Continuous Quality Improvement in Human–Robot Collaboration: A Quality 4.0 Methodological Approach

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Abstract

Human-robot collaboration (HRC) is increasingly prevalent across various industries, necessitating an in-depth exploration of the factors that enhance its quality. Evaluating HRC is not trivial, as it involves several disciplines, including engineering, computer science, and social sciences. A major problem in the literature is to find a comprehensive framework that can support the continuous enhancement of HRC. High-quality HRC requires a balanced integration of technological advancements and human-centered design principles. This chapter provides a methodology to support the implementation of continuous quality improvement strategy in HRC by including a previously presented HRC evaluation framework. This methodology is applied to a case study to better illustrates how it works and its advantages. The proposed methodology can provide insights to practitioners, supporting the analysis and implementation of HRC, as well as highlighting the areas for improvement.

Keywords: Human-robot collaboration, Industry 5.0, Quality 4.0, Manufacturing, HRC quality.

1. Introduction

In the era of Industry 5.0, characterized by the integration of cyber-physical systems, the Internet of Things (IoT), and advanced robotics, the landscape of various sectors is undergoing a profound transformation. From manufacturing and healthcare to service industries and domestic applications, Human-Robot Collaboration (HRC) has become a focal point of innovation and research. HRC is a novel interaction paradigm in which humans and robots work together to reach a common goal by combining their abilities (ISO/TS 15066:2016, 2016). This paradigm requires the implementation of robotic systems designed to work with humans, which are called collaborative robots (or cobots). The potential benefits of HRC includes enhanced productivity, improved safety, and the ability to perform complex or hazardous tasks that would be challenging for humans alone (Vicentini, 2020).

Despite the promising advantages, the success of HRC depends largely on the quality of interaction between humans and robots. High-quality collaboration involves mutual understanding, effective communication, mutual trust, coordination, and adaptivity (Gervasi et al., 2020). Achieving such quality in HRC is not trivial; it requires a multifaceted approach that considers technological, human, and environmental factors. Poorly designed interactions can lead to inefficiencies, safety hazards, and decreased user satisfaction, undermining the potential benefits of HRC.

This chapter aims to provide a comprehensive overview of the factors influencing the quality of HRC based on literature analysis. In a previous work, Gervasi et al. (2020) proposed a conceptual framework to evaluate HRC scenarios, based on several factors to provide a holistic view of the HRC problem. By examining these factors, key determinants that contribute to successful collaboration can be identified to provide guidance to practitioners for effectively evaluating and improving HRC. Therefore, the main objectives can be summarized as follows: (i) emphasizing the need for a comprehensive view in the design and analysis of HRC; (ii) showing the use of the HRC conceptual framework to evaluate and improve HRC quality in a DMAIC cycle.

The chapter is structured as follows. Section 2 provides an overview of the literature concerning HRC and its connections with Quality 4.0. Section 3 illustrates and describes the HRC evaluation framework proposed by Gervasi et al. (2020). Section 4 presents the methodology that combines the evaluative HRC framework with the DMAIC cycle to continuously improve quality in HRC processes. An application case study follows to better illustrate the implementation of the proposed methodology. Finally, discussion and conclusions are presented in Section 5.

2. Human-robot collaboration

HRC can be considered a subfield of Human-Robot Interaction (HRI), which generally studies the various interactions that can occur between robotic systems and humans, as well as the characteristics and aspects related to the robotic system (Goodrich and Schultz, 2007). In HRC, the focus is on *collaboration*, which is a type of interaction in which robots and humans work together to achieve a common goal through a coordinated effort that includes mutual engagement and accommodating other's needs (Gervasi et al., 2020). The robots involved in HRC are called collaborative robots (or cobots) which, unlike classical industrial robots, have safety features that allow physical interaction with the operator (ISO/TS 15066, 2016). Cobots find application in various industries and in different types of tasks, e.g., pick&place, assembly, joining, painting, and polishing.

Human safety has always been one of the main issues addressed in the HRC. Especially in the beginning, research focused on the development of sensor systems and policies that would avoid or minimize collisions between humans and cobots (Vicentini, 2020). In an effort to promote seamless interaction, several research works have been concerned with studying and developing intuitive methods of programming and instructing cobots (Wang et al., 2019). Programming by Demonstration (PbD) is one of the most common automatic programming methods, in which humans instruct the cobot by guiding it in the sequence of operations to be reproduced (Argall et al., 2009). In this context, it also becomes important to explore communication methods, beyond classical control panels, that are natural and effective for interacting with cobots. Several studies have tested the integration of natural means of communication, such as gestures and voice (Argall et al., 2009).

