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Original
Designing Symbiotic Human–Robot Collaboration in assembly tasks / Barravecchia, Federico; Bartolomei, Mirco; Mastrogiacomo, Luca; Franceschini, Fiorenzo. - In: PRODUCTION ENGINEERING. - ISSN 0944-6524. - STAMPA. - 19:3-4(2025), pp. 629-661. [10.1007/s11740-025-01333-2]

Availability:
This version is available at: 11583/3001964 since: 2025-07-19T17:59:47Z

Publisher:
Springer

Published
DOI:10.1007/s11740-025-01333-2

Production Engineering (2025) 19:629–661
https://doi.org/10.1007/s11740-025-01333-2

ORIGINAL PAPER

Designing Symbiotic Human–Robot Collaboration in assembly tasks

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Received: 21 November 2024 / Accepted: 20 January 2025 / Published online: 9 February 2025

Abstract

The advancement of Human–Robot Collaboration (HRC) in industrial environments has underscored the importance of establishing harmonious and symbiotic relationships between human operators and robots. This study, in line with the principles of Industry 5.0, proposes an approach to support the integration of human operators' capabilities with advanced robotics, enhancing collaborative productivity and fostering a paradigm shift towards a more interactive and beneficial human–robot symbiosis. Prior research has established the basic principles of Symbiotic Human–Robot Collaboration (SHRC) but has often neglected the critical problem of how to conduct collaborative tasks to exploit the potential of these symbiotic interactions. This paper presents a novel methodology to support the design of protocols for collaborative tasks, with the aim of promoting positive symbiotic interactions between human operators and collaborative robots. The focus is on developing tasks that integrate positive symbiotic interactions, determining task performers and optimizing the mutual benefits derived from task execution. A case study is presented to illustrate the practical application of this methodology in a real-world context.

Keywords Symbiotic human–robot collaboration · Collaborative robotics · Collaborative assembly · Task allocation · Industry 5.0

1 Introduction

Human–Robot Collaboration (HRC) is advancing rapidly and has reached a pivotal stage where the combination of human and robot capabilities has the potential to revolutionize collaborative tasks [1]. This synergy between human operators and robots offers new opportunities to enhance human potential with the precision, adaptability, and efficiency of robots [2]. As technology advances, it is of paramount importance to investigate and exploit the potential of these collaborative interactions [3]. This exploration becomes increasingly relevant as industries move towards Industry 5.0, which emphasizes the integration of human cognitive abilities with advanced robotic systems.

To enhance HRC, it is essential to establish interactions that are both efficient and mutually beneficial, i.e., that optimize the strengths of both humans and robots by ensuring ergonomic compatibility—both physical and cognitive—while achieving improved outcomes for both agents [4]. These relationships, characterized by their reciprocal benefits and collaborative nature, have been labeled as Symbiotic Human–Robot Collaboration (SHRC) [4]. To realize SHRC, Collaborative Robots (Cobot), i.e., robotic systems designed to work alongside human operators in shared workspaces, are increasingly being equipped with technologies that significantly expand their capabilities [5]. The integration of these technologies results in collaborative systems that elevate cobot beyond simple physical tasks [6]. In this study, the term *collaborative systems* is defined in a broad sense, extending beyond the traditional emphasis on physical machinery, such as cobot. In this context, a collaborative system encompasses various equipment designed to facilitate and support human activities, thereby creating an infrastructure for HRC [5].

Despite significant advancements in HRC [7], the collaborative task design aspect remains underexplored. Existing research has predominantly focused on addressing technological challenges, such as optimizing robot programming [8], developing task scheduling algorithms [9], and integrating advanced technologies like sensors and digital twins [10]. However, these studies often neglect critical aspects of task design, including the development of task protocols and human-centered considerations [11]. Traditional task

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allocation approaches frequently prioritize robot efficiency in repetitive tasks [12]. Furthermore, the ergonomic and cognitive demands of human operators are also insufficiently addressed [13], despite the well-documented benefits of reducing cognitive load and enhancing physical comfort in collaborative environments [14]. These prevailing orientations have overlooked the crucial aspect of how assembly tasks should be designed to optimize symbiotic exchanges [4].

This gap highlights the need for a methodological framework to support task execution with the objective SHRC. In this view, this study seeks to address the following research question: *how can collaborative tasks be designed to facilitate positive symbiotic interactions between human operators and collaborative systems in assembly processes?*

To address this question, this article examines the concept of SHRC within manufacturing contexts, with a particular emphasis on its application in assembly processes. It introduces a novel methodology for designing symbiotic collaborative tasks, integrating task categorization, symbiotic task allocation, and protocol generation to foster mutually beneficial interactions between humans and robots. Central to this approach is the development of task protocols, which define the series of specific actions and interactions that human operators and collaborative systems are expected to perform during their joint efforts. To guide the definition of these task protocols, a comprehensive list of support activities has been developed, specifically designed for assembly tasks.

The objective is to develop a comprehensive framework that addresses the three essential elements of "What" tasks need to be performed, "Who" is responsible for executing them, and "How" they are carried out collaboratively, with the goal of enhancing symbiotic interactions between humans and robots.

The remainder of the paper is structured as follows. Section 2 presents a conceptual background on SHRC. Section 3 provides an overview of previous research on collaborative task allocation and on collaborative task design. Section 4 introduces the proposed methodology for the design of symbiotic task for collaborative assembly, detailing the steps involved in this approach. An applied case study is presented in Sect. 5, illustrating the practical implementation of the methodology in a real-world scenario. Finally, the concluding section synthesizes the key findings, explores the broader implications of the research, and proposes paths for future exploration in this field.

2 Symbiotic Human–Robot Collaboration

The concept of Symbiotic Human–Robot Collaboration (SHRC) has been defined as the interaction between human operators and robots in a cooperative and mutually beneficial manner [15]. In this context, both agents work together to achieve a common goal, with each enhancing the capabilities of the other [16].

Wang et al. [17] outlined six key requirements of SHRC systems: (i) autonomy; (ii) context awareness; (iii) communication; (iv) digital twin; (v) learning and (vi) safety.

Barravecchia et al. [3] expand on Wang et al. [15] by categorizing symbiotic human–robot relationships based on natural symbiotic types (see Fig. 1):

- *Mutualism*: both human and robotic agent benefit, e.g., cobot handle repetitive tasks, allowing humans to focus on quality control.
- *Commensalism*: one agent benefits without affecting the other, e.g., cobot lifts heavy loads to reduce human strain.
- *Parasitism*: one agent benefits at the other's expense, e.g., a cobot fast pace stresses the human operator.
- *Amensalism*: one agent's actions hinder the other without benefit, e.g., robots in shared spaces restrict human movement.
- *Incompatibility*: both agents are negatively affected, e.g., robot integration disrupts workflow.
- *Neutralism*: no impact on either, e.g., humans and robots perform separate, independent tasks.

To fully realize the potential of SHRC, understanding the key factors that shape these relationships is crucial. Barravecchia et al. [3] identified three primary symbiotic factors: *action*, *guidance*, and *protection*, each with dimensions relevant to collaborative interactions.

Action involves the physical contributions by each agent. This dimension involves:

- Effort: each agent's contribution to task completion.
- Speed: each agent's impact on task progression.

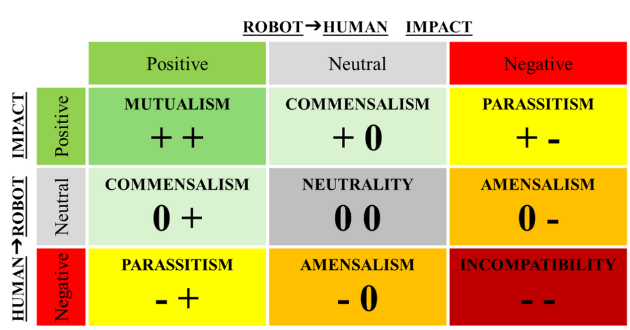

Fig. 1 Classification of symbiotic human–robot relationships [4]. Legend: "+" positive impact of the relationship. "0" neutral impact of the relationship. "–" negative impact of the relationship. The terms Human→Robot Impact and Robot→Human Impact represent the nature and direction of the interaction effects between humans and robots in a collaborative system

Effort and speed are critical dimensions of action in SHRC, representing each agent's contribution to task completion and progression. For instance, a human operator can assist the robot by pre-orienting components, reducing the complexity of the robot's motion and optimizing its effort during handling. Conversely, the robot can enhance human efficiency by holding heavy parts steady, allowing the operator to focus on precision tasks without physical effort.

Guidance refers to one agent's ability to direct the other. Its dimensions are:

- Knowledge: each agent's required knowledge for the task.
- Decision-making: each agent's ability to determine and adapt task execution.

In detail, knowledge refers to understanding task requirements and conditions, while decision-making involves selecting the best course of action based on that knowledge. While good knowledge enhances decision-making, the ability to adapt decisions in real time distinguishes the two categories, particularly in dynamic contexts. For example, a robot equipped with sensors can guide the human operator by providing real-time feedback on alignment accuracy, ensuring precise assembly. Conversely, the human operator can assist the robot by adapting the task sequence based on unforeseen variations, such as component defects, using contextual knowledge.

Protection focuses on safeguarding each agent from potential risks, involving:

- Ergonomics: enhancing physical and psychological comfort.
- Safety: protecting the other from risks or threats.

For example, robots can reduce physical strain on humans by handling heavy or repetitive tasks, thereby improving ergonomics and preventing injuries. Similarly, human operators can safeguard robots by avoiding actions that could lead to mechanical damage.

Table 1 highlights the relationships between the proposed symbiotic factors—*Action*, *Guidance*, and *Protection*—and key industrial factors such as cycle time, quality and operator well-being. This highlights how SHRC could address industrial priorities, offering possible benefits for both operational outcomes and operator well-being.

Several examples demonstrate the implementation of SHRC concepts in industrial contexts. For instance, SHRC has been successfully implemented in the aerospace industry to overcome challenges typically associated with robot-reluctant environments [23]. In detail, in the manufacturing of aircraft ribs, cobot are employed to perform high-accuracy tasks like positioning, while humans manage operations requiring flexibility, such as assembly adjustments [23]. This collaboration reduced time, risks, and costs, while improving productivity and safety.

3 Literature review

3.1 Research on collaborative task allocation

Task allocation is a crucial area of research in the domains of assembly and HRC [24]. Traditional task allocation approaches aim to distribute tasks between human operators and cobot based on their inherent capabilities [25]. Robots are typically assigned repetitive or physically demanding tasks, while humans handle activities requiring cognitive flexibility, decision-making, or complex problem-solving [9]. This structured division is primarily performance-driven and often results in functional separation rather than a deeply collaborative interaction.

