (Colim et al., 2020). By incorporating different viewpoints, the EWA assessment offers a more accurate understanding of work capacity and related risk factors. Its application deepened our understanding of the workstations, thus facilitating the subsequent application of the potentiality methodology. It not only allowed us to assess existing working conditions but also provided detailed insights into the workers' opinions according to a perspective of participatory ergonomics.

Furthermore, a primary objective of this study is to demonstrate the essentiality of this design approach, which encompasses a comprehensive assessment of the industrial tasks involved, through a novel methodology to assess potentiality for HRC implementation. This methodology includes a holistic approach that considers physical and cognitive ergonomics, health and safety, and operational efficiency indicators, as well as technical requirements for the implementation of a cobot system. The incorporation of these variables constitutes a fundamental asset when endeavoring to deploy cobots in the industrial settings. Previous studies (Bragança et al., 2019; Colim et al., 2021; Gualtieri et al., 2020b; Murata et al., 2018; Pearce et al., 2018) demonstrate the effectiveness of implementing cobots when a task is physically demanding, poses an increased risk to workers, there is a lack of productivity/quality, or when tasks are too variable. Moreover, when a task poses high cognitive demands, deploying of a cobot system could prove advantageous. This is attributed to the cobot's capacity to manage repetitive tasks, thereby allowing workers to dedicate their attention to

Table 9
Potentiality for conversion from manual to cobot workstation results.

Workstation/ production line	Indicators					Requirements score	Final Score	Meaning
	P E	C E	H S	O E	Indicator s score			
WK1.	T1	2	1	1	2	2	0	No potential
	T2	3	2	2	2	4	1	Medium potential
	T3	2	2	2	2	4	1	Medium potential
	T4	2	2	2	2	4	1	Medium potential
WK2.	T1	2	2	1	3	4	3	High potential
	T2	3	0	1	2	2	3	Medium potential
	T3	3	0	1	2	2	3	Medium potential
	T4	2	2	1	2	4	3	High potential
	T5	3	1	1	2	4	3	High potential
	T6	3	2	2	2	4	3	High potential
	T7	2	0	1	2	2	2	Medium potential
	T8	3	0	0	0	1	2	Low potential
	T9	2	1	1	1	1	1	Low potential
WK3.	T1	2	2	0	1	1	2	Low potential
	T2	3	2	1	1	3	2	Good potential
	T3	1	2	0	1	1	2	Low potential
	T4	1	2	1	1	1	1	Low potential
	T5	2	2	1	1	3	2	Good potential
WK4.	T1	3	2	2	2	4	0	No potential
	T2	3	2	2	2	4	0	No potential
Wk5.	T1	2	1	1	0	1	3	Medium potential
	T2	2	1	1	0	1	3	Medium potential
	T3	3	1	1	0	3	0	No potential
	T4	3	1	1	0	3	0	No potential
	T5	3	1	3	0	3	0	No potential
	T6	3	1	1	0	3	0	No potential
	T7	3	1	0	0	1	3	Medium potential
	T8	3	1	3	0	3	3	Good potential
	T9	2	0	1	0	1	0	No potential
	T10	3	0	2	0	3	0	No potential
WK6.	T1	3	0	1	0	1	3	Medium potential
	T2	3	1	0	0	1	3	Medium potential
	T3	3	0	0	0	1	3	Medium potential
WK7.	T1	2	1	0	0	1	3	Medium potential
	T2	3	1	3	2	4	1	Medium potential
	T3	3	1	3	2	4	1	Medium potential
WK8.	T1	0	0	0	2	0	2	No potential

(continued on next page)

Table 9 (continued)

