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ORIGINAL ARTICLE

Redefining Human–Robot Symbiosis: a bio-inspired approach to collaborative assembly

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Abstract

The advent of collaborative robotics has enabled humans and robots to collaborate closely in carrying out manufacturing activities. Together, they can leverage their unique strengths and capabilities to tackle complex tasks. This partnership between humans and robots is often described as symbiotic in literature, but this concept is frequently oversimplified to a simple exchange of mutual benefits. In reality, symbiosis encompasses a wide range of interactions, some of which may be beneficial while others might be detrimental.

To effectively manage Human–Robot Symbiosis, it is important to understand its underlying principles. In this view, this paper has two main objectives: (i) to reinterpret collaborative tasks in assembly processes based on the characteristics of symbiotic relationships; and (ii) to propose a new approach for evaluating assembly tasks inspired by the bio-inspired features of collaborative human–robot systems.

Overall, the results of this study represent a step towards achieving a deeper understanding of the principles of Human–Robot Symbiosis, useful to develop effective solutions for enhancing collaboration between humans and robots in assembly processes.

Keywords Human–Robot Collaboration · Collaborative Robotics · Human-Robot Symbiosis · Assembly · Manufacturing

1 Introduction

Collaborative robotics, or cobotics for short, allows the collaboration between human operators and robots to accomplish a shared objective in manufacturing processes [1, 2]. Collaborative robotics stands in contrast to traditional robotics, where robots operate independently and without direct human input. In collaborative robotics, humans actively participate in the process alongside robots to achieve a shared goal. [3]. To permit this interaction, collaborative robots are designed with a range of sensors and control systems that allow them to adapt their behaviors to the presence of humans in their workspace [4]. This feature ensures that the robot operates safely and avoids causing harm to humans, while also improving the overall efficiency of the manufacturing process [2].

Several studies in the literature describe Human–Robot Symbiosis as a type of collaboration where humans and robots work together in a mutually beneficial relationship, leveraging their respective strengths to enhance the overall performance of the system [5]. It is crucial to recognize that, while the concept of symbiosis suggests a mutually beneficial relationship, it can also involve negative relationships where one or both parties are adversely affected. This applies to Human–Robot Symbiosis, where collaboration can lead to both positive and negative outcomes [6]. Therefore, it is important to have a deeper understanding of the dynamics involved in Human–Robot Symbiosis, in order to avoid potential negative effects and optimize the benefits.

The primary goal of this research paper is to introduce a new perspective on Human–Robot Collaboration that draws inspiration from the relationships found in natural ecosystems. This perspective aims to enhance our understanding of the concept of Human–Robot Symbiosis. The paper proposes a taxonomy of the potential symbiotic relationships between humans and robots and examines them in detail. Furthermore, the study identifies the elements of exchange,

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which are referred to as symbiotic factors, that play a significant role in shaping the relationship.

A practical evaluation method is introduced for understanding the nature of relationships established between human and robot in assembly operations. The evaluation method is designed to help identify areas of strength and weakness in existing collaborative processes and find opportunities for improvement.

The remainder of the paper is structured as follows. Section 2 reviews existing literature on the human–robot relationships. Section 3 introduces the novel bio-inspired taxonomy of relationships between humans and robots and related symbiotic factors. Section 4 puts the framework into practice by introducing a tool for evaluating and improving collaborative assembly tasks. Section 5 presents a case study, related to a real application. Finally, section 6 summarizes the contributions of the research, its limitations, and future research directions.

2 Human–robot relationship

The study of relationships is a multi-disciplinary field that encompasses psychology, sociology, and philosophy. At its core, social behavior is driven by a balance between the rewards and costs of involvement in a relationship [7]. Individuals engage in and maintain relationships based on their expectations of the rewards they will receive, and will disengage if the costs outweigh these expectations.

Classifying the multifaceted relationships between humans and robots in a shared work environment requires considering different functional characteristics [8], that can be summarized as follows:

- *Workspace sharing*: i.e., the physical area occupied by an individual or entity during the performance of its activities [5, 9, 10].
- *Direct Contact*: i.e., the possibility of physical interaction between humans and robots [10, 11]. Direct contact can be facilitated by the design of the process or the lack of physical barriers [9].
- *Goal sharing:* i.e., the existence of a shared objective between human and robot partners while performing tasks [12–14].
- *Simultaneous process:* i.e., the timing of activities performed by human and robot within a production process. The two agents may carry out their tasks either simultaneously or sequentially [5, 12, 15].
- *Resource sharing:* during the performance of tasks, particularly when operations are shared and simultaneous, human and robot partners may share physical resources, such as by assisting each other in pick and place activities, or cognitive resources, such as during decision-making processes [5, 12].
- *Autonomy:* i.e., the level of independence an agent has in determining the pace, mode, and timing of task execution [14]. During task performance, autonomy can be shared between humans and robots for each operation, allowing both to actively participate [5, 11, 16].
- *Adaptivity:* i.e., the capability to change own parameters without external intervention, thereby demonstrating the ability to be adaptable [17]. Humans possess the ability to autonomously alter their task parameters based on their perception of the environment, as they possess decision-making capabilities. Robots, on the other hand, often lack a perceptual and computational system capable of making dynamic adjustments to the way tasks are performed [5, 9, 10].

These dimensions (Table 1 columns) provide a framework for comprehending the interaction and collaboration between humans and robots in a shared work setting. To carry out a task efficiently, it's important to understand the specific needs and requirements of the task and environment and choose the appropriate features to implement. Based on literature and the functional characteristics described above, a summary of possible human–robot relationships is presented as follows:

- *Coexistence/Autarky:* refers to relationships in which human and robot performs different task with different work goals, but they share the physical space [5, 15].
- *Supervising:* in this type of relationship, the robot has limited autonomy and requires constant input and direction from the human operator [13, 14]. The tasks are performed simultaneously and towards the same goals, but the robot has limited independence, and adaptability is not a requirement [12, 18].
- *Cooperation:* refers to the coordinated effort between humans and robots to achieve a common goal, with each party working on a specific task or set of tasks [17]. In this sense, cooperation can be defined as a structured way of working together, where roles and responsibilities are clearly defined and there is a clear division of activities [19].
- *Supportive:* robots or humans can act in a supportive way, i.e. in a master–slave relationship [12, 14]. Despite the sharing of the objective, resources and workspace there is no autonomy in the decision of the task for the supporter [5, 10].
- *Collaboration:* refers to a process where robots and humans share tasks, information, and resources to achieve a common goal [12, 14, 20]. Operations are carried out simultaneously and in direct contact, the autonomy in carrying out operations is divided equally between the agents [5, 10].

Table 1 Human–robot relationships and related characteristics

		Human- Robot functional characteristics						
		Workspace sharing [5, 9, 10]	Direct Contact [5, 9, 11]	Goal sharing [5, 13, 14]	Simultaneous Process [5, 12, 15]	Resource sharing [5, 12]	Autonomy [10, 11, 14, 16]	Adaptivity [5, 9, 10, 17]
Huma- Robot relationships	Coexistence / Autarky [5, 15]				✓		✓	
	Supervising [12–14, 18]			✓	✓			
	Cooperation [17, 19]	✓		✓	✓		✓	
	Supportive [5, 10, 12, 14]	✓	✓	✓	✓	✓		
	Collaboration [5, 10, 12, 14, 20]	✓	✓	✓	✓	✓	✓	
	Symbiotic Collaboration [5, 10]	✓	✓	✓	✓	✓	✓	✓

- *Symbiotic Collaboration:* in this kind of relationship human and robot are mutually dependent on each other [10]. In this type of collaboration, the robot and human work together in a complementary way [5].