In contrast, symbiotic task allocation, as applied in SHRC, prioritizes fostering a closer and more integrated partnership between humans and robots. Instead of focusing solely on optimizing performance, this approach emphasizes mutual support and complementary interactions during task execution. The goal is to create a balanced and dynamic collaboration, where the interaction itself is a key factor in improving process outcomes. By shifting the focus from individual task performance to the quality of collaboration, SHRC facilitates a deeper synergy between humans and robots.

Table 1 Relationships between the symbiotic factors—Action, Guidance, and Protection—and key industrial factors (cycle time, quality, and well-being)

	Cycle-time	Quality	Well-being
Action	✓ Optimizes task flow and reduces delays [18]	–	✓ Reduce physical strain [19]
Guidance	✓ Streamlines task execution with feedback [20]	✓ Enhances decision accuracy [20]	✓ Reduces cognitive demand [21]
Protection	–	–	✓ Ensures safety and comfort [22]

✓ = a positive relationship identified in the literature

– = no clear relationship identified in the literature

While the literature extensively covers traditional task allocation approaches in HRC, there is comparatively limited research addressing symbiotic task allocation, highlighting a gap in understanding how to design interactions that prioritize collaboration over mere functional efficiency.

The literature primarily categorizes HRC task allocation into two main distinct paradigms: *static task allocation* and *dynamic task allocation* [26].

In *static task allocation*, roles are determined based on an analysis that compares the suitability of both human and robotic agents for specific tasks. Once set, these roles remain fixed throughout the assembly process. Most static allocation methods evaluate suitability by matching the abilities of both human operators and robots to the characteristics of the components being assembled and the demands of the related assembly task [27]. Advanced methodologies delve deeper into the suitability assessment by incorporating additional factors like ergonomics, task completion durations, and cycle times. Other strategies promote a wider view of static task allocation, shifting from a task-focused approach to considering the entire assembly process. Such methods employ algorithms to formulate task allocation schedules, aiming to enhance the overall efficiency and effectiveness of the assembly [28, 29]. A notable extension to traditional static task allocation methods involves the use of simulation environments [30]. One primary utility of simulation environments is their ability to compare different task allocation schedules [31]. Furthermore, simulation environments can be integrated with algorithms designed for multi-criteria optimization [25]. These algorithms consider a set of factors including efficiency, effectiveness, ergonomics, and cycle times to optimize the allocation of tasks between human operators and robots.

Conversely, in *dynamic task allocation*, emphasis is placed on the adaptability of assignments and real-time responsiveness, allowing for a flexible approach to the changing demands of the assembly process. Within this framework, there are two primary approaches that are commonly identified in the literature: (i) reactive task allocation and (ii) proactive task allocation [26].

The reactive task allocation approach is defined by a centralized allocation plan that is subject to reactive adjustments in response to real-time changes or disturbances that may occur during the assembly process, such as unexpected collisions or sudden changes in the workload of the human operator [32] .This approach may involve the dynamic adaptation of individual task assignments [33] or, in more extreme cases, a complete re-planning of all remaining tasks in the assembly process [34]. This approach is flexible and responsive, allowing for adjustments to be made on-the-fly to accommodate unforeseen circumstances of the assembly process. The proactive task allocation approach takes a different stance by placing the human operator at the forefront of the assembly process. In this approach, the human operator is empowered with the autonomy to select the tasks they wish to perform [35]. Based on the human's actions, the system then dynamically decides which tasks can be performed by the robot. The objective here is to identify tasks that can be performed in parallel with the human operator's tasks, serving as preparatory work for subsequent steps in the assembly process [36]. This approach can enhance the efficiency of the assembly process and ensures that the human operator is able to work at their own pace, with the robot providing support as needed.

Table 2 proposes a brief comparative analysis of Static Task Allocation and Dynamic Task Allocation, highlighting the advantages and disadvantages of each approach in terms of flexibility, responsiveness, complexity, human operator involvement, and efficiency.

Both Static Task Allocation and Dynamic Task Allocation are valuable approaches in the field of HRC. Static Task Allocation, with its fixed roles and tasks, offers a high degree of predictability and efficiency. The tasks are allocated based on a detailed analysis of optimal suitability, ensuring that the

Table 2 Comparative analysis of static task allocation and dynamic task allocation approaches in human–robot collaboration [26]

Characteristic	Static task allocation	Dynamic task allocation
Flexibility	Limited; roles and tasks are pre-defined and remain fixed	High; tasks and roles can be adapted in real-time to meet the needs of the assembly process
Responsiveness	Limited; lacks the ability to respond to changes and disturbances in real-time	High; can quickly adjust to real-time changes and disturbances in the assembly process
Complexity	Moderate; methodologies range from simple to complex, depending on factors considered during the allocation process	High; requires real-time decision-making and coordination between human operators and robots
Human operator involvement	Moderate; human operators have clearly defined roles and tasks	High; human operators can make autonomous choices and have more control over the assembly process
Efficiency	High; tasks are allocated based on optimal suitability, leading to an efficient assembly process	Moderate; efficiency may be affected by the need to make real-time adjustments

strengths of both human operators and robots are leveraged in the most effective manner. This approach is particularly advantageous in environments where tasks and roles remain constant, allowing for a streamlined and efficient assembly process.

On the other hand, Dynamic Task Allocation is more flexible and responsive, with the ability to adapt to real-time changes in the assembly process. This approach is well-suited for unpredictable environments that require real-time adjustments to meet the demands of the assembly process.

3.2 Research on collaborative task design

Collaborative task design within assembly processes is relatively unexplored, with a handful of recent studies providing some preliminary insights into the interplay between human operators and robots.

The work of Mulesa et al. [37] sheds light on the project planning phase by emphasizing the construction of a task hierarchy and its subsequent distribution among executors. Their approach is marked by the introduction of efficiency indicators and the proposition of iterative methods aimed at evaluating the minimal duration and cost associated with the task.

The study by Garcia et al. [38] introduces a novel framework for HRC, leveraging deep learning models to manage assembly processes conducted either individually or collaboratively by human operators and robots.

Further contributing to the ergonomic aspect of collaborative task design, the research conducted by Navas-Reascos et al. [13] presents a prototype and simulation to integrate a collaborative system in a wire harness assembly process. This new emphasis on ergonomics highlights the importance of considering human well-being in the design of collaborative tasks [39].

Dmytriyev et al. [40] focus on a cooperative assembly task, using a Brain-Computer Interface (BCI) to relay commands to the collaborative robot. This allows the operator to switch between independent and cooperative assistance modes seamlessly. The study highlights the potential of integrating advanced technologies to enhance communication and cooperation.

Moreover, the integration of heterogeneous models for safety-critical mechatronic systems, as explored by Mhenni et al. [41], offers insights into the application of Model-Based Systems Engineering (MBSE), Model-Based Safety Assessment (MBSA), and multi-physics modeling in designing collaborative workplaces for aircraft assembly. This integrative approach underscores the multifaceted nature of collaborative task design, necessitating a convergence of diverse disciplines and domains to address the requirements and considerations inherent in collaborative assembly processes.

Lastly, the work of Huang et al. [42] introduces a protocol linking design and construction intent with algorithmic planning for robotic assembly of complex structures. This protocol enables designers to articulate their design intentions and process knowledge, providing a structured framework to define complete sequence of robot motions.

A critical examination of the literature highlights the absence of comprehensive methodologies for collaborative task design, with most studies focusing on specific case studies or isolated aspects such as ergonomics or communication. This narrow focus limits the generalizability of findings and overlooks the multifaceted nature of task execution. There is a clear need for an integrated framework that aligns multiple traits of collaboration to enhance both efficiency and human–robot synergy in industrial contexts.

4 A methodology for designing symbiotic tasks

Building on previous research on SHRC, this section provides a novel method to assist the design of symbiotic tasks for collaborative assembly. The method aims to guide the definition of the task protocol, according to the following steps (see Fig. 2):

1) *Task categorization*: the initial step involves characterizing the activities to be performed in the assembly process. In cases where the process is complex, it is not feasible to analyze individual activities. In such cases, categorizing activities into specific task categories can be an effective method to simplify the problem domain [43].

This step is designed to address the question "*What tasks are required to complete the assembly?*"

2) *Symbiotic Task allocation*: the second step focuses on assigning the identified task categories to the collaborative agents, whether human operator or collaborative system.

This step is dedicated to answering the question "*Who is responsible for executing the identified categories?*"

3) *Task protocol generation*: the third step involves detailing the actions of the collaborative agents.

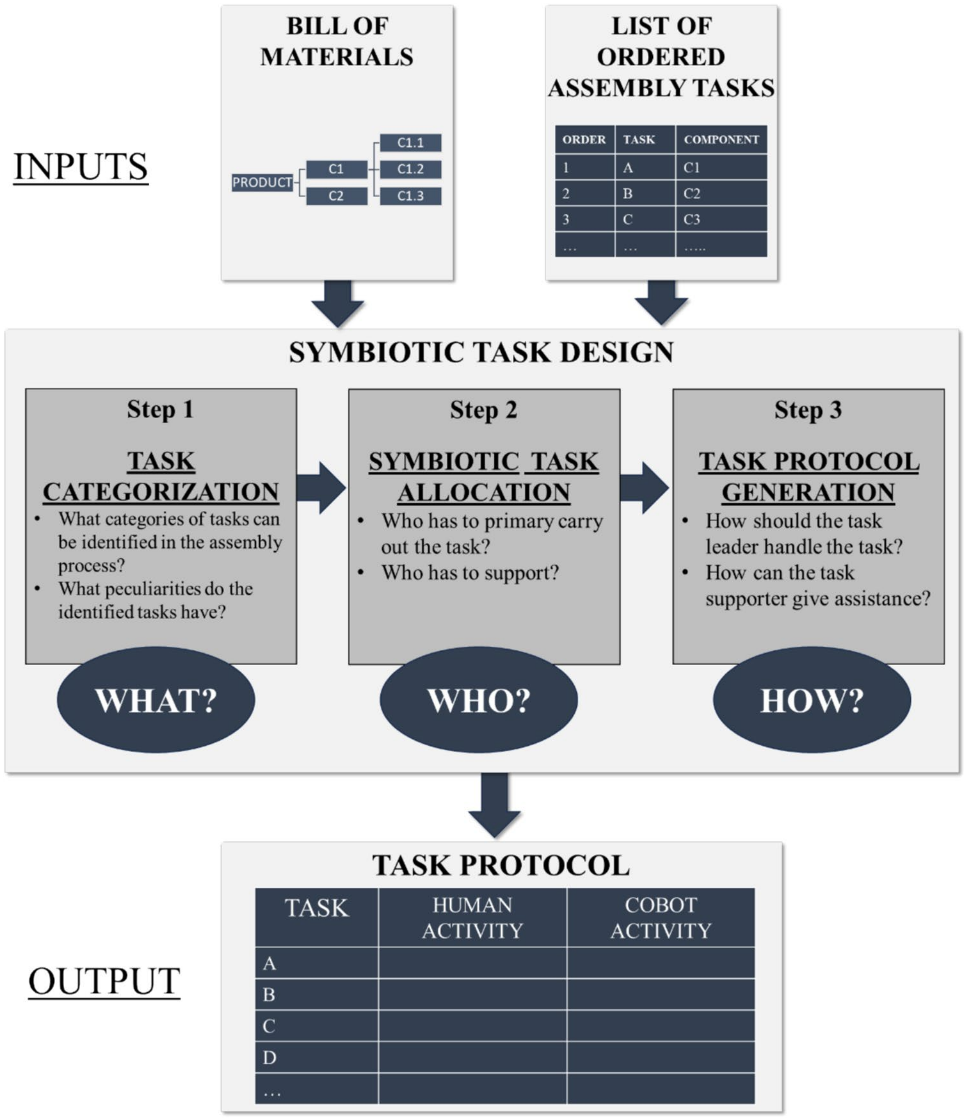

Fig. 2 Outline of the method for the design of symbiotic task. The figure illustrates the three-step methodology for designing symbiotic tasks in a collaborative human–robot assembly process

This step produces the formulation of the complete task protocol, thereby providing an answer to the question, "*How should the task be executed?*"

Note that the proposed methodology does not aim to define the selection of specific tools or technologies; rather, it focuses on developing a task protocol that can be tailored to the available technology within a given setting [44].