	T2	3	0	2	2	4	1	2	Medium potential
	T3	2	0	0	2	2	3	2	Medium potential
	T4	1	1	2	2	2	0	0	No potential
WK9.	T1	3	0	2	1	3	1	1	Low potential
	T2	3	0	2	1	3	2	3	Good potential
	T3	0	0	0	1	0	3	0	No potential
	T4	2	0	1	1	1	1	1	Low potential
WK10.	T1	1	0	1	1	1	0	0	No potential
	T2	0	0	1	1	1	3	2	Medium potential
	T3	3	1	0	1	1	0	0	No potential
	T4	3	0	1	1	1	2	1	Low potential
WK11.	T1	3	1	0	0	1	1	1	Low potential
	T2	3	1	0	0	1	1	1	Low potential
	T3	3	1	0	0	1	1	1	Low potential
	T4	3	1	0	0	1	1	1	Low potential
	T5	3	1	0	0	1	1	1	Low potential
	T6	2	1	0	0	1	0	0	No potential
	T7	3	1	0	0	1	1	1	Low potential
	T8	3	1	0	0	1	1	1	Low potential
	T9	3	1	0	0	1	1	1	Low potential
WK12.	T1	1	0	2	2	2	2	2	Medium potential
	T2	2	0	2	2	2	2	2	Medium potential
	T3	2	1	2	2	4	2	3	Good potential
	T4	2	0	2	2	2	2	2	Medium potential
	T5	2	0	2	2	2	2	2	Medium potential
WK13.	T1	2	1	2	1	3	1	1	Low potential
	T2	0	1	0	2	2	2	2	Medium potential
	T3	2	0	0	0	1	1	1	Low potential
	T4	2	0	0	0	1	1	1	Low potential
	T5	1	2	0	2	2	2	2	Medium potential
	T6	3	2	1	3	4	0	0	No potential
	T7	2	1	0	2	2	2	2	Medium potential
	T8	2	0	2	0	1	0	0	No potential

* Denotes the higher score; Workstation (WK); Physical ergonomics (PE); Cognitive ergonomics (CE); Health and Safety (HS); Operational Efficiency (OE); Technical Requirements (TR)

* Denotes the higher score; Workstation (WK); Physical ergonomics (PE); Cognitive ergonomics (CE); Health and Safety (HS); Operational Efficiency (OE); Technical Requirements (TR).

intricate and reflective assignments (Panchetti et al., 2023). Consequently, an adequate allocation of roles has the potential to mitigate the occurrence of errors while concurrently enhancing overall productivity (Maurice et al., 2017).

Considering the current study, it is crucial to emphasize that the proposed methodology aims to assess whether a given workstation exhibits potential for the HRC implementation. Therefore, its primary goal is to identify tasks within manual workstations characterized by constraints that are not solved by traditional redesign approaches, and which exhibit potential for HRC. According to the proposed methodology, the potentiality is greater when issues related to physical and cognitive ergonomics, safety and health, operational efficiency, and the

absence of technical implementation constraints are identified in manual workstations. Thus, this methodology facilitates informed decisions regarding the conversion of manual into collaborative workstations. Nevertheless, we acknowledge that the implementation of cobots on the shop floor may introduce new challenges (e.g. workers' rejection, stress, and mistrust), that must be, subsequently, assessed. Even if the objective of the methodology is not to evaluate the impact of HRC implementation, the inclusion of requirements within the scope of E&HF may aid in overcoming these challenges (Cardoso et al., 2021).

Related to the results, the potential of each workstation task was categorized ranging from 'no potential' to 'high potential'. Most workstations showed 'low potential' or 'medium potential' for HRC. A few

workstations demonstrated 'good potential' or 'high potential,' indicating promising opportunities for implementing cobots. The findings also highlighted tasks with strengths and weaknesses, guiding potential improvements and strategies for optimizing performance and well-being in the workplace redesign process. The methodology holds the potential to support industries in identifying opportunities for converting manual workstations into collaborative setups, thereby enhancing productivity, fostering innovation, and promoting more ergonomic and dynamic work environments. This approach is indispensable in ensuring the research's success and aligning the outcomes with the genuine needs and challenges encountered in real-world industrial settings.

Overall, these results emphasize the importance of a holistic approach to evaluating workstations, considering E&HF factors, the potential for collaboration with robotic systems, and the well-being and safety of workers. The findings provide valuable insights for improving workplace conditions, optimizing productivity, and ensuring the safety and satisfaction of workers. Indeed, examining the conclusive scores of the indicators reveals that values higher than 4 indicate prevalent issues within the manual workstation/task, necessitating potential modifications to enhance its functionality, in terms of worker wellbeing. Specifically, elevated scores in this composed metric point out substantial issues across one or more indicators competing within this category. Consequently, optimizing workstations or tasks is advised to improve working conditions, thereby enhancing their overall performance (Boulila et al., 2018; Nacion and Tanguangco, 2019).

Conversely, when final scores fall within the higher range (2 and 3) during the assessment of requirements, it means that the utilization of a cobot might encounter minimal or no obstacles, thereby presenting itself as a feasible solution to address identified indicators issues. In instances where both scenarios converge, an analysis of individual indicator scores becomes crucial in making informed decisions. This analysis enables a focused approach toward prioritizing specific domains such as physical ergonomics, cognitive ergonomics, occupational safety, and/or operational efficiency. Consequently, it facilitates the careful implementation of cobots tailored to address genuine needs and resolve prevailing challenges within the context of the identified issues.