Table 1 provides a structured view of the functional characteristics associated to the various human-robot relationships. The table includes comprehensive references to prior studies, each contributing to a deeper understanding of the diverse types and characteristics of human-robot relationships.

2.1 Human–Robot Collaboration

Human–Robot Collaboration (HRC) is a field of research that focuses on the design and development of systems that enable humans and robots to work together [21]. The goal of HRC is to create systems that can augment human capabilities, improve productivity and safety, and enhance overall human well-being [22]. In industrial contexts, the need for collaborative robotic systems is driven by changing demand in the manufacturing sector, which is shifting from mass production to mass customisation, becoming more individualised and rapidly evolving [2]. In this new scenario, highly flexible production systems are required [3], including collaborative robotic systems. The main benefit of using collaborative robots is the ability to combine the advantages of automation with the flexibility and human skills such as problem solving and dexterity [17].

The literature proposes different interpretations of the concept of HRC taking into account the roles of agents and spatial separation [23]. According to Bauer et al. [20], HRC can be implemented using two methods: (i) individual and sequential actions by agents aimed at achieving a common goal, or (ii) with joint and simultaneous actions toward the same purpose. El Zaatari et al. [12] define as collaborative any process in which robot and human share the same workspace without fences and draw out four categories of possible interactions:

- *Independent*, operator and cobot operate on separate workpieces independently for their individual manufacturing processes;
- *Simultaneous,* operator and cobot operate on separate processes on the same work piece at the same time.
- *Sequential*, operator and cobot perform sequential manufacturing processes on the same work piece. There are time dependencies between the cobot and operator for their processes.
- *Supportive*, operator and cobot work towards the same process on the same work piece interactively. There is dependency between the actions of the cobot and the operator.

Segura et al. [14] defined three different work roles of the human operator in a collaborative process:

- *Supervisor*: the operator is responsible for setting the pace while the robot follows;

- *Peer*: in human and the robot mutually set and follow the pace during the task;
- *Subordinate:* the robot assumes the role of master and sets the pace.

3 Reinterpreting Human–Robot Symbiosis

The focus on Human–Robot Symbiosis in manufacturing processes has primarily been on the technological aspects, with little attention was given to the nature of the interaction. The question of what is being exchanged between humans and robots and how this interaction takes place remains largely unexplored.

The bio-inspired reinterpretation of this symbiotic relationship presented in the following sections aims to address this gap.

3.1 A taxonomy of human–robot symbiotic relationships

This section will provide a taxonomy of the different types of relationships that could exist between humans and robots. This framework may provide the basis for analyzing and designing symbiotic relationships in various applications.

The categorization of the potential symbiotic relationships between humans and robots can be achieved by using the same symbiotic relationships present in nature. In natural ecosystems, symbiotic relationships can be classified into six different typologies according to the type of mutual impact: *mutualism*, *commensalism* and *parasitism*, *amensalism*, *incompatibility* and *neutralism*.

Also in the context of Human–Robot Collaboration, the concept of symbiotic relationships can encompass a wide range of interactions ranging from those with positive impacts, where both the human and robot reap the benefits, to those with negative impacts where one or both parties experience drawbacks. Figure 1 outlines the framework of the possible human–robot symbiotic relationships.

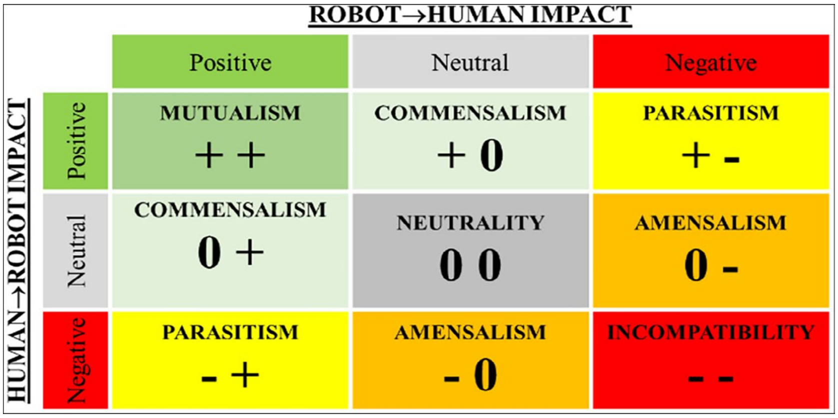
The following paragraphs include short descriptions and examples for each human–robot symbiotic relationship with a particular focus on assembly process.

Mutualism is a symbiotic relationship in which both the human and the robot benefit from the collaboration. This relationship occurs when the human and the robot work together to achieve a common goal, each bringing their strengths and abilities to the task. An example of human–robot mutualism could be an assembly process where the robot performs repetitive and physically demanding tasks, such as fastening bolts and screws, allowing the human worker to focus on tasks that require dexterity, critical thinking and problem-solving. The robot's precision and speed in completing the repetitive tasks increases the overall efficiency and productivity of the assembly process, while the human's cognitive skills enhance the quality control of the final product. In this exemplificative collaborative setting, both the human and the robot complement each other, leading to a mutually beneficial outcome.

Commensalism between humans and robots can be defined as a relationship in which one agent benefits while the other agent is neither helped nor harmed. For example, at the end of an assembly process, robot could be used to lift and move heavy finished products. On the one hand, this would benefit the human since the robot's work reduce the workload and risk of injury from moving heavy loads. On the other hand, the robot is not directly impacted negatively or positively by the human's presence.

It's important to consider that HRC can have many benefits, but it's crucial to also consider the potential negative impacts on human workers and process performances in order to mitigate them.

Parasitism is a symbiotic relationship in which one agent benefits at the expense of the other agent. An example of



HUMAN→ROBOT IMPACT	ROBOT→HUMAN IMPACT: Positive	ROBOT→HUMAN IMPACT: Neutral	ROBOT→HUMAN IMPACT: Negative
Positive	MUTUALISM + +	COMMENSALISM + 0	PARASITISM + -
Neutral	COMMENSALISM 0 +	NEUTRALITY 0 0	AMENSALISM 0 -
Negative	PARASITISM - +	AMENSALISM - 0	INCOMPATIBILITY - -

Fig. 1 Classification of symbiotic human–robot relationships. Legenda: "+" positive impact of the relationship. "0" neutral impact of the relationship. "-" negative impact of the relationship

human–robot parasitism in the assembly process could occur when the robot has to perform a task that a human worker can complete faster. This results in a negative impact from the robot's perspective as it slows down task completion, while the human worker benefits by saving physical effort.

Amensalism is a symbiotic relationship in which one agent has a negative effect on the other agent without any benefit to itself. An example of amensalism could be the use of robots that emit high levels of noise or vibrations. When the robot performs its tasks, the noise and vibrations it emits interferes with the human worker's ability to communicate and hear warning signals, leading to an increased risk of accidents. The human worker is negatively impacted by the robot's presence, while the robot don't have benefits by the presence of the human.

Incompatibility in HRC refers to a situation where human and robot are unable to work together effectively or safely. An example of human–robot incompatibility is during a robotized welding task where the robot poses a risk to the worker's safety by exposing them to the welding flame. Conversely, the presence of the human worker can also impede the movement and speed of the robot, reducing its efficiency in completing the task.

Finally, there may be situations where the mutual impacts are negligible. This is the case of the symbiotic relationship called *neutralism*. In this type of relationship, both the human and the robot coexist without impacting or affecting each other. This can occur when the human and the robot are working on different tasks or in different areas and do not interact with each other.