The following sub-section provides an overview of the proposed approach. Subsequently, a case study will be presented to exemplify the practical application of the method.

4.1 Input of the method

The methodology requires two primary inputs:

- *Bill of Materials* (B.O.M.): a comprehensive list that outlines all the components, materials, and sub-assemblies required to manufacture the final product [45]. The B.O.M. typically follows a hierarchical structure, where components and sub-assemblies are organized in levels to represent their relationships and dependencies within the overall assembly process [46].
- *List of ordered assembly tasks*: this list should outline each step involved in the assembly, from the initial identification and handling of components to the final checking and adjustment of the assembled product, while considering task precedence to ensure a logical workflow.

To illustrate these concepts, consider the assembly of a simple wooden stool. The B.O.M. for the stool including the components is reported in Table 3, while the List of Ordered Tasks for assembly outlining the specific steps necessary to assemble the stool is reported in Table 4.

Table 3 Example of bill of material (bom) for a wooden stool

Level	Component code	Component description	Quantity
1	D	Seat	1
1	L	Leg	4
1	S	Screw	8
2	E	Entire stool	1

Level: indicates the hierarchical level of the components in the assembly. Component code: unique identifier for each component type. Component description: a brief description of the component. Quantity: specifies the number of each component required for the assembly

4.2 Step 1: task categorization

An essential step for organizing the various tasks involved in an assembly process is the task categorization. This categorization takes into account two aspects. The first is represented by the *elementary task type* with common execution attributes. Five elementary task types can be considered as fundamental components of a generic assembly process [47]:

- *Identification and Handling*: involves recognizing the necessary components and their handling.
- *Alignment*: requires aligning the components in the correct orientation and position.
- *Joining*: involves connecting the components together.
- *Checking*: involves inspecting the assembly to ensure that it meets the required specifications.
- *Adjustment*: involves making any necessary adjustments to the assembly to ensure a correct functioning.

The second aspect that can be considered for categorizing a task concerns the *critical properties* of the component interested. In fact, by identifying these characteristics, it is possible to allocate different tasks accordingly [12]. The following are potential properties that can influence task execution and can be used to classify components:

- *Grippability*: The ease of gripping and manipulating a component during the assembly process is crucial in determining who will perform the assembly task and how it will be done [12]. Certain types of components may pose challenges for human operators or collaborative systems in terms of grippability.

Table 4 Example of list of ordered tasks for the wooden stool assembly

Order	Component code	Task descprition	Component description
1	S	Identify and gather the seat	Seat
2	L	Identify and gather the first leg	Leg 1
3	L	Align the first leg to the seat in the correct orientation	Leg 1
4	S	Identify and gather two screws	Screw 1–2
5	S	Join the first leg to the seat by fastening 2 screws	Screw 1–2
6	L	Identify and gather the second leg	Leg 2
7	L	Align the second leg to the seat in the correct orientation	Leg 2
8	S	Identify and gather two screws	Screw 3–4
9	S	Join the second leg to the seat by fastening 2 screws	Screw 3–4
10	L	Identify and gather the third leg	Leg 3
11	L	Align the third leg to the seat in the correct orientation	Leg 3
12	S	Identify and gather two screws	Screw 5–6
13	S	Join the third leg to the seat by fastening 2 screws	Screw 5–6
14	L	Identify and gather the fourth leg	Leg 4
15	L	Align the fourth leg to the seat in the correct orientation	Leg 4
16	S	Identify and gather two screws	Screw 7–8
17	S	Join the fourth leg to the seat by fastening 2 screws	Screw 7–8
18	E	Check that all legs are securely attached to the seat and ensure the stool is stable	Entire stool
19	E	Adjust any loose legs or screws if necessary to ensure proper stability and function	Entire stool

Order: the sequence in which the tasks should be performed during the assembly process. Component code: unique identifier for each component type involved in the assembly. Task description: the specific action to be performed at each step. Component description: brief description of the component being worked on during the specific task

- *Feeding*: It basically refers to the ease with which the component can be located and retrieved from the feeding zone [12].
- *Orientation*: This refers to the specific position or alignment that a component must have in relation to other components or the assembled product as a whole [12] .
- *Temperature*: The temperature of a component during assembly can affect how easily it can be handled and assembled [48].
- *Surface treatment*: The presence of paints, coatings, lubricants, etc., can affect the task design choices. In cases where components have surface treatments that influence assembly activities, it is important to distinguish them during this task categorization phase [49].
- *ESD Sensitivity*: Electrostatic discharge sensitivity is a critical factor in some assembly processes, particularly in the electronics industry. If some components have specific ESD requirements, this should be distinguished [50].
- *Cost*: Components with higher costs, such as integrated circuits, may require stricter handling, inspections, or quality controls to mitigate potential losses, whereas lower-cost components might prioritize efficiency. This classification helps tailor assembly activities to optimize resource allocation and minimize risks [3].

Component properties influence task execution by dictating the specific requirements and constraints. For instance, properties like grippability determine the ease with which a component can be manipulated, influencing whether a human operator or a collaborative system is better suited for the task. Similarly, factors such as surface treatment or temperature impact the choice methods used during assembly, while ESD sensitivity or cost can dictate additional precautions or inspections.

The reported list includes some common properties, but specific contexts may require additional or alternative classification criteria for components. Properties can be used individually (e.g., ESD sensible/non ESD Sensible) or combined (e.g., grippable and inexpensive component, grippable and expensive component, ungrippable and inexpensive component, ungrippable and expensive component).

Choosing the critical properties of a component for their categorization requires an evaluation based on the specific characteristics of the product, the assembly environment, and the constraints of the operators or machines involved. This selection of properties should focus on those that significantly impact the efficiency, safety, and quality of the assembly.

By combining these component properties with the elementary task types, it is possible to create a comprehensive task categorization scheme.

In the preceding section, the wooden stool was introduced as an example. In this section, the focus is on the task categorization. The criterion identified as influencing task execution was the grippability of the components. The *Seat* (D), *Legs* (L), and *Entire Stool* (E) were considered grippable components, while the *Screws* (S) were not considered as grippable due to their small size and the limitations of the system's end effector capabilities. By intersecting the types of tasks performed with the grippability of the associated components, the following task categories are identified: (i) *Identification and Handling on Grippable components*; (ii) *Identification and Handling on Ungrippable components*; (iii) Alignment on grippable components; (iv) *Joining on Ungrippable components*; (v) *Checking on Grippable components*; and (vi) *Adjustment on Grippable components*.

As a result, from the initial 19 elementary tasks (Table 4), the problem was reduced to analyzing and optimizing the execution of these six task categories.

4.3 Step 2: symbiotic task allocation

In this step, the task categories are allocated to the appropriate agent, whether human or collaborative system. One agent will assume the role of the leader, while the other will assume the role of supporter. The leader is primarily responsible for completing the task, while the supporter assists and helps the leader in completing the task. All tasks belonging to a specific category are allocated to the same agent.

The goal is designing the task to enhance the symbiosis between the human operator and collaborative system, thereby maximizing exchanges on the six dimensions of the SHRC factors outlined in Sect. 2: *effort*, *speed*, *knowledge*, *decision-making*, *ergonomics*, and *safety*.

In order to facilitate the decision-making process, the methodology involves the assessment of the capabilities of both human operators and collaborative systems in relation to each dimension of SHRC. It is essential that this evaluation considers the distinctive capabilities and limitations of both agents in relation to the specific task category under consideration. To guide decision-making, Table 5 presents a series of questions designed to assess the capabilities of human operators and collaborative systems across the six symbiotic dimensions. The objective of each question is to ascertain which agent is better equipped to handle the task category with respect to the specific dimension. For each symbiotic dimension, responses should be provided in the

Table 5 Questions to assess the capabilities of human operators and collaborative systems across symbiotic dimensions

Symbiotic dimension	Question	Description	Implications
Effort	Who performs better in terms of effort required for the task?	Assessing the physical or cognitive load required to perform the task	A lower effort suggests a more efficient process
Speed	Who performs better in terms of speed and efficiency for the task?	Evaluating the time taken to complete the task	Faster completion typically results in higher productivity
Knowledge	Who is better equipped with the necessary knowledge and expertise for the task?	Determining the level of technical or domain-specific expertise required for the task	The agent with the relevant knowledge is likely to perform the task more accurately
Decision-making	Who is better equipped to make informed and accurate decisions for the task?	Assessing the capability to process information and make the right decisions based on the task requirements	A good decision-making process can impact the task outcome
Ergonomics	Who provides a more ergonomic solution for the task?	Evaluating the comfort and ease of performing the task	An ergonomic solution can reduce physical and psychological strain and enhance productivity
Safety	Who ensures a safer execution of the task?	Assessing the potential risks involved and the measures taken to mitigate those risks	Ensuring safety is critical in any task

form of “Human”, “Collaborative System”, “Equivalent”, or “Not Applicable”. “Human” indicates that the human operator is better equipped to handle the task category in that specific dimension; “Collaborative System” suggests that the robotic system is more suitable; " Equivalent " implies that both agents are equally able; “Not Applicable” indicates that the dimension in question is not relevant or cannot be assessed for the particular task category at hand.

A straightforward method for task allocation, based on criteria reported in Table 5, suggests that if the majority of evaluated dimensions indicate one agent as more suitable, then that agent should be designated as the responsible for executing that task category. In cases where there is an equivalent suitability between agents, the task category should be delegated to the collaborative system to reduce physical and cognitive load on the human operator.