In recent years, special attention has also been given to user-experience, psychological and social aspects involved in HRC (Gervasi et al., 2023a). The in-depth study of the human aspects proves to be crucial in order to take full advantage of HRC and obtain its benefits, both in terms of process performance and worker well-being (Gervasi et al., 2023b). For example, some studies have focused on analyzing mental effort in HRC (Arai et al., 2010; Gervasi et al., 2022a), trust toward the cobot (Charalambous et al., 2016), and social dynamics within a factory (Charalambous et al., 2015; Sauppé and Mutlu, 2015).

In the context of Quality 4.0, the development and implementation of evaluation tools to monitor HRC processes are critical. However, quality in HRC processes is not only determined by traditional performance indices, such as efficiency and effectiveness, but, as the literature reveals, is also influenced by factors related to human aspects which can be challenging to measure. In exploring the improvement of HRC, Wang et al. (2019) highlighted the importance of psychological factors in increasing the efficiency of a human-robot team, such as acceptance, trust, social dynamics, and the emotional processes involved. Kopp et al. (2021) outlined success factors to be considered during HRC implementation, showing the importance of both human and corporate environment aspects as well, such as how operators view cobots, mental stress reduction, training courses, and introductory support toward operators. In order to obtain a holistic view on the HRC problem, Gervasi et al. (2020) proposed a conceptual framework to evaluate HRC by considering aspects related to the collaborative system, human operators, the interaction process, and the organizational context. Through such a framework, it is possible to obtain a complete picture of an HRC scenario from which to identify areas to improve.

3. HRC evaluation framework

Gervasi et al. (2020) introduced a conceptual framework for assessing HRC applications based on various analysis dimensions (Table 1). To support the use of the framework by practitioners, an evaluation metric was also proposed for each dimension. The advantages of such a framework lie in the holistic view of the HRC problem and the generality of the framework, which allows for the evaluation of collaborative tasks of various kinds (e.g., assembly, welding, inspection, and so on).

The HRC evaluation framework is composed by eight main dimensions, which are briefly described below:

- *Autonomy* represents the robot's ability to sense the surroundings, plan and act based on the environment and other entities. In HRC it can be associated with the concept of independence from external control (e.g., humans) and self-directedness (Bradshaw et al., 2004). High autonomy enables more advanced and deeper interaction with humans, as in human-human interaction.
- *Information Exchange* concerns the mediums and methods through which humans and robots interact and exchange information (e.g., giving commands, transferring information, and notifying status). It includes two sub-dimensions: (i) *Communication format*, referring to the senses involved in the communication; (ii) *Communication medium*, referring to the way communication takes place.
- *Team Organization* encompasses the organizational configuration of the agents involved in the HRC. It is composed of two sub-dimensions: (i) *Structure of the team*, referring to the number of robots and humans in the team; (ii) *Role of members*, which specifies the role of each team member.
- *Adaptivity and Training* encompasses cobot's ability of modifying its behavior in response to different situations and of being instructed, as well as the training needed for the operators involved in the HRC. This dimension is composed of three sub-dimensions: (i) *Robot adaptivity*, which refers to the ability of accomplishing a given task despite unexpected situations; (ii) *Robot training method*, i.e., the methods for instructing the robot to perform a certain task; (iii) *Operator training*, indicating the training effort required for humans to perform the collaborative task.
- *Task* refers to the characteristics, performance, and organization of the collaborative task. It consists of four sub-dimensions: (i) *Field of application*, i.e., the context in which the task takes place; (ii) *Task organization*, which contains details on the assignment of each operations to each team agent; (iii) *Performance*, concerning the evaluation of the collaborative outcome, e.g., in terms of effectiveness and/or efficiency, which may vary according to the type and goals of the task; (iv) *Safety*, referring to the identification and assessment of risks and hazards introduced by the collaborative task and its setting.