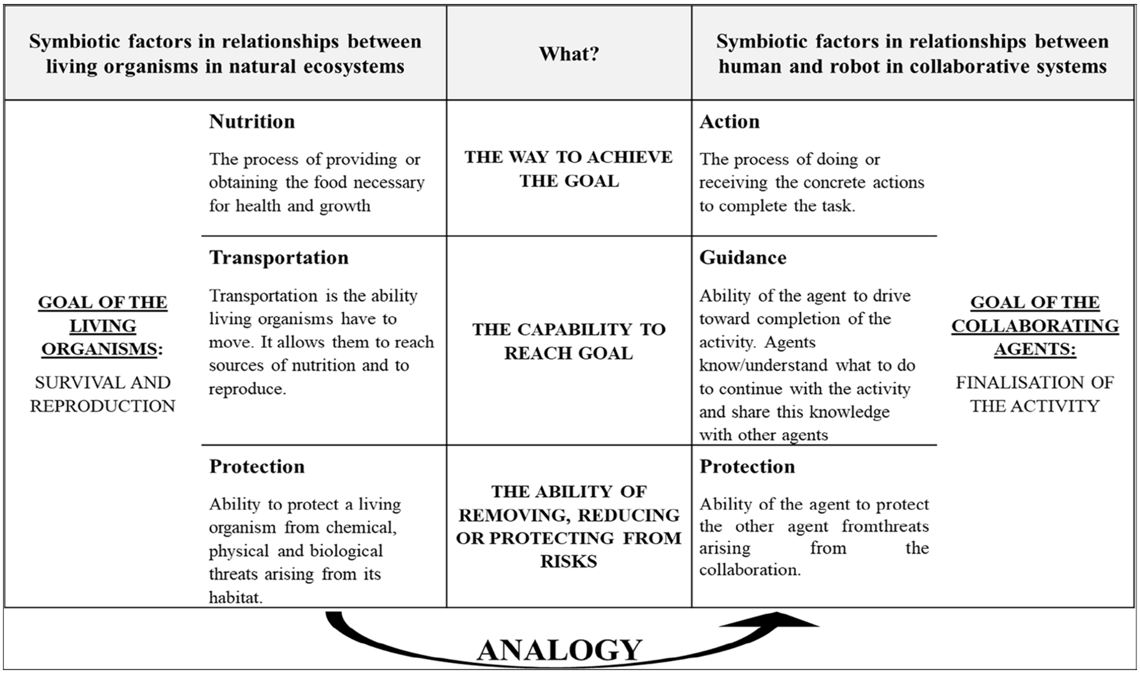
3.2 Symbiotic factors

Symbiotic relationships between living organisms are regulated by the exchange of elements, which literature identifies as symbiotic factors. To fully understand and optimize Human–Robot Symbiosis, it is necessary to recognize symbiotic factors exchanged between humans and robots and how they operate in the interaction**.**

In order to identify the symbiotic factors of Human–Robot Symbiosis, we took a two-step approach. Firstly, we examined natural symbiotic relationships as a starting point and then, through analogy, we identified the relevant symbiotic factors for HRC (see Fig. 2).

Living organisms typically exchange *nutrition*, *transportation* and *protection* [24]. To find an analogy between natural symbiotic factors and human–robot symbiotic factors, we initially defined the objectives of the two types of symbioses. The symbiosis between living organisms aims to allow the survival and reproduction of natural organisms. On the other hand, the goal of the symbiotic relationship between collaborative agents (humans and robots) is to complete a task or activity.

By analogy, and considering the objectives of the collaboration, we identified the symbiotic factors between humans



Symbiotic factors in relationships between living organisms in natural ecosystems		What?	Symbiotic factors in relationships between human and robot in collaborative systems	
GOAL OF THE LIVING ORGANISMS: SURVIVAL AND REPRODUCTION	**Nutrition** The process of providing or obtaining the food necessary for health and growth	**THE WAY TO ACHIEVE THE GOAL**	**Action** The process of doing or receiving the concrete actions to complete the task.	**GOAL OF THE COLLABORATING AGENTS:** FINALISATION OF THE ACTIVITY
	Transportation Transportation is the ability living organisms have to move. It allows them to reach sources of nutrition and to reproduce.	**THE CAPABILITY TO REACH GOAL**	**Guidance** Ability of the agent to drive toward completion of the activity. Agents know/understand what to do to continue with the activity and share this knowledge with other agents	
	Protection Ability to protect a living organism from chemical, physical and biological threats arising from its habitat.	**THE ABILITY OF REMOVING, REDUCING OR PROTECTING FROM RISKS**	**Protection** Ability of the agent to protect the other agent fromthreats arising from the collaboration.	

Fig. 2 Symbiotic factors in natural ecosystems and in collaborative systems

and robots as: *action*, *guidance* and *protection*. Figure 2 depicts the analogy process followed for the definition of the HRC symbiotic factors.

A key symbiotic factor in HRC is the *Action*. It refers to the process of doing or receiving the activities that are necessary to complete a task. It encompasses the physical actions of the agents, such as grasping, moving, and manipulating objects. One example of exchange of the action factor in Human–Robot Collaboration occurs when a robot, assisting a human operator in an assembly process, physically grasps and moves the parts into position, while the human operator is responsible for manipulating and tightening bolts and screws. Both agents exchange some actions to complete the task.

In collaborative tasks, it is common to see one agent providing instructions to the other on how to proceed. The symbiotic factor of *guidance* refers to the capability of the agent, whether human or robot, to lead the completion of the activity through understanding what needs to be done and how, and sharing that knowledge with the other agent. An example of exchange of guidance in HRC occurs when a robot is programmed to assist a human operator in assembly operations can identify and locate the necessary parts, direct the human operator in positioning them correctly, and help with the correct tightening of bolts and screws. The robot's direction enables the human operator to effectively complete the task by providing step-by-step instructions and real-time feedback.

The last human–robot symbiotic factor is referred to as *protection*. It pertains to the ability of an agent (human or robot) to safeguard the other agent from any threats that may arise from the collaboration. This can include physical hazards, such as collision or malfunction, as well as ergonomic and psychological risks, such as repetitive stress injuries. An example of protection in Human–Robot Symbiosis is a robot that is programmed to perform repetitive tasks, such as lifting heavy objects or performing repetitive motions, which can cause cognitive overload and physical stress on the human operator. By allowing the robot to take on these tasks, the human operator is protected from stresses, which can lead to increased productivity and reduced risk of injury.

3.3 Levels of analysis of assembly processes

The proposed bio-inspired framework could be particularly useful in analyzing collaborative assembly processes, offering a novel perspective on how humans and robots can work together in a symbiotic manner. This framework can be applied at two levels within assembly contexts (see Fig. 3).

The first possible application is at the *elementary task level*, where the symbiotic relationship between humans and robots can be examined in terms of a specific elementary task within an assembly process. This approach can be useful in designing and optimizing the collaboration between humans and robots for specific assembly tasks.

The second possible perspective of analysis is at the *process level*, where the symbiotic relationship can be examined in terms of the overall assembly process. This analysis can be useful for identifying potential technological advances in the assembly station and for defining better task allocation strategies.

In assembly processes, the proposed framework can be applied in two different scenarios: to design assembly processes that have yet to be implemented (ex-ante analysis), and to analyse and optimize existing human–robot collaborative processes (ex-post analysis).

In the *ex-ante analysis*, the framework helps to design a collaboration that maximizes the benefits for both humans and robots. This can result in a more efficient and effective assembly process, reducing the risk of inefficiency, errors and safety hazards.