Table 6 Symbiotic task allocation application for the wooden stool assembly

Task category	Symbiotic dimensions						Leader	Supporter
	Effort	Speed	Knowledge	Decision making	Ergonomics	Safety		
Identification and handling grippable	Collaborative system	Human	Collaborative system	Collaborative system	Collaborative system	Collaborative system	Collaborative system	Human
Identification and handling ungrippable	Human	Human	Equivalent	N.A.	Equivalent	Equivalent	Human	Collaborative system
Alignment grippable	Collaborative system	Collaborative system	Collaborative system	Human	Collaborative system	Collaborative system	Collaborative system	Human
Joining ungrippable	Human	Human	Human	Human	Human	Human	Human	Collaborative system
Checking ungrippable	Collaborative system	Human	Human	Human	Human	N.A.	Human	Collaborative system
Adjustment ungrippable	Collaborative system	Human	Human	Human	Collaborative system	N.A.	Human	Collaborative system

Task category lists the task categories identified in the task categorization phase. Symbiotic dimensions refers to the criteria used for evaluating the potential for maximizing symbiotic exchanges, as outlined in Sect. 2. The columns Leader and Supporter indicate the assignments of agents to these two roles for each task category. Regarding the evaluation of Symbiotic dimensions, the cells contain responses to the questions presented in Table 5

N.A. not applicable

As alternatives to this basic approach, more sophisticated decision-making mechanisms can be applied [51–53]. For instance, assigning different weights to the symbiotic dimensions or considering some veto conditions. This would allow the evaluation process to be tailored to the needs of specific applications.

This methodology is classified as a *static task allocation* approach, allowing role allocation based on pre-defined criteria.

Table 6 provides a summary of the task categories identified for the Wooden Stool example, the symbiotic dimension evaluations for each category, and the assignment of leader and supporter roles between the collaborative system and the human operator.

4.4 Step 3: task protocol generation

Once "what" needs to be done and "who" will be responsible are defined, the next step is to establish "how" the collaborative tasks should be executed. This entails the development of a task protocol. Each task category is mapped with the activities of the leader and the supporter.

Tables 7 and 8 assist in this process by providing a comprehensive summary of basic activities for both the leader and the supporter (whether human or collaborative system) for each task type. These activities are generic and not tied to any specific process; rather, they serve as a guide for designers, allowing them to select those activities that align with the capabilities of the collaborative system and the needs of the particular process. Detailed descriptions of the support activities are listed in Appendix A (Tables 16 and 17).

The supporting activities were identified through a process aimed at strengthening SHRC. This included:

- *Capability analysis*: Assessing the capabilities and needs of both human operators and collaborative systems.
- *Operational Analysis*: Time and method measurement (MTM) and Robot Time and Motion (RTM) [54] techniques were applied in the definition of support actions to ensure their suitability for cycle time improvement, thus contributing to the *Speed* dimension.
- *Ergonomic assessments*: Rapid Entire Body Assessment (REBA) [55] technique was used in the development of the support actions to ensure their effectiveness in fostering *Effort* and *Ergonomics* dimensions.
- *Compliance with ISO Standards*: ISO compliance was ensured by aligning support actions with key standards. ISO 10218-1 [56], ISO 10218-2 [57], and ISO/TS 15,066 [58] addressed safety for industrial robots, while ISO 11,228 [59] guided ergonomic considerations in manual handling, ensuring both *Safety* and *Ergonomics* dimensions.
- *Decision-making analysis*: From the task types, critical decision points were identified, and support actions were derived to enhance *Knowledge* and *Decision-Making* dimensions. These actions assist the responsible agent in making informed decisions, improving the overall quality and consistency of the process.
- *Field observations and operator feedback*: Identifying where system support is most effective.
- *Industry benchmarking and expert advice*: Incorporating best practice and guidance into the design of support activities.

This mixed approach, combining contextual analysis with established frameworks, aims to guide support actions that enhance key dimensions promoting SHRC.

The deliberately broad activity descriptions (see Tables 16 and 17 in Appendix A) allow for flexibility in application to different technologies. For example, the "*identification of a target component*" can be achieved through various technologies and procedures, such as using a screen, a laser, verbal description of component characteristics, or simply physically pointing to it. This flexibility ensures that the guidelines remain relevant and adaptable, maintaining their utility in the ever-changing landscape of collaborative assembly.

Table 9 presents the task protocol developed for the exemplary assembly of the wooden stool. It outlines the specific activities performed by each agent. The construction of this table was based on the task categories identified in the previous steps and the capabilities of the human operator and the collaborative system within our exemplificative case. By applying the design of the task categories to the entire assembly process, it is possible to obtain the complete task protocol.

To assess the quality, performance, and impact of the results achieved through the proposed methodology the following evaluation metrics can be applied:

- *Error Rate*: the frequency of assembly errors (e.g., misalignments, fastening defects) that may impact product quality, allowing comparison between traditional approaches and SHRC-enhanced processes [60].
- *Rework Rate*: the percentage of assemblies requiring corrections or adjustments, serving as an indicator of process reliability and final product quality [60].

Table 7 Summary of the activities of an assembly process, with the human as the leader and the collaborative system acting as the supporter

Task type	Human leader activity	Collaborative system supportive activity	Symbiotic factors					
			Action		Guidance		Protection	
			Effort	Speed	Knowledge	Decision making	Ergonomics	Safety
Identification & handling	The human operator identifies the correct component from the feed area and moves the selected component to the work area	Target component		●	●		●	
		Real-time identification feedback		●	●		●	
		Sorting assistance		●	●		●	
		List of activity sharing		●	●	●	●	
		Component defects detection		●		●	●	
		Lifting assistance	●	●			●	
		Component pre-positioning		●	●		●	
		Posture monitoring	●				●	
		Real-time handling feedback		●	●		●	●
		Grip assistance		●	●		●	●
		Safety alerts						●
		Stress-driven handling scheduling				●	●	
		Process-driven handling scheduling		●		●		
		Tool handover	●	●	●		●	
		Data logging			●	●		●
Alignment	The human operator aligns and places the component in its designated mounting location	Target component position		●	●		●	
		Active alignment stabilization	●	●			●	
		Subassembly pre-orientation	●	●	●		●	
		Operator-optimized subassembly orientation	●	●			●	
		Real-time alignment feedback (profile matching)		●	●		●	
		Alignment sequence sharing	●	●	●			
		Stress-driven alignment scheduling					●	
		Process-driven alignment scheduling	●			●		
		Safety alerts			●			●
		Precision positioning		●	●		●	
		Alignment instructions	●	●	●			
		Visual field optimization		●			●	
Joining	The human operator physically joins the components	Synchronized component joining	●	●	●		●	
		Secure holding	●	●			●	

Table 7 (continued)

Task type	Human leader activity	Collaborative system supportive activity	Symbiotic factors: Action – Effort	Action – Speed	Guidance – Knowledge	Guidance – Decision making	Protection – Ergonomics	Protection – Safety
		Subassembly pre-orientation		●	●			
		Operator-optimized subassembly orientation	●	●			●	
		Joining instructions	●	●	●			
		Real time joining feedback		●	●	●	●	
		Ergonomic subassembly positioning					●	
		Adaptive ergonomic subassembly positioning					●	
		Stress-driven joining scheduling					●	
		Process-driven joining scheduling	●			●		
		Safety alerts						●
		Tool handover	●	●	●		●	
		Visual field optimization		●			●	
		Data logging			●	●		●
Checking	The human operator performs a quality assessment to confirm that the assembly complies with specifications	Human-error mitigation		●	●		●	
		Operator-optimized product orientation	●	●			●	
		Inspection instructions	●	●	●			
		Safety alerts						●
		Ergonomic product positioning					●	
		Adaptive ergonomic product positioning					●	
		Stress-driven checking scheduling					●	
		Process-driven checking scheduling	●			●		
		Defect tracking assistance		●	●			
		Visual field optimization		●			●	
		Tool handover	●	●	●		●	
Adjustment	The human operator rectifies defects in the assembled product to ensure that the final product meets specifications	In-process validation	●	●		●		
		Real-time adjustment guidance		●	●		●	
		Operator-optimized product orientation	●	●			●	
		Adjustment instructions	●	●	●			
		Safety alerts						●

Table 7 (continued)

Task type	Human leader activity	Collaborative system supportive activity	Symbiotic factors					
			Action		Guidance		Protection	
			Effort	Speed	Knowledge	Decision making	Ergonomics	Safety
		Ergonomic product positioning					●	
		Adaptive ergonomic product positioning					●	
		Stress-driven adjustment scheduling					●	
		Process-driven adjustment scheduling	●			●		
		Visual field optimization		●			●	
		Tool handover	●	●	●		●	

The dots in the last six columns represent the dimensions in which the support activities can significantly enhance human–robot symbiosis. Table 16 in appendix A details the supportive activities of the collaborative system

- *Task Completion Time*: tracking the duration for specific task executions within the collaborative process.
- *Cognitive Load*: assessment of the mental effort required by human operators to collaborate with the system, including the ease of interpreting guidance and interacting with the cobot [14].
- *Ergonomic Impact*: evaluation of the human operator's comfort and physical well-being during the process, including posture, strain, and long-term fatigue [61].

5 Case study

In the previous section, a simple application example was provided to illustrate the methodology. Here, a more complex case study is introduced, demonstrating the application of the proposed methodology to skateboard assembly tasks within a collaborative assembly station. Figure 3A shows a graphical representation of the skateboard, outlining its complete assembled state. Figure 3B breaks down the skateboard into its various components.

The case study considers a collaborative system equipped with a dual arm cobot (see Fig. 4). The cobot features two independent robotic arms, each capable of 6 degrees of freedom. One arm is equipped with a two-finger parallel gripper with a maximum payload capacity of 5 kg. Additionally, one arm is equipped with a robotic screwdriver capable of automated fastening operations with adjustable torque settings ranging from 0.5 to 5 Nm.

The dual-arm configuration allows simultaneous or sequential task execution, enabling the cobot to perform bimanual operations, such as holding a component with one arm while fastening with the other.

A key feature of the station is the tracer laser projector, which provides graphical real-time guidance by projecting interactive visual elements onto the workspace. These elements include dynamic instructions, such as highlighting the correct component to pick, showing placement positions, or indicating task progression. The projector operates with a precision of ± 1 mm.

The assembly station is further equipped with an integrated vision system, consisting of high-resolution cameras for component detection, quality control, and monitoring the workspace. The vision system enables real-time feedback, dynamically adjusting task execution based on component positions, assembly progress, or environmental changes.

To facilitate human-system interaction, the station includes a Graphical User Interface (GUI) displayed on a 15-inch touch screen monitor. The GUI provides an intuitive platform for the operator to: (i) monitor task progress and system status; (ii) interact with the system by confirming task completions or requesting manual overrides; (iii) adjust operational parameters such as tool settings, task priorities, or component handling preferences.