4.1. Limitations and future work

While the present study has provided comprehensive outcomes and made significant contributions, it is important to acknowledge its limitations for the purpose of informing future research. The methodology, which was based on a bibliographic review and real-world application, does have a subjective element due to the limited number of focus group experts. However, this also opens up exciting possibilities for future research, particularly in the inclusion of additional indicators, such as psychosocial factors, to enhance the proposed methodology.

Regarding the application of the methodology, it's worth noting that the sample size and contextual specificity are limitations. However, it is crucial to recognize that this study's findings are the result of a comprehensive assessment that covered a specific subset of industrial workstations. While the applicability of these results to broader industrial settings may be subject to constraints, the thoroughness of the study's approach should inspire confidence in the validity of the findings. Furthermore, the proposed methodology is well-suited for task assessment, although it is not intended to assign a composite value of potentiality for a workstation with several tasks. It is also important to acknowledge the limitation of the methodology's validation in terms of evaluators' perspectives on its usefulness, ease of scoring, and time spent. Despite these limitations, the positive results indicate that this methodology holds promise and could be a valuable tool in supporting the conceptualization of human-centric, efficient, and safe collaborative

work environments.

Building upon the foundational insights and contributions provided by the present study, several future research proposals emerge. Drawing from our results, the window assembly workstation was identified as the one with more suitable tasks for conversion. This work serves as an initial phase within a comprehensive research endeavor aimed at advancing the state of the art of natural and efficient HRC within an industrial context, establishing a true peer-to-peer interaction paradigm. The potential impact of this research is immense. Considering the precision and reliability of these results, the development of a prototype workstation, inspired by the window assembly workstation, will be pursued. The development of this prototype will consider various ergonomic principles, thereby aiding in the facilitation of both the development and testing phases of advanced HRC workstations. Before implementing the robotic solution within the prototype workstation, a series of user studies involving human-human interactions will be conducted. These studies aim to assess the viability of the proposed concept for achieving natural and efficient HRC. In this context, the human helper is intended to emulate, to some extent, the behaviour of the cobot as a proof of concept for the proposed idea.

5. Conclusions

The principles introduced by the Industry 5.0 paradigm are presently guiding the prevailing patterns in workplace design. They emphasize workers' safety and well-being while incorporating the demand for flexibility and productivity standards highlighted by Industry 4.0. Through this trajectory, the present study aligns with the contemporary emphasis on a human-centered approach to design.

A novel methodology has been introduced to evaluate the viability of transforming manual workstations into collaborative robotic systems, effectively overcoming limitations in existing methodologies. To the best of our comprehension, none of the previous methods articulates all the factors this methodology encompasses with the same level of objectivity. This aligns with the industry's needs, which require comprehensive and easy-to-use integrated tools (Huck et al., 2021). In addition to that, and as stated by Blandford and Green (2008), a pivotal criterion for any method in human-computer interaction (which can be generalized to any method) involves the ability to provide insights conducive to enhancing the prevailing circumstances. An illustration of the proposed methodology advancements lies in its capacity to meticulously evaluate the inherent issues in manual workstations. Moreover, this facilitates a systematic assessment of tasks suitable for conversion and the recognition and understanding of pertinent issues. This serves as a comprehensive guide for implementing cobots, allowing resolving identified issues upon their integration into the workstations.

This methodology was applied to industrial workstations. The analysis included the tasks assigned to each workstation collection, assessments conducted through EWA, and potentiality assessment for converting from manual to collaborative robotic systems. The outcomes of this application indicate that the windows assembly workstation (WK2) stands out as the most suitable candidate for an HRC workstation.

In summary, the study underscored the importance of considering both worker perceptions and expert observations in characterizing a workstation. As well as the harmonious integration of comprehensive methodology to identify the potential for cobot integration. Hence, these efforts will contribute to the next steps of our project, with a specific emphasis on an industrial assembly assignment. Furthermore, the chosen methodological framework may possess applicability for researchers and professionals in the industrial domain who are dedicated to the human-centric formulation of HRC contexts.

CRediT authorship contribution statement

André Cardoso: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Ana Colim:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Estela Bicho:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Ana Cristina Braga:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition. **Pedro Arezes:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

Appendix A

Acknowledgements

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Physical Ergonomics (PE):

A. In the checklist provided below, select (x) the questions that elicit an affirmative response for the task under analysis.