In the *ex-post analysis*, it is possible to pinpoint areas that could benefit from improvement and to optimize the existing collaboration between humans and robots.

4 Evaluating Human–Robot Symbiosis

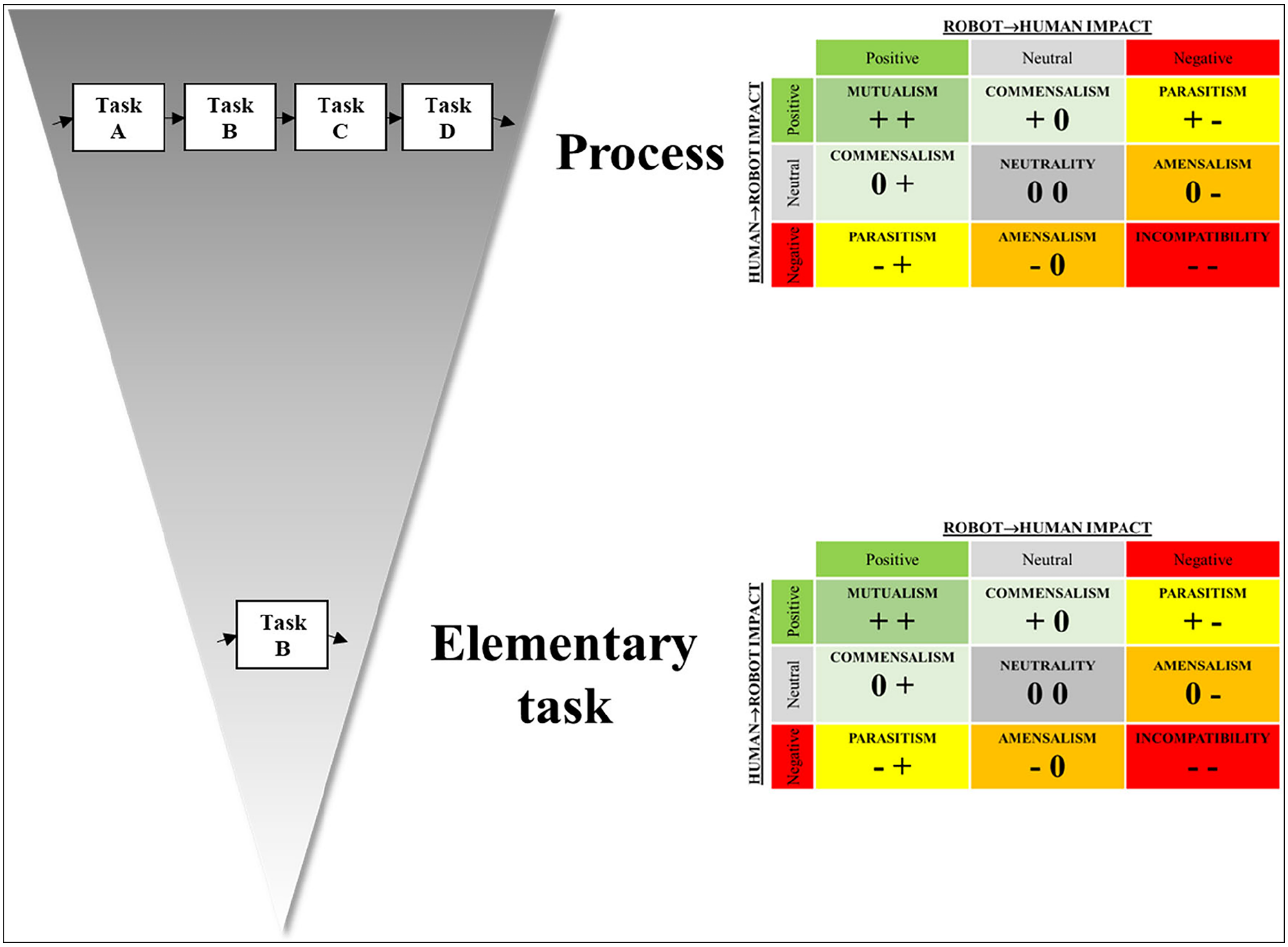
This section introduces an evaluation tool to characterise the nature of the relationship between humans and robots during collaborative assembly processes. The proposed approach is a first attempt to apply the proposed framework and specifically focuses on an ex-post analysis of existing collaborative processes. The output of the evaluation tool can help to identify areas where the collaboration between humans and robots can be optimized, leading to increased efficiency, safety, and productivity.

4.1 Symbiotic factor dimensions

The evaluation tool is designed to be easy to use for a team of experts that after observing a collaborative task, assigns ratings based on the symbiotic factors introduced in the previous sections. These factors (action, guidance and protection) are further detailed into specific dimensions to capture the distinguishing features of the symbiotic human–robot relationship.

In detail, the action factor is broken down into the dimensions:

- *Effort*: agents can provide the necessary effort to complete a task, or they can cause an increase in effort for the other agent.



ROBOT→HUMAN IMPACT

HUMAN→ROBOT IMPACT	Positive	Neutral	Negative
Positive	MUTUALISM + +	COMMENSALISM + 0	PARASITISM + -
Neutral	COMMENSALISM 0 +	NEUTRALITY 0 0	AMENSALISM 0 -
Negative	PARASITISM - +	AMENSALISM - 0	INCOMPATIBILITY - -

ROBOT→HUMAN IMPACT

HUMAN→ROBOT IMPACT	Positive	Neutral	Negative
Positive	MUTUALISM + +	COMMENSALISM + 0	PARASITISM + -
Neutral	COMMENSALISM 0 +	NEUTRALITY 0 0	AMENSALISM 0 -
Negative	PARASITISM - +	AMENSALISM - 0	INCOMPATIBILITY - -

Fig. 3 Levels of analysis of collaborative assembly processes

- *Speed*: agents can speed up or slow down the execution of an activity

The guidance factor is divided into two specific aspects:

- *Knowledge*: agents can know and share the sequence of activities to be completed.
- *Decision-making*: agents can use their decision-making ability to choose which task to perform and how to perform it.

The protection factor is decomposed into the dimensions:

- *Ergonomics*: the activity of one agent may affect the working conditions and ergonomics (physical and mental) of the other agent.
- *Safety*: agents can expose/protect the other agent from risks or threats

The evaluations focus on the individual elementary tasks of the assembly process. These tasks are the building blocks of the overall assembly process and therefore, it is important to assess the mutual impact of the agents on each dimension. The impact of the agents may be positive or negative depending on the specific task and the design of the collaborative system. The ratings are expressed on a five level ordinal scale. L1 represent a significant negative impact, L2 a slightly negative impact, L3 a neutral impact, L4 a slightly positive impact and L5 a significant positive impact. Appendix A details the rating scales for the six dimensions of analysis.

4.2 Relationship identification

The operational form in Fig. 4 supports the application of the proposed evaluation method. The central section of the form includes evaluations of the impacts that the robot has

Factor	Action		Guidance		Protection			
Dimension	Effort	Speed	Knowledge	Decision making	Ergonomics	Safety	Total impact	Symbiotic relationships
ROBOT→HUMAN								
HUMAN→ROBOT								

Fig. 4 Operational scheme for the Human–Robot Symbiosis evaluation approach

on the human and vice versa, in relation to the six dimensions of analysis. These evaluations are done separately, allowing for a thorough understanding of the effects of the Human–Robot Collaboration on each dimension. The right side of the form displays the total impacts and the type of symbiotic relationship established between human and robot at the elementary task level.