The system's collaborative tasks are programmed to adhere to ISO 10218-1 safety standards for robotic systems [56], ensuring safe human–robot interaction. Force and torque sensors integrated into the cobot arms enable collision detection and compliant control, protecting the human operator during close-proximity tasks.

The team responsible for the symbiotic task design comprised three individuals.

Table 8 Summary of the activities of an assembly process, with the collaborative system as the leader and the human acting as the supporter

Task type	Collaborative system leader activity	Human supportive activity	Symbiotic factors					
			Action		Guidance		Protection	
			Effort	Speed	Knowledge	Decision making	Ergonomics	Safety
Identification & handling	The collaborative system identifies the correct component from the feed area and moves the selected component to the work area	Target component		●	●			
		Component feeding		●	●			
		Component defects detection		●		●		
		Component pre-positioning		●	●		●	●
		Handling prompting		●	●			
		Balance assistance	●	●			●	●
		Gripping optimization	●	●				
		Handling instructions	●	●	●			
		Tool handover	●	●	●	●		
		Data logging			●	●		
Alignment	The collaborative system aligns and places the component in its designated mounting location	Target component positioning	●	●	●			
		Subassembly pre-orientation		●	●		●	●
		Active alignment stabilization	●	●				
		Precision positioning	●	●			●	
		Alignment prompting		●	●			
		Alignment instructions	●	●	●			
		Manual alignment assistance		●	●		●	●
Joining	The collaborative system physically joins the components	Synchronized component joining	●	●	●			
		Secure holding	●	●				●
		Subassembly pre-orientation		●	●			●
		Joining prompting		●	●			
		Joining instructions	●	●	●			
		Tool handover	●	●	●	●		
		Data logging			●	●		
Checking	The collaborative system performs a quality assessment to confirm that the assembly complies with specifications	Collaborative system error mitigation		●	●			
		Product orientation for inspection		●	●		●	●
		Inspection instructions	●	●	●			
		Checking prompting		●	●			
		Defect tracking assistance			●	●		
		Tool handover	●	●	●	●		
Adjustment	The collaborative system rectifies defects in the assembled product to ensure that the final product meets specifications	Product orientation for adjustment		●	●		●	●
		In-process validation	●	●		●		
		Adjustment instructions	●	●	●			
		Real-time adjustment guidance		●	●		●	●
		Adjustment prompting		●	●			
		Tool handover	●	●	●	●		

The dots in the last six columns represent the dimensions in which the support activities can significantly enhance human–robot symbiosis. Table 17 in appendix A details the supportive activities of the human operator

Table 9 Results of the task protocol development for the for the wooden stool assembly

Task category	Leader	Supporter	Leader activity	Supportive activity
Identification and handling grippable	Collaborative system	Human	The collaborative system identifies the correct grippable component from the feed area and moves it to the work area	Human operator supports by: Component feeding: supplying components to the collaborative system's pick-up area Component defects detection: inspecting components for defects before feeding them Handling prompting: providing signals if the collaborative system requires assistance
Identification and handling ungrippable	Human	Collaborative system	The human operator identifies and gathers ungrippable components and moves them to the work area	Collaborative system supports by: Target component: highlighting or indicating the location of screws
Alignment grippable	Collaborative system	Human	The collaborative system aligns and places the grippable components in their designated positions	Human operator supports by: Active alignment stabilization: helping stabilize components during placement
Joining ungrippable	Human	Collaborative system	The human operator joins the ungrippable components	Collaborative system supports by: Tool Handover: providing screwdrivers or other tools Ergonomic subassembly positioning: adjusting the assembly height or angle for comfort
Checking ungrippable	Human	Collaborative system	The human operator checks that the component is securely attached and ensures the stool is stable	Collaborative system supports by: Ergonomic product positioning: adjusting stool position for easier inspection Defect tracking assistance: recording any issues found Tool handover: providing tools for adjustments if needed
Adjustment ungrippable	Human	Collaborative system	The human operator adjusts issues on the components to ensure proper stability and function	Collaborative system supports by: Ergonomic product positioning: positioning the stool for optimal access Tool handover: supplying necessary tools for adjustments

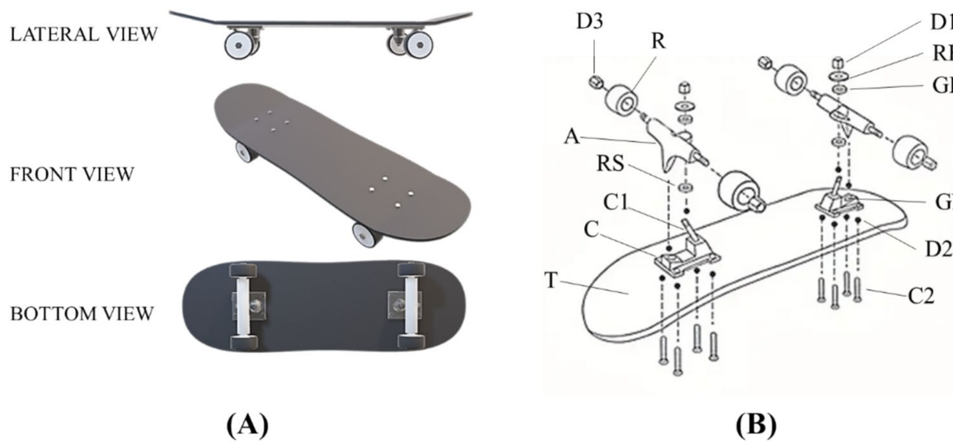

Fig. 3 Assembled product case study: skateboard. **A** The graphical representation shows different views of the fully assembled skateboard, including a lateral view, a front view, and a bottom view. **B** Exploded view of the skateboard assembly, highlighting individual components. Each part is labeled with a corresponding code, as referenced in Table 10

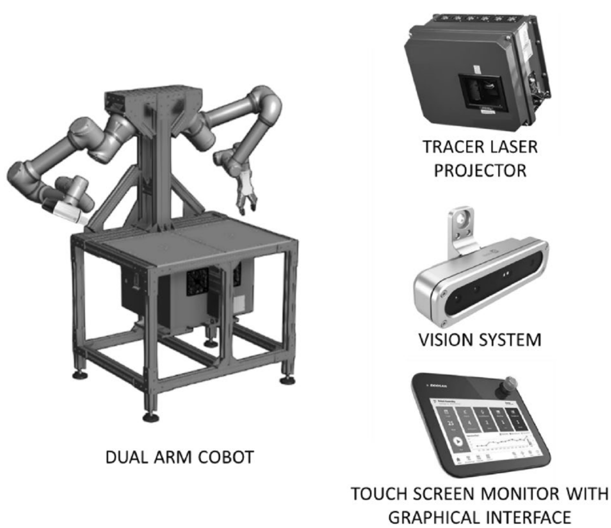

Fig. 4 Equipment of the collaborative assembly workstation considered in the case study: (i) dual arm cobot, (ii) tracer laser projector, (iii) vision system (iv) touch screen monitor with graphical interface

The main inputs of the methodology are the Bill of Material (B.O.M) (see Table 10) and a comprehensive ordered list of assembly tasks (see an extract in Table 11). The list of elementary tasks required to assemble the skateboard follows the taxonomy outlined in Sect. 4.2: *identification and handling*, *alignment*, *joining*, *checking*, and *adjustment*. A total of 107 elementary tasks were delineated, providing a first roadmap from individual components to the completed skateboard assembly.

5.1 Step 1: task categorization

Tasks were categorized accordingly to two criteria: the elementary task type and the characteristic of grippability of the components, i.e., whether a component can be effectively grasped by the cobot's grippers [12, 62]. Due to the limitations of the existing two-finger grippers in handling certain types of components, this feature was considered critical. In this specific application case, no other properties of components were considered relevant.

To ensure a comprehensive evaluation of grippability, components in the skateboard assembly process were analyzed against five key factors: size and thickness, weight, shape, stability, and sensitivity [12, 62]. Components failing to meet any one of these criteria were classified as 'ungrippable,' by the cobot.

Table 12 illustrates this classification, correlating the physical attributes of the skateboard components with their grippability status.

The combination of grippability properties with the elementary task types resulted in the identification of seven task categories in the skateboard assembly process: (i) *identification and handling tasks for grippable components*; (ii) *identification and handling tasks for ungrippable components*; (iii) *alignment tasks for grippable components*; (iv) *alignment tasks for ungrippable components*; (v*) joining tasks for ungrippable components*; (vi) *checking tasks for ungrippable components* and (vii) *adjustment tasks for ungrippable components*. Some elementary types of tasks are associated with both grippable and ungrippable components, reflecting their relevance to both types of parts. Other types of tasks are only associated with the ungrippable category.

5.2 Step 2: symbiotic task allocation

In the second step the goal is to assign the roles of leader or supporter to either the human operator or the collaborative system for each task category. This process uses the task allocation approach described in Sect. 4.3, where each task category is evaluated against six key symbiotic dimensions: *effort*, *speed*, *knowledge*, *decision-making*, *ergonomics*, and *safety* (see Table 5). Through this detailed evaluation, the development team aimed to identify the

Table 10 Bill of material of the skateboard product

Level	Code	Description	Quantity
1	B	Base plate	2
1	C1	Kingpin	2
1	RB	Top cup	2
1	GB	Bushing	2
1	RS	Lower cup	2
1	GS	Cone bushing	2
1	GN	Pivot bushing	2
1	A	Hanger	2
1	D1	Kingpin nut	2
1	C2	Deck bolt	8
1	D2	Deck nut	8
1	R	Wheel	4
1	D3	Axle nut	4
1	T	Skateboard deck	1
2	ST	Sub-assembled truck	2
3	CP	Complete product	1

Level indicates the hierarchy of each component within the product's structure. Code refers to the unique identifier assigned to each component. Description provides an explanation or name of each component. Quantitiy specifies the number of each component required in the product

Table 11 List of elementary tasks for the assembly of the skateboard product

Order	Component code	task TYPE	Component description
1	B	Identification and handling	Base plate
2	C1	Identification and handling	Kingpin
3	C1	Alignment	Kingpin
4	RB	Identification and handling	Top cup
5	RB	Alignment	Top cup
…	…	…	…
36	T	Identification and handling	Skateboard deck
37	ST	Identification and handling	Sub-assembled truck
38	ST	Alignment	Sub-assembled truck
39	C2	Identification and handling	Deck bolt
40	C2	Alignment	Deck bolt
…	…	…	…
102	R	Alignment	Wheel
103	D3	Identification and handling	Axle nut
104	D3	Joining	Axle nut
105	D3	Checking	Axle nut
106	D3	Adjustment	Axle nut
107	CP	Identification and handling	Complete product

Only an excerpt of the 107 elementary tasks required for skateboard assembly is reported

optimal leader or supporter for each category to enhance symbiotic interactions. The allocation approach involves systematically assessing each task category according to the symbiotic dimensions. For example, in the "Identification and Handling Grippable" task category, which involves identifying and moving components that are easy to grip, In this case: *Effort*: the collaborative system was designated as the leader for this dimension, as it can handle repetitive movements and heavy lifting more effectively, reducing the physical strain compared to a human operator; *Speed*: The human operator was chosen as the leader for speed, since it can perform these tasks often more rapidly than a the collaborative system; *Knowledge* and *Decision-Making*: the collaborative system was preferred due to its programmed precision and ability to follow standardized identification protocols, requiring minimal cognitive input for routine tasks; *Ergonomics* and *Safety*: The collaborative system takes the lead, as its handling capabilities minimize ergonomic risks and prevent injuries for the human operator.