Checklist questions	Yes
1. Have any worker been previously diagnosed with any work-related musculoskeletal disorder?	
2. Have there been any worker complaints concerning ergonomic issues?	
3. Do workers perform high repetition tasks? (100 reps/hour to 2000 per/day)	
4. Do workers' routine tasks require repeated heavy lifting? (>20kg) or occasional heavy lifting (>30 kg)	
5. Are workers using awkwardly designed tools, which cause them to operate the tool outside of a neutral position for an extended period of time? (> 1 hour)	
6. Do workers perform tasks with an awkward head or neck position for an extended period of time? (1 to 3 hours)	
7. Do workers perform tasks that require awkward back angles to be held for extended periods of time (2 to 3 hours)?	
8. Do workers perform tasks with an awkward elbow angle for an extended period of time (1 to 3 hours) or with extreme force application?	
9. Do workers perform tasks with an awkward elbow abduction angle for an extended period of time (1 to 3 hours) or with extreme force application?	
10. Do workers perform tasks with an awkward wrist flexion angle for an extended period of time (1 to 3 hours) or with extreme force application?	
11. Do workers perform tasks with an awkward wrist extension angle for an extended period of time (1 to 3 hours) or with extreme force application?	
12. Do workers perform tasks with an awkward back/hip flexion angle for an extended period of time (1 to 3 hours) or with extreme force application?	
13. Do workers perform tasks with an extreme reaching distance for an extended period of time (1 to 3 hours) or with extreme force application?	
14. Do workers perform tasks with an odd workstation height (either standing or sitting) for an extended period of time (1-3 hours) or with extreme force application?	
15. Are high impact tools used routinely? i.e., riveters, bucking bars, or impact wrenches	
16. Are high vibration producing tools used routinely? i.e., die grinders, sanders, weed eaters	
17. Do employees perform tasks at an extreme height (high or low) for an extended period of time (1 to 3 hours) or with extreme force application?	
18. Are there any other areas of concern either from your observations or employee complaints?	

B. Was question number 1 selected?

B1. Any changes have been made in the workplace to solve this situation?

C. Was questions number 2 or 3 selected?

D. How many question were selected from 4 to 15?

Fig. A1. Tool for assessing PE indicator. Retrieved and adapted from Occupational Safety and Health Administration (OSHA), (n.d.).

Cognitive ergonomics (CE):

A. In the following 11 topics select a level for the task under analysis according to the sentences below.

Level	1. Saturation	2. Variant Flora	3. Level of Difficulty	4. Difficulty of tool use	5. Production awareness	6. Number of tools available	7. Mapping	8. Parts identification	9. Information cost	10. Quality of instructions	11. Poke A Yoke & constraints
8	85% saturation or higher.	One piece production. Full variation.	The task is very difficult and requires significant training and experience.	The assembly task requires complex tools/tool use and/or special tools to perform.	The assembly task is highly variable and contains little to very little routine work.	More than 8 tools.	Workstation layout does not correspond to assembly sequence.	Majority of parts identification through article numbers.	Significant movement or actions are required for information access.	Instruction is filled with non-priority information. Visibility AND readability is diminished.	No poke-a-yoke solutions are implemented in the task.
7											
6	75-85% saturation.	Up to 50% variant products.	The task is slightly complex and requires moderate training and experience.	The assembly task contains moderate tool use of some complexity.	The assembly task is quite variable but still contains much routine work.	5-8 tools and not easily identified.	Workstation layout somewhat corresponds to assembly sequence.	Majority of parts identification through symbol syntax or similar.	Information is accessible through some cognitive or physical effort (several steps or visual search).	Assembly sequences are not clearly separated and visibility OR readability is diminished.	Assembly constraints are present but not throughout the assembly sequence.
5											
4	65-75% saturation.	Up to 35% variant products.	The task is quite simple with little training required.	The assembly task contains little to moderate tool use.	The assembly task is mostly done on routine, but deviant parts or assemblies do occur.	More than 5 tools and easily identified.	Workstation layout heavily corresponds to assembly sequence.	Unsequenced kits or kanban is used for most items.	Information is no more than one step away and easily found.	Assembly sequences are separated and contains mostly relevant information.	Assembly constraints are present in most of the assembly sequence.
3											
2	65% saturation or lower.	Up to 10% variant products.	The task requires little to no training and is recommended for newly employed personnel.	The assembly task is performed mostly by hand and requires little or very simple tool use.	The assembly task is done purely out of routine and the sequence seldom changes.	1 to 5 tools and easily identified.	Workstation layout almost completely corresponds to assembly sequence.	Sequenced kits or kanban is used for most items.	Information is not required for standard operations.	Assembly sequences are clearly separated and contains only relevant information.	Assembly errors can barely be made due to the design and fit of the product.
1											
0	Not applicable.	No variant products.	Not applicable.	No tool use.	Not applicable.	No tools used.	Not applicable/the worker is free to set up the workstation and all its components to their own preferences.	Not applicable.	No instructions required.	No instructions required.	Assembly errors cannot be made due to the design and fit of the product.