The composition of the evaluations of the six dimensions allows for an assessment of the impact of the relationship. In order to effectively evaluate the combined impact that an agent has on the other across the six dimensions, we propose the use the operator Ordered Weighted Average (OWA), firstly introduced by Yager and Filev [25, 26]. The OWA operator is described as follows:

$$OWA = Max_{k=1}^{n}\left(Min\left(Q(k), b_k\right)\right) \tag{1}$$

where:

- $Q(k) = L[f(k)] \quad (k = 1, \dots, n)$ is the average linguistic quantifier (the weights of the OWA operator), with $f(k) = Int\left(1 + \left(k\frac{t-1}{n}\right)\right)$
- $Int(a)$is a function that gives the integer closest to a.
- t is the number of scale levels (5 in our case).
- n is the number of aggregated dimensions (6 in our case).
- b_k is the k-th element of the sample previously ordered in decreasing order.

This operator is an emulator of the arithmetic mean which can take values only in the set of levels of the original ordinal scale, thus avoiding the problems of numerical codification of ordinal scale levels [27–30].

Accordingly, the total impact from an agent to the other can be calculated as follows:

$$TI = Max_{k=1}^{6}\left(Min\left(Q(k), PI_k\right)\right) \tag{2}$$

Being k the dimension of analysis and PI_k the evaluations on the k-th dimension.

As an illustrative example, consider a task where the partial impacts from the robot to the human operator, are that reported in Fig. 5.

Regarding the influence exerted by the robot on the human, the partial impact evaluations ordered in decreasing order (b_k) are {L5, L5, L4, L4, L3, L3}. The weights of the OWA operator $Q(k)$ are as follows: Q(1) = L2, Q(2) = L2, Q(3) = L3, Q(4) = L4, Q(5) = L4, Q(6) = L5. The following result is obtained, by implementing Eq. (2):

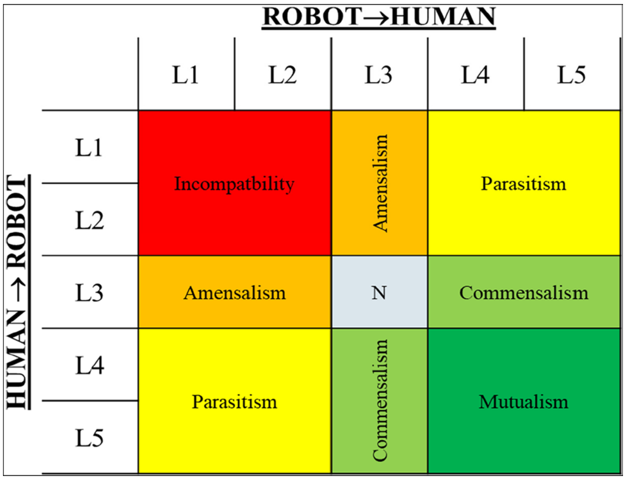
$$\begin{gathered} TI_{Robot\rightarrow Human} = Max(Min(L2, L5), Min(L2, L5), \\ Min(L3, L4), Min(L4, L4), Min(L4, L3), Min(L5, L3)) = L4 \end{gathered} \tag{3}$$

Thus, the total impact from the robot to the human is slightly positive and equal to L4.

Depending on the mutual impact, the relationship can be classified into the taxonomy outlined in Section 3.1. The map shown in Fig. 6, can be used to connect the mutual impact values with the different types of relationships. For the example in Fig. 5, the mutual impacts result in a parasitic relationship between agents.

Factor	Action		Guidance		Protection			
Dimension	Effort	Speed	Knowledge	Decision making	Ergonomics	Safety	Total impact	Symbiotic relationships
ROBOT→HUMAN	L5	L5	L3	L3	L4	L4	L4	Parassitism
HUMAN→ROBOT	L1	L1	L3	L3	L2	L2	L2	

Fig. 5 Example of application of the operational scheme for the evaluation of Human–Robot Symbiosis



ROBOT→HUMAN

HUMAN → ROBOT	L1	L2	L3	L4	L5
L1	Incompatbility		Amensalism	Parasitism	
L2					
L3	Amensalism		N	Commensalism	
L4	Parasitism		Commensalism	Mutualism	
L5					

Fig. 6 Relationship map. "N" refers to the relationship of neutralism

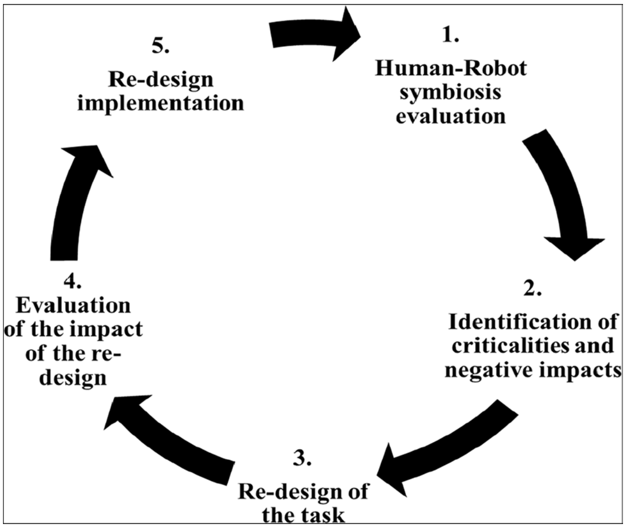


Fig. 7 Continuous improvement and collaborative task re-design

5 Continuous improvement and process re-design

The evaluation tool not only provides a method for assessing the nature of the symbiotic relationship between humans and robots but may also serves as a starting point for improving a collaborative assembly process. The tool is designed to provide a detailed analysis of the exchange of symbiotic factors between humans and robots at the elementary task level, which is particularly useful in identifying areas for improvement in existing processes.

Figure 7 reports a potential step-by-step approach to improving Human–Robot Symbiosis. This approach can be divided in five main steps:

1. *Human–Robot Symbiosis evaluation*: the first step consists of providing a detailed analysis of the exchange of symbiotic factors between humans and robots at the elementary task level. An effective way to evaluate the exchange of symbiotic factors between humans and robots is to use the tool presented in the previous section.
2. *Identification of criticalities and negative impacts*: the second step involves the identification of criticalities and negative impacts on the different symbiotic factors. This level of analysis can be particularly useful in identifying areas for improvement, as it allows for a more granular understanding of how the agents interact and how the collaboration can be optimized.
3. *Re-design of the tasks*: once the criticalities and negative impacts are identified, it is important to take steps to re-design the task in a way that mitigates these issues. This can involve modifying the task to better accommodate the strengths and weaknesses of both humans and robots, as well as implementing new technologies or tools to facilitate collaboration or reallocating tasks between agents.
4. *Evaluation of the impact of the re-design*: once the task has been re-designed, it is also important to consider the impact of these changes on the overall performance of the collaborative process. For example, while modifications may be effective in mitigating negative impacts on Human–Robot Symbiosis, they may also introduce new issues that need to be addressed. Therefore, it is crucial to carefully evaluate the impact of any proposed changes and to continuously monitor and refine the collaborative process to ensure that it is effective and efficient.
5. *Re-design implementation*: after the re-designed tasks are developed and re-evaluated, they can be implemented in the production process.

The iterative approach described in Fig. 7 can lead to improvements in the symbiotic relationship between humans and robots in assembly processes. By taking into account the symbiotic factors, humans and robots can work together more effectively, resulting in a more streamlined and efficient workflow. Additionally, this approach can lead to an improved working environment by reducing physical and mental strain on human operators, which can contribute to higher job satisfaction and better overall well-being.