Evaluations and the outcomes of this task allocation process are presented in Table 13. Notably, it was determined that the *'Identification and handling of Grippable'* components category was optimally led by the collaborative system. Conversely, for all other task categories, the human operator emerged as the preferable leader. The supporter role, in each case, complements the leader by assisting in task execution, ensuring that the collaboration is smooth, and the symbiotic potential is exploited. In the following section, practical detail will be provided to specify how the leader and supporter roles interact and execute their respective responsibilities across different task types.

5.3 Step 3: task protocol generation

This phase outlines the execution of tasks in the collaborative assembly process. Tables 7 and 8 were used to map the actions required for each task category, considering factors such as the collaborative system's capabilities, ergonomic needs, and process efficiency to enhance the leader's role and foster symbiotic exchange.

Table 12 Component classification based on grippability criteria

Code	Description	Grippability criteria					Component category
		Size and thickness	Weight	Shape	Stability	Sensitivity	
B	Base plate	Yes	Yes	Yes	Yes	Yes	Grippable
C1	Kingpin	Yes	Yes	No	Yes	Yes	Ungrippable
RB	Top cup	No	Yes	No	Yes	Yes	Ungrippable
GB	Bushing	Yes	Yes	Yes	Yes	Yes	Grippable
RS	Lower cup	No	Yes	No	Yes	Yes	Ungrippable
GS	Cone bushing	Yes	Yes	Yes	Yes	Yes	Grippable
GN	Pivot bushing	No	Yes	No	No	No	Ungrippable
A	Hanger	Yes	Yes	No	Yes	Yes	Ungrippable
D1	Kingpin nut	No	Yes	No	Yes	Yes	Ungrippable
C2	Deck bolt	No	Yes	No	Yes	Yes	Ungrippable
D2	Deck nut	No	Yes	No	Yes	Yes	Ungrippable
R	Wheel	Yes	Yes	Yes	Yes	Yes	Grippable
D3	Axle nut	No	Yes	No	Yes	Yes	Ungrippable
T	Skateboard deck	Yes	Yes	Yes	Yes	Yes	Grippable
ST	Sub-assembled truck	Yes	Yes	Yes	Yes	Yes	Grippable
CP	Complete product	Yes	Yes	Yes	Yes	Yes	Grippable

Code refers to the unique identifier for each component. Description provides an explanation or name of each component. Component category indicates the classification of the component into two categories: grippable and ungrippable. Yes and No refers to whether the grippability criteria as defined by Malik and Bilberg [12] are met

Table 13 Symbiotic Task allocation application

Task category	Symbiotic dimensions						Leader	Supporter
	Effort	Speed	Knowledge	Decision making	Ergonomics	Safety		
Identification and handling grippable	Collaborative system	Collaborative system	Collaborative system	N.A.	Collaborative system	Collaborative system	Collaborative system	Human
Identification and handling ungrippable	Human	Human	Collaborative system	N.A.	Equivalent	Equivalent	Human	Collaborative system
Alignment grippable	Human	Human	Human	Human	N.A.	N.A.	Human	Collaborative system
Alignment ungrippable	Human	Human	Human	Human	N.A.	N.A.	Human	Collaborative system
Joining ungrippable	Collaborative system	Collaborative system	Collaborative system	N.A.	Collaborative system	N.A.	Collaborative system	Human
Checking ungrippable	Human	Human	Human	Human	N.A.	N.A.	Human	Collaborative system
Adjustment ungrippable	Human	Human	Human	Human	N.A.	N.A.	Human	Collaborative system

Task category lists the task categories identified in the task categorization phase. Symbiotic dimensions refers to the criteria used for evaluating the potential for maximizing symbiotic exchanges, as outlined in Sect. 2. The columns Leader and Supporter indicate the assignments of agents to these two roles for each task category using the allocation approach outlined in Sect. 4.3. Regarding the evaluation of Symbiotic dimensions, the cells contain responses to the questions presented in Table 5

N.A. not applicable

Table 14 Results of the task protocol development for the skateboard case study

Task category	Allocation leader	Allocation supporter	Leader activity	Supportive activity
Identification and handling Grippable	Collaborative system	Human	The collaborative system identifies the component in the feeding area with the vision system and moves the component with the robotic arm 1	Handling prompting: the human operator tells the collaborative system when to proceed with component handling via a trigger on the interface screen Component pre-positioning: if the component is not in the optimal position, the human operator corrects the component's position
Identification and handling Ungrippable	Human	Collaborative system	The operator identifies and handles the component	Target component: the vision system identifies the position of the component and through the projector laser tracer, the collaborative system highlights the component to be handled by the human operator
Alignment grippable	Human	Collaborative system	The operator correctly positions the component	Subassembly pre-orientation: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment
Alignment ungrippable	Human	Collaborative system	The operator correctly positions the component	Secure holding: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment
Joining ungrippable	Collaborative system	Human	Using the robotic arm with the automatic screwdriver, the collaborative system performs the joining on the component.	Synchronized component joining: The human operator aids in stabilization of the components allowing the collaborative system to focus on securing the bolts Joining prompting: Human operator signals via gesture commands to the collaborative system on when to execute the joining task
Checking ungrippable	Human	Collaborative system	The operator checks the correct assembly of the component	Secure holding: the collaborative system with robotic arm 1 holds the workpiece in a fixed and comfortable position to perform assembly tasks Visual field optimization: the collaborative system illuminates through the projector the areas to be controlled Adaptive ergonomic product positioning: the collaborative system with robotic arm 1 moves the component so as to bring the areas to be checked closer to the operator Checking instructions: through the graphic interface the collaborative system shows the instructions on correct checking

Table 14 (continued)

Task category	Allocation leader	Allocation supporter	Leader activity	Supportive activity
Adjustment ungrippable	Human	Collaborative system	The operator adjusts the assembly of the component	Tool handover: the collaborative system with robotic arm 2 brings the tool required to perform the operation closer to the operator Secure holding: the collaborative system with robotic arm 1 holds the workpiece in a fixed and comfortable position to perform the adjustment tasks Adjustment instructions: through the graphic interface the collaborative system shows the instructions on correct adjustment

The basic activities in Tables 7 and 8 were tailored to match the specific capabilities of the collaborative system, translating the conceptual framework into practical, technology-specific actions. Table 14 provides a detailed breakdown of the activities assigned to the leader and supporter in each task category, offering a structured guide for the collaborative assembly process. Table 15 presents an excerpt of the complete task protocol for the skateboard assembly, showcasing the dynamic interaction between human and collaborative system roles across assembly stages.

In simplifying the task design, the complexity of 107 individual assembly tasks was reduced to just 7 homogeneous task categories, enabling focused design efforts. Solutions from these categories were then systematically applied to the original tasks, ensuring both efficiency and consistency throughout the assembly process.

During the implementation of the skateboard assembly case study, some practical challenges were encountered and addressed to ensure the effective application of the proposed methodology. One major challenge was the variability in component positioning within the feeding area, which affected the cobot's ability to accurately identify and handle components. This issue was mitigated by leveraging the high-resolution vision system capable of dynamically detecting and adjusting for positional discrepancies in real time.

Another challenge involved the grippability of certain components, such as small or irregularly shaped parts. These components posed difficulties for the two-finger gripper. To address this, the design team prioritized task allocation for these components to the human operator while leveraging the cobot's vision system and laser projector for precise guidance.

Lastly, ensuring seamless communication between the human operator and the cobot during collaborative tasks was a key consideration. Initial difficulties arose in synchronizing actions, particularly in tasks requiring real-time feedback, such as joining and adjustment tasks. This was resolved by introducing a graphical user interface (GUI) with intuitive controls and feedback mechanisms, allowing the operator to trigger or modify cobot actions effectively.

Table 15 Assembly task protocol

Order	Components code	Task category	Leader	Supporter	Leader activity	Supportive activity
1	B	Identification and handling Grippable	Collaborative system	Human	The collaborative system identifies and moves the component B with the robotic arm 1	Handling prompting: the human operator indicates to the collaborative system when to proceed with the handling of the component B via a trigger on the interface screen + Component pre-positioning: if the component is not in the optimal position, the human operator corrects the component's position
2	C1	Identification and handling Ungrippable	Human	Collaborative system	The operator identifies and handles the component C1	Target component: the vision system identifies the position of the component C1 and through the projector laser tracer, the collaborative system highlights the component C1 to be handled by the human operator
3	C1	Alignment Ungrippable	Human	Collaborative system	The operator correctly positions the component C1	Secure holding: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities + Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment of component C1
4	RB	Identification and handling Ungrippable	Human	Collaborative system	The operator identifies and handles the component RB	Target component: the vision system identifies the position of the component RB and through the projector laser tracer, the collaborative system highlights the component RB to be handled by the human operator
5	RB	Alignment Ungrippable	Human	Collaborative system	The operator correctly positions the component RB	Secure holding: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities + Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment
…	…	…	…	…	…	…
36	T	Identification and handling Grippable	Collaborative system	Human	The collaborative system identifies and moves the component T	Handling prompting: the human operator indicates to the collaborative system when to proceed with the handling of the component T via a trigger on the interface screen + Component pre-positioning: if the component is not in the optimal position, the human operator corrects the component's position

Table 15 (continued)

Order	Components code	Task category	Leader	Supporter	Leader activity	Supportive activity
37	ST	Identification and handling Grippable	Collaborative system	Human	The collaborative system identifies and moves the Sub-assembled truck	Handling prompting: the human operator indicates to the collaborative system when to proceed with the handling of the component ST via a trigger on the interface screen + Component pre-positioning: if the component is not in the optimal position, the human operator corrects the component's position
38	ST	Alignment Grippable	Human	Collaborative system	The operator correctly positions the Sub-assembled truck	Subassembly pre-orientation: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities + Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment
39	C2	Identification and handling Ungrippable	Human	Collaborative system	The operator identifies and handles the component C2	Target component: the vision system identifies the position of the component C2 and through the projector laser tracer, the collaborative system highlights the component C2 to be handled by the human operator
40	C2	Alignment Ungrippable	Human	Collaborative system	The operator correctly positions the component C2	Secure holding: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities + Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment
…	…	…	…	…	…	…
102	R	Alignment Grippable	Human	Collaborative system	The operator correctly positions the component R	Subassembly pre-orientation: the collaborative system with robotic arm 1 conveniently holds the part in a position to perform assembly activities + Alignment instructions: through the graphic interface the collaborative system shows instructions on correct alignment