B. For each topic fill in the Level column according to the level considered in the previous step (A).
To derive a score for each topic, one must multiply the weight assigned to the topic by its corresponding level.

	Weight (W)	Level (L)	Score (W x L)
1. Saturation	0,17		
2. Variant Flora	0,11		
3. Level of Difficulty	0,07		
4. Difficulty of tool use	0,02		
5. Production awareness	0,07		
6. Number of tools available	0,01		
7. Mapping	0,13		
8. Parts identification	0,11		
9. Information cost	0,12		
10. Quality of instructions	0,11		
11. Poke A Yoke & constraints	0,07		

Sum of Score

Fig. A2. Tool for assessing CE indicator. Retrieved and adapted from Thorvald et al., (2019).

Health and safety (HS):

Questions:	Probability	Severity	Score
1. Is it possible for a bump, blow or fall to occur caused by a protruding or moving part of a machine, or a piece of furniture or equipment?			
2. Is it possible for a machine, a work object, or a piece of equipment to tip over or fall or move to cause an accident?			
3. Is it possible for moving parts (or pinching between them), or flying objects, or aerosols, or liquid projections to cause an accident?			
4. Is it possible for missing or inadequate guardrails, or slippery, congested, or untidy flooring to cause a fall?			
5. Is it possible for interface controls or indicators to cause accidents because they were not designed according to ergonomic criteria?			
6. Is it possible that accidental starting and stopping, or the lack of a safety device could cause an accident?			
7. Are there conditions in which a sudden effort (e.g., lifting) or incorrect movement or posture could cause an accident?			
8. Is it possible that an overload on the worker's perception or attention capacity causes an accident? (Give special attention to aspects such as the use of individual protection devices, high noise, insufficient visibility, excessive temperature and/or humidity, etc., which may affect the worker's perception).			
9. Is it possible for an electric current or gas or compressed air flow to cause an accident?			
10. Is it possible for a temperature to cause a fire or explosion?			
11. Is it possible for a chemical agent to cause an accident?			

Highest score:

Probability	Meaning
Low	If the worker can avoid accidents only by resorting to normal care and general safety procedures. The probability of occurrence of an accident < 1 in 5 years.
Considerable	If the worker can avoid an accident only by following special instructions and being more careful and vigilant than usual.
High	If the worker can only avoid an accident if he is particularly careful and strictly observes the safety regulations. The risk is apparent, and it is predictable that 1 accident will occur in every 3 months.
Very High	If the worker can only avoid an accident if he strictly complies with particularly precise regulations. The occurrence of 1 accident per month is expected.

Severity	Meaning
Minimum	If the accident does not cause more than 1 day of sick leave.
Small	If the accident causes less than 1 week of sick leave.
Serious	If, at most, the accident causes 1 month of sick leave
Very serious	If the accident causes at least 6 months of sick leave or permanent disability.

		Probability			
		Low	Considerable	High	Very High
Severity	Minimum	0	1	1	2
	Small	1	1	2	3
	Serious	1	2	3	3
	Very serious	2	3	3	3

Fig. A3. Tool for assessing HS indicator. Retrieved and adapted from Ahonen et al., (1989).

Operational efficiency (OE):

A. In the statements provided below, select (x) the ones that elicit an affirmative response for the task under analysis.

Statements	Yes
1.Existence of not-constant/satisfactory product quality	
2.Existence of high variability/low standardization on the production process	
3.Inefficient use of time and/or resources that can leads to low value to the final costumers.	
4.Existence of low/not satisfactory process productivity and/or production efficiency.	

Fig. A4. Tool for assessing OE indicator. Retrieved and adapted from Gualtieri, Palomba, et al., (2020)

Technical requirements (TR):

A. In the statements provided below, select (x) the ones that elicit an affirmative response for the task under analysis.