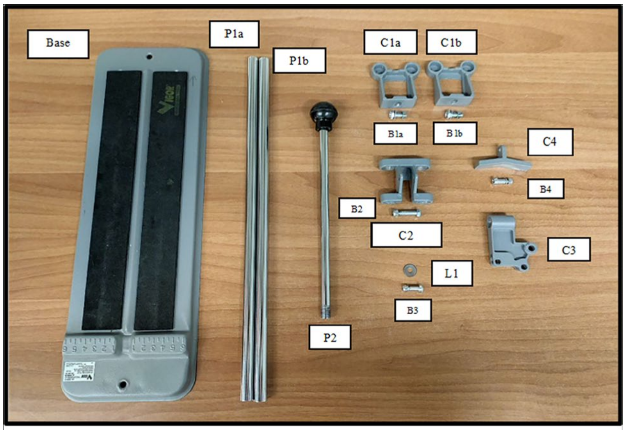
The case study presented in the following section will provide a practical example of the application of the proposed approach.

5.1 Case study

In order to show the practical application of the proposed approach, a case study was conducted focusing on the collaborative assembly process of a manual tile cutter, whose components are shown in Fig. 8. The assembly process involved a Universal Robots (UR3) cobot integrated into the process to increase efficiency, safety, and productivity. The assembly process was divided into 16 elementary tasks (see the first column in Fig. 9), and for each task, the impacts generated by the robot on the human and vice versa were evaluated in the 6 rating dimensions.

Evaluations were conducted on the occurrences of both positive and negative interactions between the human operator and the cobot across each task and every dimension, as detailed in Section 4.1.

The evaluation process involved formulating questions that investigated the interaction between humans and cobots. For example, considering the speed dimension, experts were asked about the mutual impact of human and cobot actions on each other's task completion time. Questions such as: "What effect do the cobot's actions have on the human's task execution speed?" and conversely, "What effect do the human's actions have on the cobot's task execution speed?" were directed to the experts. Answering these questions enabled a comprehensive evaluation of all tasks and interactions across all six analysis dimensions. Detailed rating scales for the six analysis dimensions are reported in Table 3 in Appendix A.



Identifier	Component
Base	Base plate of the tile cutter
C1a	Support for the rails of the tile cutter
C1b	Support for the rails of the tile cutter
B1a	Bolt for fixing the rail support to the base plate
B1b	Bolt for fixing the rail support to the base plate
C2	Joint component between the rails and the cutting mechanism
B2	Bolt for joining C2 with C3
C3	Component of the cutting mechanism
L1	Washer blade to cut the tile
B3	Bolt for joining the washer blade with C3
C4	Component to break the tile
B4	Bolt for joining C3 with C4
P1a	Rail rod of the tile cutter
P1b	Rail rod of the tile cutter
P2	Handle of the tile cutter

Fig. 8 Tile cutter components and fastener with their respective identifiers

Table 2 provides an example of the ratings and related considerations for one of the tasks (Task 5) in the assembly process of the manual tile cutter. In this task, the human operator performs the screwing actions while the cobot assists by securely holding the component in the correct position and displaying the precise area where the operation should be conducted.

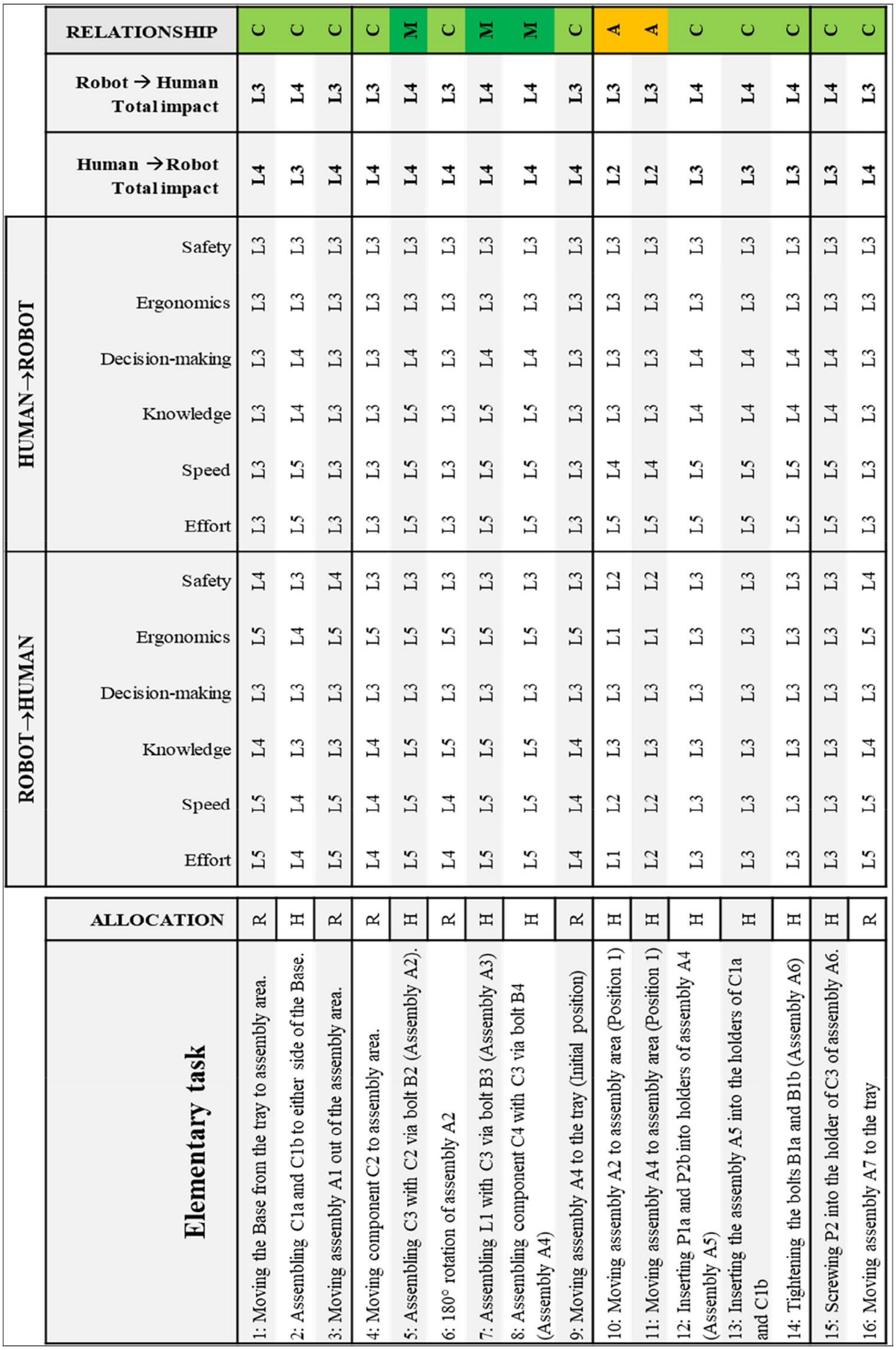
These evaluations were performed for all 16 elementary tasks in the assembly process, enabling a comprehensive analysis of the symbiotic relationship between the human and robot at the elementary task level. The resulting ratings were then processed by the OWA operator to identify the type of symbiotic relationship established between the human and robot. The aggregated impact values and comprehensive ratings for all the elementary tasks are presented in Fig. 9 (see the last columns).