- *Human Factors* focuses on the human-side aspects that are directly involved during the interaction with cobots (ISO 26800:2011, 2011). It includes five sub-dimensions: (i) *Workload*, which consider both physical and mental strain of operators involved in a collaborative task; (ii) *Trust*, which represents the attitude of operators to achieve a certain goal in a situation induced by a collaborative task characterized by uncertainty (Charalambous et al., 2015); (iii) *Robot morphology*, i.e., the morphological features and design of the cobot; (iv) *Physical ergonomics*, which refers to the evaluation of anatomical and biomechanical characteristics of humans in relation to physical activity involved in the collaborative task; (v) *Usability*, that is, the extent to which the achievement of task objectives through HRC is perceived as effective, efficient, and satisfactory from the user's perspective.
- *Ethics* represents the common understanding of the principles that constrain and guide human behavior (BS 8611:2016, 2016). This dimension contains two sub-dimensions: (i) *Social impact*, referring to the consequences of introducing HRC within a working community; (ii) *Social acceptance*, concerning the perception and predisposition of the HRC system within a working community.
- *Cybersecurity* refers to the process of protecting systems and sensitive data by preventing, detecting, and responding to cyberattacks (NIST, 2018). It includes five sub-dimensions: (i) *Identification*, representing the actions related to understanding policies, cybersecurity risks, and priorities that can be relevant to manage cybersecurity risks; (ii) *Protection*, i.e., activities related to the development and implementation of safeguards to protect infrastructure services; (iii) *Detection*, involving activities related to the deployment of appropriate searching, monitoring, and detection activities to identify cybersecurity events; (iv) *Response*, involving the implementation of plans and processes to take action regarding a detected cybersecurity event; (v) *Recovery*, concerning the activities to recover from a certain cyberattack.

Further details on the dimensions of the HRC framework are available in Gervasi et al. (2020). In the next section, it will be shown how such a framework can be implemented in a continuous HRC quality improvement strategy.

Table 1 – Overview of the HRC evaluation framework proposed by Gervasi et al. (2020).

Dimension	Sub-dimension	Evaluation method	Scale levels

Autonomy	-	LORA (Beer et al., 2014)	L0 – Manual L1– Teleoperation L2 – Assisted Teleoperation L3 – Batch Processing L4 – Decision Support L5 – Shared Control with Human Initiative L6 – Shared Control with Robot Initiative L7 – Executive Control L8 – Supervisory Control L9 – Full Autonomy
Information Exchange	*Communication medium*	4-level scale	L0 – No senses involved L1 – A sense between sight, hearing, and touch is involved L2 – Two senses between sight, hearing, and touch are involved L3 – Sight, hearing, and touch are involved
	Communication format	4-level scale	L0 – No means L1 – Only control panel/displays L2 – A human-natural communication mean is implemented L3 – At least two human-natural communication means are implemented
Team Organization	*Team structure*	Categorical scale	List of robots and humans involved.
	Member role	3-level scale	L0 – Executor L1 – Assistant L2 – Master
Adaptivity and Training	*Robot adaptivity*	4-level scale	L0 – No adaptivity L1 – No flexible adaptivity L2 – Adaptivity L3 – Adaptivity with respect to human
	Robot training method	3-level scale	L0 – Only manual programming L1 – Automatic programming are implemented

			L2 – Automatic programming methods based on natural communication are implemented
	Operator training	4-level scale	L0 – Very Heavy L1 – Heavy L2 – Medium L3 – Light
Task	*Field of application*	Categorical scale	Description of the application context.
	Task organization	List of operations	-
	Performance	4-level scale	L0 – Low L1 – Medium L2 – High L3 – Very High
	Safety	Risk Assessment (ISO 10218-2, 2011; ISO/TR 14121-2, 2012)	L0 – Low L1 – Medium L2 – High L3 – Very High
Human Factors	*Workload*	NASA-TLX (Hart and Staveland, 1988)	L0 – Very High L1 – High L2 – Medium L3 – Low
	Trust	Trust Scale questionnaire (Charalambous et al., 2016)	L0 – Low L1 – Medium L2 – High L3 – Very High
	Robot morphology	Categorical scale (Yanco and Drury, 2004)	Anthropomorphic Zoomorphic Functional
	Physical ergonomics	EAWS (Schaub et al., 2013)	L0 – Red L1 – Yellow L2 – Green