Statements	Yes
Feeding critical issues	
1. The component is magnetic or sticky.	
2. The component is nest or tangle.	
Handling critical issues	
3. The component has no symmetry axis.	
4. The component is fragile or delicate.	
5. The component is flexible.	
6. The component is very small or very big (referring to a human hand).	
7. The component is light so that air resistance would create conveying problems.	
8. The component weight is greater than the robot and gripper payload.	
Assembly critical issues	
9. Components do not have a "datum surface" (reference surface) which simplify a precise positioning during the assembly.	
10. Components cannot be easily orientated.	
11. Components do not include features which allow a self-aligning during the assembly.	
12. Components cannot be located before they are released.	
13. Components provide resistance to insertion.	
14. Components do not provide chamfers or tapers that help to guide and position the parts in the correct position.	
15. Components have not a suitable base part on which to build the assembly.	
16. Components cannot be assembled in layer fashion from directly above (z-axis assembly).	
17. The assembly is over constrained.	
18. It is difficult to reach the assembly area / the components access for assembly operations is restricted or not easy to reach.	
19. The component and/or the assembly sequence requires high physical dexterity.	
20. The assembly requires high accuracy and/or demanding insertion tolerances.	
21. The assembly needs to reposition the partially completed sub-assembly, other components or fixtures.	
22. The assembly requires to reorient the partial assembly or to manipulate previously assembled parts.	
23. Components requires to be compress during the assembly.	
24. The component and/or the assembly sequence requires two hands for handling.	
26. The component and/or the assembly sequence require typical human skills (for example touch perception, haring, ability to interpret situations...).	

Fig. A5. Tool for assessing TR requirement. Retrieved and adapted from [Gualtieri et al., \(2019\)](#).

Appendix B

Table B1

EWA results across Wk1 – Wk5 from the expert assessment with justifications for each score.

Topic	WK1	WK2	WK3	WK4	WK5
1. Workspace	2 Despite the necessary compromises, the postures and movements carried out are adequate considering the requirements of the activity.	3 Not all recommendations were met (Such as workstation height).	2 Despite the necessary compromises, the postures and movements carried out are adequate considering the requirements of the activity.	3 Not all recommendations were met (such as workstation height).	4 There are serious variations from the recommendations (such as the organization of the workplace).
2. General physical activity	3 The activity depends on work organization. The risk of overload due to work peaks is present in some situations.	3 The activity depends on work organization. The risk of overload due to work peaks is present in some situations.	2 The activity depends in some way on the methods of production or the organization of work. There are some work peaks but no risk of causing overload.	2 The activity depends in some way on the methods of production or the organization of work. There are some work peaks but no risk of causing overload.	2 The activity depends in some way on the methods of production or the organization of work. There are some work peaks but no risk of causing overload.
3. Lifting tasks	1 The load can be easily lifted with mechanical assistance.	2 Heavier load weights 6 kg.	3 Heavier load weights 19 kg.	3 Heavier load weights 25 kg.	2 Heavier load weights 8 kg.
4. Work postures and movements	3 Extreme joint position of the arm and forearm.	4 Rotation or flexion of the neck and/or raising the arms. Trunk rotation and inclination without support	4 Trunk rotation and inclination without support	3 Neck and shoulder with tense posture due to activity. Hunched or poorly supported trunk	4 Rotation or flexion of the neck and/or raising the arms. Arms in static contraction and/or repetition of the same movement for long periods
5. Risk of accident	2 It is possible that a bump, blow, or fall caused by a protruding part (low severity, considerable probability)	2 There are conditions for incorrect postures (serious severity, low probability).	2 A bump, blow, or fall may be caused by a protruding part (low severity, considerable probability).	3 It is possible to fall due to a slippery floor (low severity, high probability).	4 Crushing in moving parts of the molding machine due to the actuation being done with only one hand or with the pedals (serious severity, considerable probability).
6. Work content	5 The worker is only responsible for a single task or operation.	3 The worker only performs a part of the work entity.	3 The worker only performs a part of the work entity.	5 The worker is only responsible for a single task or operation.	5 The worker is only responsible for a single task or operation.
7. Restrictiveness	3 Tasks or the method may occasionally restrict the pace of work and require concentration on a task at any given time.	2 Tasks or work methods are sometimes constrained by process requirements or production methods.	2 Tasks or work methods are sometimes constrained by process requirements or production methods.	3 Tasks or the method may occasionally restrict the pace of work and require concentration on a task at any given time.	5 The work task or methods are completely constrained by the machines, process, or workgroup.
8. Workers' communication	4 Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.	1 Special care is taken to ensure that communication and contacts between workers and other people are possible.	2 Communication and contact with people are possible but limited due to noise.	1 Special care is taken to ensure that communication and contacts between workers and other people are possible.	2 Communication and contact with people are possible but limited due to noise.
9. Decision-making	2 The work consists of simple tasks.	5 The worker involves several levels of education. A wrong decision can lead to material damage.	5 The worker involves several levels of education. A wrong decision can lead to material damage.	2 The work consists of simple tasks.	2 The work consists of simple tasks.
10. Work repetitiveness	4 Cycle duration less than 5 min.	2 Cycle duration between 20–30 min.	2	5 Cycle duration less than 0.5 min.	4 Cycle duration less than 5 min.
11. Level of required attention	3 Medium level of attention in more than 80 % of the cycle.	3 High level of attention in more than 50 % of the cycle.	3 Medium level of attention in less than 60 % of the cycle.	3 Medium level of attention in more than 80 % of the cycle.	3 Medium level of attention in more than 50 % of the cycle.
12. Lightning	2 50–100 % of the recommended value.	1 100 % of the recommended value.	1 100 % of the recommended value.	2 50–100 % of the recommended value.	2 50–100 % of the recommended value.
13. Thermal environment	2 Moderate work; 19–23 °C.	2 Moderate work; 19–23 °C.	2 Moderate work; 19–23 °C.	3 Moderate work; 23–25 °C.	2 Moderate work; 19–23 °C.
14. Noise	5 Work that does not require verbal communication; 100 dB(A).	2 Work that requires verbal communication; 55 dB(A).	2 Work that does not require verbal communication; 65 dB(A).	2 Work that does not require verbal communication; 70 dB (A).	4 Work that does not require verbal communication; 85 dB (A).