In the presented case study, the symbiotic relationship between the human operator and cobot was analyzed across the various elementary tasks, and positive outcomes were reported in most of them. The predominant relationship type was commensalism, which emerged due to the rigid programming of these tasks. In commensalism, the principal task executor plays an active role and positively influences the counterpart, while the supportive agent entails passive activities that do not exert significant influence on the counterpart.

However, the evaluations conducted in the case study revealed that elementary tasks 10 and 11 had a critical negative impact on symbiosis, resulting in an amensalistic relationship. This emphasized the need for a redesign to overcome the negative impacts identified during the evaluation process. These two tasks involved pick and place activities, and were both assigned to the human operator. The evaluations were negative in the dimensions of practice and protection, since these tasks had limited dexterity requirements and could be performed relatively easily by the cobot, thereby relieving the operator of simple but physically demanding tasks due to the weight of the components.

Following the process outlined in Section 5, the re-design process involved reallocating the tasks to the cobot, freeing the operator from the physically demanding tasks. After the re-design, the two tasks were re-evaluated, and the results showed improvements in the symbiotic relationship between the human and the cobot (see Fig. 10). The evaluation of the impact of the redesign showed an improvement in the overall efficiency of the assembly process, in addition to the positive impact on the symbiotic relationship between the human operator and the cobot. The

Fig. 9 Scheme of the application of the proposed evaluation method. Allocation: H = Human, R = Robot. Relationships: N = neutralism, M = Mutualism, A = Amensalism, C = Commensalism

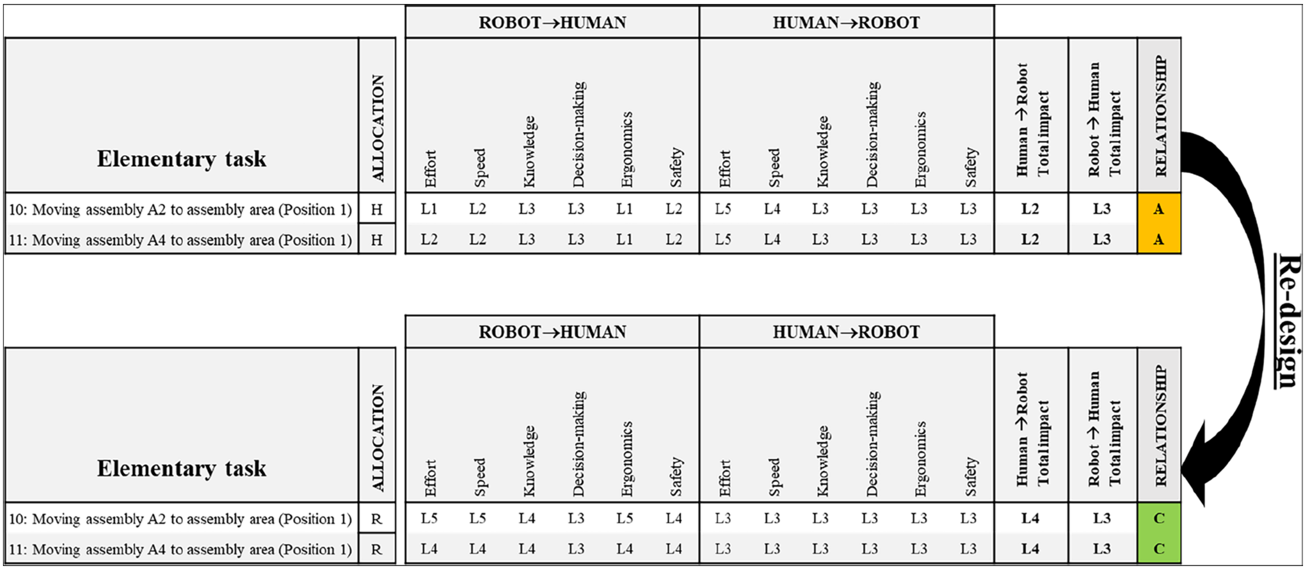


Elementary task	ALLOCATION	ROBOT→HUMAN						HUMAN→ROBOT								
		Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	**Human → Robot Total impact**	**Robot → Human Total impact**	**RELATIONSHIP**
1: Moving the Base from the tray to assembly area.	R	L5	L5	L4	L3	L5	L4	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C
2: Assembling C1a and C1b to either side of the Base.	H	L4	L4	L3	L3	L4	L3	L5	L5	L4	L4	L3	L3	**L3**	**L4**	C
3: Moving assembly A1 out of the assembly area.	R	L5	L5	L3	L3	L5	L4	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C
4: Moving component C2 to assembly area.	R	L4	L4	L4	L3	L5	L3	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C
5: Assembling C3 with C2 via bolt B2 (Assembly A2).	H	L5	L5	L5	L3	L5	L3	L5	L5	L5	L4	L3	L3	**L4**	**L4**	M
6: 180° rotation of assembly A2	R	L4	L4	L5	L3	L5	L3	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C
7: Assembling L1 with C3 via bolt B3 (Assembly A3)	H	L5	L5	L5	L3	L5	L3	L5	L5	L5	L4	L3	L3	**L4**	**L4**	M
8: Assembling component C4 with C3 via bolt B4 (Assembly A4)	H	L5	L5	L5	L3	L5	L3	L5	L5	L5	L4	L3	L3	**L4**	**L4**	M
9: Moving assembly A4 to the tray (Initial position)	R	L4	L4	L4	L3	L5	L3	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C
10: Moving assembly A2 to assembly area (Position 1)	H	L1	L2	L3	L3	L1	L2	L5	L4	L3	L3	L3	L3	**L2**	**L3**	A
11: Moving assembly A4 to assembly area (Position 1)	H	L2	L2	L3	L3	L1	L2	L5	L4	L3	L3	L3	L3	**L2**	**L3**	A
12: Inserting P1a and P2b into holders of assembly A4 (Assembly A5)	H	L3	L3	L3	L3	L3	L3	L5	L5	L4	L4	L3	L3	**L3**	**L4**	C
13: Inserting the assembly A5 into the holders of C1a and C1b	H	L3	L3	L3	L3	L3	L3	L5	L5	L4	L4	L3	L3	**L3**	**L4**	C
14: Tightening the bolts B1a and B1b (Assembly A6)	H	L3	L3	L3	L3	L3	L3	L5	L5	L4	L4	L3	L3	**L3**	**L4**	C
15: Screwing P2 into the holder of C3 of assembly A6.	H	L3	L3	L3	L3	L3	L3	L5	L5	L4	L4	L3	L3	**L3**	**L4**	C
16: Moving assembly A7 to the tray	R	L5	L5	L4	L3	L5	L4	L3	L3	L3	L3	L3	L3	**L4**	**L3**	C

reallocation of elementary tasks 10 and 11 from the human to the cobot resulted in a decrease in the average process duration, improving the celerity of the process. Moreover, the enhancement of ergonomics and safety reduced the physical and mental stress on the operator, potentially leading to increased productivity and improved production quality.