Table 15 (continued)

Order	Components code	Task category	Leader	Supporter	Leader activity	Supportive activity
103	D3	Identification and handling Ungrippable	Human	Collaborative system	The operator identifies and handles the component D3	Target component: the vision system identifies the position of the component D3 and through the projector laser tracer, the collaborative system highlights the component D3 to be handled by the human operator
104	D3	Joining Ungrippable	Collaborative system	Human	Using the robotic arm with the automatic screwdriver, the collaborative system performs the joining of D3	Synchronized component joining: The human operator aids in stabilization of D3 allowing the collaborative system to focus on securing the bolts + Joining Prompting: Human operator signals via gesture commands to the collaborative system on when to execute the joining task
105	D3	Checking Ungrippable	Human	Collaborative system	The operator checks the correct assembly of the component D3	Secure holding: the collaborative system with robotic arm 2 holds the part in a fixed and comfortable position to perform assembly tasks + Visual field optimization: the collaborative system illuminates through the projector the areas to be controlled + Adaptive ergonomic product positioning: the collaborative system with robotic arm 1 moves the part so as to bring the areas to be checked closer to the operator. + Checking instructions: through the graphic interface the collaborative system shows the instructions on correct checking
106	D3	Adjustment Ungrippable	Human	Collaborative system	The operator adjusts the assembly of the component D3	Tool handover: the collaborative system with robotic arm 2 brings the tool required to perform the operation closer to the operator. + Secure holding: the collaborative system with robotic arm 1 holds the workpiece in a fixed and comfortable position to perform the adjustment tasks + Adjustment instructions: through the graphic interface the collaborative system shows the instructions on correct adjustment

Table 15 (continued)

Order	Components code	Task category	Leader	Supporter	Leader activity	Supportive activity
107	CP	Identification and handling Grippable	Collaborative system	Human	The collaborative system identifies and moves complete product CP with the robotic arm 1	Handling prompting: the human operator indicates to the collaborative system when to proceed with the handling of the final product CP via a trigger on the interface screen + Component prepositioning: if the component is not in the optimal position, the human operator corrects the component's position

Only an excerpt of the 107 elementary tasks required for assembly of the considered product has been reported

6 Conclusions

In conclusion, this study addressed the research question by proposing a novel methodology for enhancing collaborative assembly processes through the design of symbiotic tasks. The objective of this methodology is to facilitate positive symbiotic interactions between human operators and collaborative systems, leveraging their respective strengths to enhance efficiency, adaptability, and ergonomic outcomes. Unlike traditional methodologies that often emphasize efficiency and productivity, this framework aims to optimize the dynamic interplay between human operators and collaborative systems.

The methodology starts with the analysis of the activities involved in an assembly process, decomposing complex processes into task categories, which simplifies the problem domain and addresses the core questions of what actions are necessary to accomplish each task. Following this categorization, the process concerns the allocation of leader and supporter roles for each elementary task, with the aim of enhancing the symbiotic exchanges between partners. The third and final step involves the generation of the specific task protocol. This stage is where the behavior of the collaborative agents is outlined. For the design of the task protocol, a list of supportive activities impacting on specific components of Symbiotic human–robot Collaboration (SHRC) is proposed to guide the process.

The proposed approach suggests that improving collaboration involves more than just task allocation; it requires creating an environment where human operators and collaborative systems can mutually support and enhance each other's work. The methodology also focuses on elevating the well-being and ergonomic comfort of the human workforce, aligning with the principles of Human-Centric Manufacturing and Industry 5.0.

It is essential also to recognize the limitations of the proposed methodology. One key limitation lies in the specificity of the identified supportive activities, which are predominantly tailored to assembly processes. Although the methodology's core principles are flexible and could be extended to various manufacturing contexts, such adaptation would necessitate defining new supportive activities. Additionally, while the methodology offers a systematic framework, its effectiveness relies heavily on the precision of task categorization and capability assessments, which can vary depending on contextual factors. These constraints emphasize the need for refinement and highlight the critical role of user expertise and judgment in successfully implementing the methodology. Finally, the methodology is designed to improve symbiotic collaboration, its impact on other dimensions such as overall performance or cost-effectiveness has not been fully considered within this study.

In conclusion, future advancements in this methodology could be enhanced by integrating AI and machine learning to improve decision-making in symbiotic task design. Developing dynamic and adaptable task allocation models would enable the methodology to respond more effectively to real-time changes. Moreover, creating objective metrics to assess key symbiotic dimensions could reduce subjectivity and ensure more consistent application across varied settings. Expanding the methodology's applicability to diverse industrial contexts and compare the impact of the results with other existing approaches also represents a valuable avenue for research, increasing its overall relevance in real-world collaborative environments.

Appendix

See Tables 16 and 17.

Table 16 Detailed description of the support activities that the collaborative system can perform categorized by the different elementary type of task

Task type	Collaborative system supportive activity	Description
Identification & handling	Target component	The collaborative system shows the operator which component is to be assembled from the set of components present in the servicing area
	Real-time identification feedback	The collaborative system provides real-time feedback on the correctness of the component identified by the operator
	Sorting assistance	The collaborative system provides a systematic and continuous arrangement of parts based on specific attributes like size, type, or function. By reducing alternatives diminishes the likelihood of selection inaccuracies, thereby promoting process efficiency
	List of activity sharing	The collaborative system maintains a real-time, dynamic list outlining the sequence of components for identification and assembly. This list adapts to assembly progress and component availability, enhancing the operator's contextual knowledge and decision-making
	Component defects detection	The collaborative system scans and evaluates components to determine if they meet specified requirements, indicating any discrepancies to assist the human operator in decision-making
	Lifting assistance	The collaborative system provides mechanical assistance, such as a counterbalance or leverage aid, to help the operator lift heavy components
	Component pre-positioning	The collaborative system places the component in an optimal position and orientation for the operator to easily pick it up
	Posture monitoring	The collaborative system monitors the operator's posture during the handling task and provides feedback or adjustments. This aims to reduce long-term physical strain and the risk of injury by encouraging ergonomic practices
	Real-time handling feedback	The collaborative system continuously monitors the operator's actions during the handling process, focusing on whether the component has been gripped in the correct manner and whether it is following the correct trajectory
	Grip assistance	The collaborative system displays the most ergonomic and efficient point to grip the component. This minimizes physical strain and maximizes timeliness of the handling process
	Safety alerts	The collaborative system detects potentially unsafe handling practices by the operator, such as gripping at points that could lead to slippage or imbalance. Upon detecting such actions, the collaborative system issues immediate safety alerts
	Stress-driven handling scheduling	The collaborative system suggests an ideal work pace to the operator and dynamically adjusts it according to the operator's current workload
	Process-driven handling scheduling	The collaborative system assesses the current state of the process and the importance of pending tasks to suggest an optimal pace for task execution to the human operator
	Tool handover	The collaborative system provides the necessary tool to the human operator for component handling, facilitating tool identification and reducing the likelihood of errors
	Data logging	The collaborative system records handling-related data for future analysis and continuous improvement. This enables more informed decision-making and facilitates the fine-tuning of the process over time

Table 16 (continued)

Task type	Collaborative system supportive activity	Description
Alignment	Target component positioning	The collaborative system places the component onto its mounting position, requiring the human operator only to precisely align it for the subsequent joining phase
	Active alignment stabilization	The collaborative system holds the subassembly in a stable position, reducing operator effort and increasing the speed of alignment
	Subassembly pre-orientation	The collaborative system orients the sub-assembly in a manner that facilitates the identification of the mounting position and the correct alignment of the component by the operator
	Operator-optimized subassembly orientation	Upon receiving specific requests from the operator, the collaborative system dynamically adjusts the position and orientation of the subassembly to better suit the operator's needs for the alignment task
	Real-time alignment feedback (profile matching)	The collaborative system monitors the alignment process in real time and reports any errors in the procedure. This allows for immediate corrective action to be taken by the operator, enhancing the efficiency and quality of the process
	Alignment sequence sharing	The collaborative system provides the operator with a sequence of steps for optimal alignment. This action enhances the operator's understanding of the task at hand, thereby aiding in decision-making and improving the overall speed of the alignment process
	Stress-driven alignment scheduling	The collaborative system suggests an ideal work pace to the operator and dynamically adjusts it according to the operator's current workload
	Process-driven alignment scheduling	The collaborative system assesses the current state of the production line, including bottlenecks, delays, and inventory levels. Based on this information, it suggests an optimal work pace to the operator to meet process-driven needs
	Safety alerts	The collaborative system issues alerts if it detects that the operator is about to align the component in a manner that could be unsafe, such as aligning near sharp edges, hot surfaces, or electrical components
	Precision positioning	Involves the collaborative system fine-tuning the alignment after the human operator has completed the initial alignment
	Alignment instructions	The collaborative system provides step-by-step instructions to the operator for correctly executing the alignment
	Visual field optimization	The collaborative system provides accurate and targeted illumination within the work area, facilitating accurate identification and manipulation of components during assembly processes
Joining	Synchronized component joining	The collaborative system aids in stabilization and alignment and also takes part in the joining, while the operator focuses on complementary joining tasks
	Secure holding	The collaborative system maintains the sub-assembly stable during the fastening phase, reducing the effort required from the operator and favoring the timeliness of the task
	Subassembly pre-orientation	The collaborative system sets the sub-assembly's position and orientation to facilitate a more comfortable and efficient fastening process for the operator
	Operator-optimized subassembly orientation	Upon receiving specific requests from the operator, the collaborative system dynamically adjusts the position and orientation of the subassembly to better suit the operator's needs for the joining task
	Joining instructions	The collaborative system provides step-by-step instructions to the operator for correctly executing the fastening
	Real time joining feedback	The collaborative system monitors the progress of the fixing in real time, providing feedback to the operator on its accuracy. This allows for immediate corrective action to be taken by the operator, enhancing the efficiency and quality of the process

Table 16 (continued)