Table B2

EWA results across Wk6 – Wk9 from the expert assessment with justifications for each score.

Topic	WK6	WK7	WK8	WK9
1. Workspace	4 There are serious variations from the recommendations. (Such as the chair).	4 There are serious variations from the recommendations (such as the workstation organization).	2 Despite the necessary compromises, the postures and movements carried out are adequate considering the requirements of the activity.	2 Despite the necessary compromises, the postures and movements carried out are adequate considering the requirements of the activity.
2. General physical activity	3 Workspace, equipment, and methods limit the operator's movements. There is the possibility for the worker to move during breaks.	4 The workspace, equipment, and methods used restrict the worker's movements.	2 The activity depends in some way on the methods of production or the organization of work. There are some work peaks but no risk of causing overload.	3 The activity depends on work organization. The risk of overload due to work peaks is present in some situations.
3. Lifting tasks	2 Heavier load weights 5 kg.	2 Heavier load weights 3 kg.	2 The handle distance is 40 cm. The load is < 10 kg.	2 The handle distance is < 30 cm. The load is < 10 kg.
4. Work postures and movements	3 Neck with tense posture due to activity.	4 Rotation or flexion of the neck and/or raising the arms. Arms in static contraction and/or repetition of the same movement for long periods	5 Need to apply considerable force with the arms with the need to perform quick movements	5 Need to apply considerable force with the arms with the need to perform quick movements. Poor leg posture during heavy lifting.
5. Risk of accident	2 There are conditions for incorrect postures (serious severity, low probability).	4 Hands entrapment in sander machine belts (serious severity, low probability).	3 There are conditions for a sudden effort that can cause an accident.	3 It is possible to experience a bump, blow, or fall caused by a protruding or moving part of a machine. Moving parts can cause an accident. There are conditions for a sudden effort that can cause an accident.
6. Work content	5 The worker is only responsible for a single task or operation.	5 The worker is only responsible for a single task or operation.	5 The worker is only responsible for a single task or operation.	5 The worker is only responsible for a single task or operation.
7. Restrictiveness	4 The work task or methods are mostly constrained by the machines, process, or workgroup.	4 The work task or methods are mostly constrained by the machines, process, or workgroup.	4 The work task or methods are mostly constrained by the machines, process, or workgroup.	5 The work task or methods are mostly constrained by the machines, process, or workgroup.
8. Workers' communication	1 Special care is taken to ensure that communication and contacts between workers and other people are possible.	4 Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.	3 Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.	3 Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.
9. Decision-making	2 The work consists of simple tasks.	2 The work consists of simple tasks.	2 The work consists of simple tasks.	2 The work consists of simple tasks.
10. Work repetitiveness	5 Cycle duration less than 0.5 min.	5 Cycle duration less than 0.5 min.	4 Cycle duration less than 5 min.	5 Cycle duration less than 0.5 min.
11. Level of required attention	3 Low level of attention in more than 80 % of the cycle.	4 High level of attention in more 80 %than of the cycle.	2 Observation period > 30 % of the cycle. A superficial level of attention is required.	2 Observation period < 80 % of the cycle. A superficial level of attention is required.
12. Lightning	1 100 % of the recommended value.	2 50–100 % of the recommended value.	1 100 % of the recommended value.	1 100 % of the recommended value.
13. Thermal environment	2 Moderate work; 19–23 °C.	3 Moderate work; 23–25 °C.	2 Moderate work; 19–23 °C.	2 Moderate work; 19–23 °C.
14. Noise	4 Work that does not require verbal communication; 85 dB (A).	4 Work that does not require verbal communication; 85 dB (A).	2 Work that requires verbal communication; 60 dB(A).	2 Work that requires verbal communication; 60 dB(A).