Table 2 Analysis of the Human–Robot Symbiosis for the elementary task 5

		Robot → Human	Human → Robot
Action	Effort	Expert evaluation: L5 The cobot orientates the mounting location to a more comfortable position, thereby reducing the required physical effort	Expert evaluation: L5 The human carries out the screwing task that the robot cannot accomplish due to the complicated shape of component (C2)
	Speed	Expert evaluation: L5 The cobot orients the mounting location to a more comfortable position, thereby increasing the screwing speed	Expert evaluation: L5 The human carries out the task of screwing at a faster speed than the cobot could
Guidance	Knowledge	Expert evaluation: L5 The cobot guides the assembly process by orienting the part and indicating its proper placement, thereby reducing ambiguity in part placement	Expert evaluation: L5 The human performing the task has a guiding role towards the cobot
	Decision Making	Expert evaluation: L3 The agents are not involved in making decisions	Expert evaluation: L4 The operator identifies the correct mounting position and orientation of the C3 component
Protection	Ergonomics	Expert evaluation: L5 The cobot orientates the mounting location to a more ergonomic position, improving comfort for the human	Expert evaluation: L3 The human does not negatively impact the wear on the robot's joints or end effectors during task execution
	Safety	Expert evaluation: L3 The task did not present any significant risks to the human and the cobot did not have any negative impact on safety	Expert evaluation: L3 The human does not interfere with the functioning of the robot's components during task execution



		ROBOT→HUMAN						HUMAN→ROBOT								
Elementary task	ALLOCATION	Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	Human → Robot Total impact	Robot → Human Total impact	RELATIONSHIP
10: Moving assembly A2 to assembly area (Position 1)	H	L1	L2	L3	L3	L1	L2	L5	L4	L3	L3	L3	L3	**L2**	**L3**	**A**
11: Moving assembly A4 to assembly area (Position 1)	H	L2	L2	L3	L3	L1	L2	L5	L4	L3	L3	L3	L3	**L2**	**L3**	**A**

		ROBOT→HUMAN						HUMAN→ROBOT								
Elementary task	ALLOCATION	Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	Effort	Speed	Knowledge	Decision-making	Ergonomics	Safety	Human → Robot Total impact	Robot → Human Total impact	RELATIONSHIP
10: Moving assembly A2 to assembly area (Position 1)	R	L5	L5	L4	L3	L5	L4	L3	L3	L3	L3	L3	L3	**L4**	**L3**	**C**
11: Moving assembly A4 to assembly area (Position 1)	R	L4	L4	L4	L3	L4	L4	L3	L3	L3	L3	L3	L3	**L4**	**L3**	**C**

Fig. 10 Evaluation of the elementary activities 10 and 11 before and after the re-design. Allocation: H = Human, R = Robot. Relationships: N = neutralism, A = Amensalism

6 Discussion and conclusions

As robotics continues to advance, it is becoming crucial to develop a more profound comprehension of the nature of Human–Robot Collaboration to ensure the successful implementation of collaborative systems.

In this view, this paper proposed a novel view on Human–Robot Collaboration, based on the concept of *symbiotic relationships*. With the aim of characterizing this relationship in more detail, we proposed a bio-inspired taxonomy of symbiotic relationships between humans and robots. In detail, depending on the type of impact (negative, neutral, or positive) generated by the robot on the human and vice versa, it is possible to identify six different types of relationships: *mutualism*, *commensalism*, *neutralism*, *parasitism*, *amensalism*, and *incompatibility*. These kinds of relationships provide a comprehensive explanation of the possible symbiotic interactions between the human and the robot.

To fully understand and optimize Human-Robot Symbiosis, it was crucial to identify and analyze what humans and robots can exchange during the execution of a task, namely the symbiotic factors. Drawing again on bio-inspired concepts, symbiotic factors of the Human–Robot Symbiosis have been identified. These factors can be grouped into three main categories: *action*, *guidance*, and *protection*.

This new perspective could serve as a novel basis for designing, evaluating, and enhancing human–robot collaborative systems.

To offer a practical application of this new perspective, an evaluation method has been developed to identify the nature of relationships between humans and robots, as well as potential areas for improvement in Human–Robot Collaboration.

While the proposed framework for analyzing Human–Robot Collaboration provides a comprehensive understanding of the different types of relationships between humans and robots, it also presents some limitations. The first, is that it only considers the direct interactions between humans and robots and does not take into account the broader environmental and organizational context in which the collaboration takes place. A second limitation is related to the evaluation tool developed in the study. While it is useful for identifying the relationships between humans and robots, it provides a static representation of the mutual impacts between human and cobot. It does not take into account the possible evolution of the impact and of the relationships over time. As an example, the creation of stable a relationship between two agents can lead to the loss of skills and know-how over time, which the proposed framework does not take into account. In addition, while human–robot interactions span several domains, this approach focuses on collaborative assembly processes. As part of this analysis, assessing different dimensions of impact can be very time-consuming, especially for assembly sequences involving numerous tasks. However, the methodology ensures a thorough understanding of each task and the role of human and robotic agents within it. Taken together, these limitations provide new opportunities for further research and refinement of the evaluation process.

Moving forward, future research could explore the development of a design tool based on the proposed perspective to optimize Human–Robot Collaboration already in the design phase. Such a tool could not only enhance the productivity and efficiency of the collaboration but also improve the overall experience of humans working with robots.

Finally, it should be remarked that this study only represents a first step towards the interpretation of symbiotic relationships between humans and robots. Further research is needed to better validate the proposed model and its practical applications.

Appendix A

Table 3 presents the rating scales for the six analysis dimensions. For the Effort dimension, different evaluation scales have been formulated to assess the impact on both the robot and the human, as the concept of effort must be approached differently for these two agents. While the robot's effort is mainly related to its computational load and physical capabilities, the human's effort encompasses a broader range of factors, including cognitive and physical aspects, workload, and stress.

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Table 3 Rating scale for the six dimensions of analysis of Human–Robot Symbiosis

Scale level	Action			Guidance		Protection	
	Effort		Speed	Knowledge	Decision-making	Ergonomics	Safety
	ROBOT →HUMAN	HUMAN →ROBOT					
L1	The robot has a significantly negative impact on the human effort required to complete the task, or it does not execute actions that could significantly reduce the effort of the human operator	The human has a significantly negative impact on the amount of actions that the robot has to perform	The agent has a significant negative impact on the speed of completing the task	The agent's actions significantly contribute to errors in completing the task	The agent utilizes a flawed decision-making process that results in errors	The agent significantly worsens the working conditions of the other agent	The agent exposes the other agent to significant risk or threats
L2	The robot has a slightly negative impact on the human effort required to complete the task, or it does not execute actions that could partially reduce the effort of the human operator	The human has a slightly negative impact on the amount of actions that the robot has to perform	The agent has a slightly negative impact on the speed of completing the task	The agent's actions potentially contribute to errors in completing the task	The agent employs a decision-making process that may lead to errors	The agent partially worsens the working conditions of the other agent	The agent exposes the other agent to minor risk or threats
L3	The robot has a neutral impact on the human effort required to complete the task	The human has a neutral negative impact on the amount of actions that the robot has to perform	The agent has a neutral negative impact on the speed of completing the task	The agent's actions do not provide any information on how to complete the task	The agent does not carry out a decision-making process	The agent does not influence the working conditions of the other agent	The agent does not influence the other agent's exposure to risks or threats
L4	The robot has a slightly positive impact on the human effort required to complete the task	The human has a slightly positive impact on the amount of actions that the robot has to perform	The agent has a slightly positive impact on the speed of completing the task	The agent's actions partially helpful information on how to complete a task	The agent applies a potentially helpful decision-making process	The agent partially improves the working conditions of the other agent	The agent protects the other agent from minor risk or threats
L5	The robot has a significant positive impact on the human effort required to complete the task	The human has a significant positive impact on the amount of actions that the robot has to perform the robot has to perform	The agent has a significant positive impact on the speed of completing the task	The agent's actions provide helpful information on how to complete a task	The agent applies a successful and helpful decision-making process	The agent significantly improves the working conditions of the other agent	The agent protects the other agent from significant risk or threats

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