Task type	Collaborative system supportive activity	Description
	Ergonomic subassembly positioning	The collaborative system positions the subassembly to avoid awkward or uncomfortable assembly angles, bringing it to a level that is ergonomic for the operator
	Adaptive ergonomic subassembly positioning	The collaborative system dynamically adjusts the position of the sub-assembly based on the operator's physical stress levels, i.e. bringing it closer to the operator or lowering it
	Stress-driven joining scheduling	The collaborative system suggests an ideal work pace to the operator and dynamically adjusts it according to the operator's current workload
	Process-driven joining scheduling	The collaborative system assesses the current state of the production line, including bottlenecks, delays, and inventory levels. Based on this information, it suggests an optimal work pace to the operator to meet process-driven needs
	Safety alerts	The collaborative system continuously monitors the joining process and identifies if the operator is engaging in potentially hazardous actions or touching risky areas on the sub-assembly
	Tool handover	The collaborative system identifies and supplies the necessary joining tool to the human operator. By automating tool retrieval, it allows the operator to focus on critical aspects of the joining process, thus enhancing overall workflow efficiency
	Visual field optimization	The collaborative system adjusts the lighting conditions to provide the human operator with an optimal visual field for the joining task
	Data logging	The collaborative system records relevant data during the joining process, such as torque values, component positions, and time stamps. This data is made accessible to the human operator for future analysis and continuous improvement of the joining process
Checking	Human-error mitigation	The collaborative system continuously monitors the subassembly for quality compliance and provides immediate feedback to the operator if any nonconformities persist post-inspection
	Operator-optimized product orientation	Upon receiving specific requests from the operator, the collaborative system dynamically adjusts the position and orientation of the product to better suit the operator's needs for the inspection
	Inspection instructions	The collaborative system provides a step-by-step procedure for the operator to follow during the inspection process
	Safety alerts	The collaborative system actively monitors the assembly and the operator's actions during checking. This allows the operator to be alerted if he is approaching hazardous areas or if a defective assembly is detected that could potentially result in unsafe conditions
	Ergonomic product positioning	Based on the areas requiring inspection, the collaborative system autonomously adjusts the position of the product to ensure ergonomics
	Adaptive ergonomic product positioning	The collaborative system dynamically repositions the sub-assembly during the inspection process, taking into account the operator's physiological stress indicators. This may involve bringing the sub-assembly closer or adjusting its height to facilitate more comfortable and efficient inspection
	Stress-driven checking scheduling	The collaborative system suggests an ideal work pace to the operator and dynamically adjusts it according to the operator's current workload
	Process-driven checking scheduling	The collaborative system analyzes the current state of the assembly process to suggest an optimal schedule for checking tasks
	Defect tracking assistance	The collaborative system assists the human operator by systematically tracking defects detected during the inspection or assembly process and logging them in a dedicated system. This action enables informed adjustment decisions and defect management
	Visual field optimization	The collaborative system furnishes targeted lighting to assist the operator in inspecting areas that suffer from low visibility or inadequate illumination

Table 16 (continued)

Task type	Collaborative system supportive activity	Description
	Tool handover	The collaborative system supplies the operator with the necessary inspection tools and positions them conveniently. This action eliminates the need for the operator to search for or retrieve tools, thereby streamlining the inspection process and reducing effort
Adjustment	In-process validation	The collaborative system performs real-time validations during adjustments to confirm that all changes fall within specified tolerances
	Real-time adjustment guidance	The collaborative system supplies operators with real-time data concerning the state of the assembled component during the adjustment process. This targeted feedback improves decision-making, leading to a more accurate and efficient inspection process
	Operator-optimized product orientation	In response to specific directives from the operator, the collaborative system dynamically modifies the product position and orientation to streamline the adjustment process
	Adjustment instructions	The collaborative system delivers step-by-step guidance to the operator, outlining the appropriate torque and tolerances to be maintained during the adjustment process
	Safety alerts	The collaborative system monitors the operator's activities and the condition of the assembly during the adjustment. It provides immediate warnings if the operator is about to interact with defective, dangerously shaped or fragile components, reducing potential safety risks
	Ergonomic product positioning	The collaborative system autonomously reorients the component to enhance ergonomic accessibility for the operator during the adjustment process
	Adaptive ergonomic positioning	The collaborative system responsively changes the sub-assembly's orientation in real-time, based on the operator's physiological stress indicators. This optimization may involve bringing the sub-assembly nearer or altering its elevation to create a more ergonomic setting for adjustment activities
	Stress-driven adjustment scheduling	The collaborative system proposes a suitable work rhythm to the operator, making dynamic adjustments in response to the operator's ongoing workload
	Process-driven adjustment scheduling	The collaborative system evaluates the prevailing conditions of the assembly process to offer a well-timed schedule for adjustment activities
	Visual field optimization	The collaborative system adjusts the lighting conditions to provide the human operator with an optimal visual field during the adjustment
	Tool handover	The collaborative system provides the operator with essential tools for adjustment tasks and places them strategically for easy access. By eliminating the operator's need to locate and retrieve tools, the adjustment process becomes more efficient and less labor onerous

Table 17 Detailed description of the support activities that the human can perform categorized by the different elementary type of task

Task type	Human supportive activity	Description
Identification & Handling	Target component	The operator indicates to the collaborative system the specific component for assembly, thereby enhancing the collaborative system's accuracy in the identification stage and boosting the overall efficiency of the task
	Component feeding	The operator places the chosen component for assembly in a designated, consistent location. This action serves as a cue for the collaborative system, which is programmed to exclusively retrieve components from this designated area
	Component defects detection	The human operator scans and assesses components to verify if they conform to specified tolerances, alerting the collaborative system to any deviations that require further action or decision-making
	Component pre-positioning	The operator places the component in a specific orientation that aligns with the collaborative system's programmed picking mechanism
	Handling prompting	The act of signaling to the collaborative system on when to execute a handling task
	Balance assistance	During the component's movement, the operator assists the collaborative system by manually stabilizing the component to maintain its balance. This action minimizes the risk of component slippage or misalignment during transit, thereby enhancing the accuracy and safety of the handling process
	Gripping optimization	After the collaborative system secures an initial grip on the component, the operator conducts a rapid verification to assess its adequacy, minimizing the risk of component slippage or breakage
	Handling instructions	The operator provides cues or signals to the collaborative system to guide it in picking up and moving the component. By offering real-time guidance, the operator enhances the collaborative system's ability to handle components more efficiently and accurately
	Tool handover	Humans equip the collaborative system with the most suitable tool for handling the component involved in the assembly. By doing so, efficiency and flexibility of handling are maximized
	Data logging	Human operator records inefficiencies or non-conformities detected during the handling process. This data collection enables the future refinement of gripping procedures, or the redefinition of the gripping tools used by the robot
Alignment	Target component positioning	The human operator positions the component onto its mounting location, enabling the collaborative system to focus on precise alignment for the subsequent joining phase
	Subassembly pre-orientation	The operator ensures that the subassembly is positioned in a manner that facilitates the collaborative system's alignment task. This involves placing the subassembly in a stable and accessible location, so the collaborative system can easily align the component
	Active alignment stabilization	The operator holds the subassembly in a stable position, increasing the speed and precision of alignment
	Precision positioning	Following the collaborative system's initial alignment, the operator conducts a rapid review, adjusting enhance alignment precision. This step minimizes the requirement for subsequent corrections, thereby optimizing assembly process efficiency
	Alignment prompting	The act of signaling to the collaborative system on when to execute an alignment task
	Alignment instructions	The operator communicates to the collaborative system the precise position on the subassembly where the component should be positioned
	Manual alignment assistance	As the collaborative system proceeds with aligning the component onto the subassembly, the operator collaboratively ensures the alignment's accuracy and correctness. The human's role is to provide real-time adjustments and confirmations during the collaborative system's alignment process

Table 17 (continued)

Task type	Human supportive activity	Description
Joining	Synchronized component joining	The human operator and collaborative system work in tandem to join components. The human operator aids in stabilization and alignment while also participating in the actual joining tasks, allowing the collaborative system to focus on complementary aspects of the joining process
	Secure holding	The operator holds the subassembly or component in a stable position to facilitate the collaborative system's joining task
	Subassembly pre-orientation	The operator positions the subassembly in a predetermined orientation that aligns with the collaborative system's programmed task sequence. This ensures that the collaborative system can easily access and work on the subassembly
	Joining prompting	The act of signaling to the collaborative system on when to execute a joining task
	Joining instructions	The operator guides the collaborative system in the exact positioning of connectors and the specific procedures for completing the joining process. This dynamic interaction enables the collaborative system to adapt to various product configurations, with the operator's decision-making determining the appropriate methods and steps to follow
	Data logging	The human operator logs any inefficiencies or non-conformities encountered during the joining process. This data collection informs future refinements in the methods of component assembly, or the tools used for secure and accurate joining
	Tool handover	The operator replaces the collaborative system's current tool for one that is better suited to the shapes and sizes of the components to be joined. This ensures that the collaborative system is equipped with the most appropriate tool for the specific joining task at hand, enhancing collaborative system's adaptability to different component shapes
Checking	Collaborative system error mitigation	The human operator continuously monitors the product for quality compliance and provides immediate feedback to the collaborative system if any non-conformities are detected post-inspection
	Product orientation for inspection	The operator adjusts the orientation of the product to provide optimal access to the inspection areas, aligning it according to the collaborative system's needs
	Inspection instructions	The operator provides step-by-step guidance to the collaborative system during the inspection process, indicating which areas to examine in a specific order. This approach leverages the operator's expertise and problem-solving skills with the collaborative system's accuracy
	Checking prompting	The act of signaling to the collaborative system on when to start a checking task
	Defect tracking assistance	Human operator aids the collaborative system by systematically identifying and logging defects detected during the inspection into a dedicated system
	Tool handover	The operator mounts the necessary inspection tool on the collaborative system, enabling inspection
Adjustments	Product orientation for adjustment	The operator reorients the product to facilitate targeted adjustments, aligning it in accordance with the collaborative system needs
	In-process validation	The human operator conducts real-time validations during the collaborative system's adjustments to ensure all changes are within specified tolerances
	Adjustment instruction	The operator provides step-by-step guidance to the collaborative system during the adjustment process, indicating the appropriate torque or tolerances to be maintained
	Real-time adjustment guidance	The human operator provides the collaborative system with real-time data about the state of the assembled component during the adjustment process. This targeted input aids the collaborative system's decision-making, resulting in a more accurate and efficient adjustment process
	Adjustment prompting	The act of signaling to the collaborative system on when to start an adjustment task
	Tool handover	The operator affixes the requisite tool to the collaborative system, thereby enabling precise adjustment

Acknowledgements This publication is part of the project PNRR-NGEU which has received funding from the MUR – DM 352/2022.

Author contributions All authors provided an equal contribution to the drafting of the paper. All authors read and approved the final manuscript.

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement. This work has been partially supported by the European Union – NextGenerationEU (project PNRR-NGEU which has received funding from the MUR – DM 352/2022).

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The authors respect the Ethical Guidelines of the Journal.

Consent to participate Not applicable.

Consent for publication Not applicable.

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