Table B3

EWA results across Wk10 – Wk13 from the expert assessment with justifications for each score.

Topic	WK10	WK11	Wk12	Wk13
1. Workspace	1 The workstation is fully adjustable by the operator.	3 Not all recommendations were met and therefore there are less recommended postures and movements.	3 Not all recommendations were met and therefore there are less recommended postures and movements.	2 Despite the necessary compromises, the postures and movements carried out are adequate considering the requirements of the activity.
2. General physical activity	3 The activity depends on n work organization. The risk of overload due to work peaks is present in some situations.	2 The activity depends in some way on the methods of production or the organization of work. There are some work peaks but no risk of causing overload.	3 The activity depends on work organization. The risk of overload due to work peaks is present in some situations.	3 Workspace, equipment, and methods limit the operator's movements. There is the possibility for the worker to move during breaks.
3. Lifting tasks	2 The handle distance is <30 cm. The load is <10 kg.	2 The handle distance is 50 cm. The load is < 80 kg.	2 The handle distance is <30 cm. The load is <10 kg.	4 The handle distance is between 50–70 cm, and the load is about 20 kg.

(continued on next page)

Table B3 (continued)

Topic		WK10		WK11		Wk12		Wk13
4. Work postures and movements	4	Neck rotation and flexion Back rotation is flexion without support.	4	Rotation and flexion of the neck and raising the arms to shoulder level.	4	Rotation and flexion of the neck and raising the arms to shoulder level.	4	Rotation and flexion of the neck.
5. Risk of accident	2	There are conditions for a sudden effort that can cause an accident.	1	It is possible to experience a bump, blow, or fall caused by a protruding or moving part of a machine.	3	It is possible for accidental starting or stopping to cause an accident.	2	It is possible to experience a bump, blow, or fall caused by a protruding or moving part of a machine. It is possible to occur a sudden effort or incorrect movement or posture. Entrapment can occur.
6. Work content	5	The worker is only responsible for a single task or operation.	5	The worker is only responsible for a single task or operation.	5	The worker is only responsible for a single task or operation.	3	The worker only performs a part of the work entity.
7. Restrictiveness	5	The work task or methods are mostly constrained by the machines, process, or workgroup.	3	Tasks or the method may occasionally restrict the pace of work and require concentration on a task at any given time.	4	The work task or methods are mostly constrained by the machines, process, or workgroup.	3	Tasks or the method may occasionally restrict the pace of work and require concentration on a task at any given time.
8. Workers' communication	3	Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.	1	Special care is taken to ensure that communication and contacts between workers and other people are possible.	3	Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.	3	Communication and contact with other people are limited during most of the working period. It is mainly due to the use of personal protective equipment and noise.
9. Decision-making	2	The work consists of simple tasks.	5	The worker involves several levels of education. A wrong decision can lead to material damage.	3	The work consists of complex tasks with several possible solution alternatives and the ease of comparison is low. There is a need for workers to control their own results.	2	The work consists of simple tasks.
10. Work repetitiveness	5	Cycle duration less than 0.5 min.	4	Cycle duration less than 3 min.	4	Cycle duration less than 3 min.	4	Cycle duration less than 5 min.
11. Level of required attention	2	Observation period < 80 % of the cycle. A superficial level of attention is required.	4	Observation period > 80 % of the cycle. A high level of attention is required.	4	Observation period > 80 % of the cycle. A high level of attention is required.	4	Observation period > 80 % of the cycle. A high level of attention is required.
12. Lightning	1	100 % of the recommended value.	1	100 % of the recommended value.	1	100 % of the recommended value.	2	50–100 % of the recommended value.
13. Thermal environment	2	Moderate work; 19–23 °C.	2	Moderate work; 19–23 °C.	2	Moderate work; 19–23 °C.	2	Moderate work; 19–23 °C.
14. Noise	2	Work that requires verbal communication; 60 dB(A).	2	Work that requires verbal communication; 60 dB(A).	2	Work that requires verbal communication; 60 dB(A).	1	Work that does not require verbal communication; 55 dB (A).

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