	Usability	SUS (Bangor et al., 2008; Brooke, 1996)	L0 – Not acceptable L1 – Marginal L2 – Acceptable
Ethics	*Social impact*	3-level scale	L0 – Heavy L1 – Medium L2 – Light
	Social acceptance	Brohl TAM (Bröhl et al., 2016)	L0 – Low L1 – Medium L2 – High L3 – Very High
Cybersecurity	*Identification*	Dedeke framework (Dedeke, 2017)	L0 – Partial L1 – Risk informed L2 – Repeatable L3 – Adaptive
	Protection	Dedeke framework (Dedeke, 2017)	L0 – Partial L1 – Risk informed L2 – Repeatable L3 – Adaptive
	Detection	Dedeke framework (Dedeke, 2017)	L0 – Partial L1 – Risk informed L2 – Repeatable L3 – Adaptive
	Response	Dedeke framework (Dedeke, 2017)	L0 – Partial L1 – Risk informed L2 – Repeatable L3 – Adaptive
	Recovery	Dedeke framework (Dedeke, 2017)	L0 – Partial L1 – Risk informed L2 – Repeatable L3 – Adaptive

4. Continuous improvement of HRC quality

In the Quality 4.0 vision, in order to establish a continuous HRC quality improvement process, it is essential to identify an implementation strategy for the HRC evaluation framework. The HRC design, implementation, and improvement process can be supported by integrating Six Sigma models, such as DMAIC (de Mast and Lokkerbol, 2012). The DMAIC cycle is a data-driven quality strategy used for improving processes and stands for *Define*, *Measure*, *Analyze*, *Improve*, and *Control*. Below follows a description of each step and how each can be applied to HRC:

- *Define* involves identifying the problem, setting the project goals, and determining the requirements of the stakeholders. In the context of HRC, this consists of defining the problem under analysis, describing the collaborative task and goals, and the key performance indicators (KPIs) that will measure the success of the specific task. The HRC evaluation framework can provide support to practitioners at this stage in describing the collaborative task and initial identification of factors to be considered.
- *Measure* concerns data collection to understand current process performance, establishing a baseline for improvement. For HRC, it consists of measuring the current efficiency and effectiveness of the process, error rates, and other KPIs established in the previous phase, as well as understanding user experience and needs of the operators involved. The HRC evaluation framework allows practitioners to keep track of relevant factors in HRC by also providing measurement tools.
- *Analyze* refers to analyzing the data collected in the *Measure* phase for identifying root causes of problems or inefficiency areas. In HRC, the analysis can reveal the degree of coordination and attunement between humans and robots, identify bottlenecks in the workflow, and highlight any safety issues that need to be addressed. The HRC evaluation framework provides a dashboard on which to reason about the causes of any problem encountered.
- *Improve* focuses on implementing solutions to address the problems identified in the *Analyze* phase. Pilot testing and iterative improvements are common practices at this stage. Improvements in HRC include redesigning collaborative tasks to better match the strengths of both humans and robots, improving robot capabilities for better collaboration, meeting the needs of operators, and providing additional training for operators to work effectively with cobots. Through the various evaluation levels contained in the dimensions of the HRC framework, hints for process quality improvement can be obtained.
- *Control* is the final phase aimed at sustaining improvements by monitoring the process and implementing controls to ensure that improvements are maintained over time. For HRC, this can involve establishing continuous monitoring systems, regular training updates, and

periodic reviews of the collaborative process to ensure that it remains efficient, safe, and satisfactory for operators.

In the next sub-section, an example case study is provided to show the implementation of the improvement strategy.

4.1. Case study on HRC assembly

Let us consider a collaborative assembly of a water pump (Figure 1). The assembly takes place in a manufacturing company, involving a human operator and a single-arm cobot UR5e equipped with a gripper. The operator is the "master", having full control of the execution time of the task and providing commands to the cobots when it has to execute its operations. The list of operations can be summarized as follows:

1. The cobot brings the flanges F1 and F2 and the diaphragm D1 close to the operator, who wedges them together.
2. The operator inserts the three screws V2 into the holes of D1 and tightens them with a screwdriver.
3. The cobot brings the cover C close to the operator; over C, the operator inserts the diaphragm D2 and fixes the pressure switch PS through the two screws V5.
4. The operator takes cover C and fixes it on flange F2 by inserting and screwing in the three screws V3 with a screwdriver (subassembly SA1).
5. The cobot picks up and holds the engine block EB in front of the operator.
6. The operator picks up the rubber support RF, places it on EB, and secures it with the two screws V1 using a screwdriver.
7. The cobot places EB in front of the operator.
8. The operator inserts the ring R in EB, takes subassembly SA1 and inserts it into the rotor shaft of EB.
9. The operator inserts the three screws V3 into the holes of SA1 and tightens them with a screwdriver, fixating SA1 with EB.
10. The operator takes the filter adapter FA1 and the filter FIL and screws them together.
11. The operator screws FIL and the filter adapter FA2 into the threaded housings of C.

Table 2 summarized the evaluation carried out by a team of expert in the *Measure* phase of the DMAIC model. *Autonomy* was rated L3 (Batch processing), as the cobot can sense the environment and implement pre-programmed actions, but the human decides the objectives and precise path for the cobot.

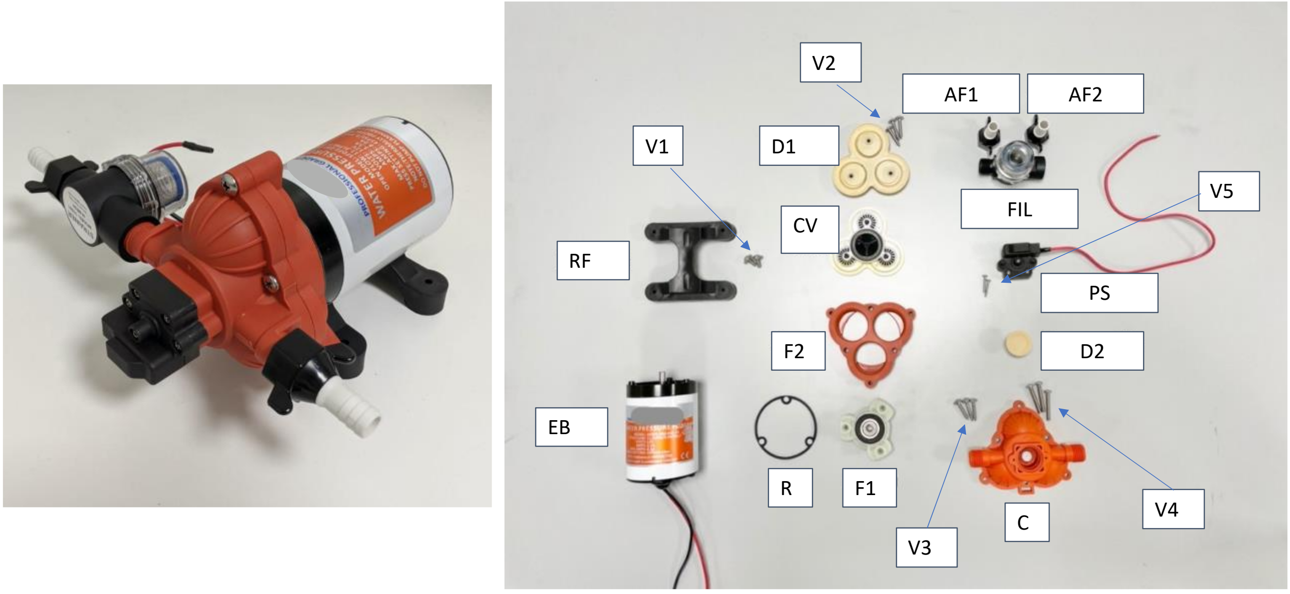

Figure 1 - Water pump and its components.

Table 2 – Evaluation summary of the water pump assembly before and after improvement.

Dimension	Sub-dimension	Evaluation	
		Initial setup	**After *Improve***
Autonomy	-	L3 (Batch Processing)	L4 (Decision Support)
Information Exchange	*Communication medium*	L2	L2
	Communication format	L1	L1
Team Organization	*Team structure*	1 Human 1 Cobot	1 Human 1 Cobot
	Member role	Human L2 (Master) Cobot L0 (Executor)	Human L2 (Master) Cobot L0 (Executor)
Adaptivity and Training	*Robot adaptivity*	L1	L2
	Robot training method	L1	L1
	Operator training	L2 (Medium)	L2 (Medium)
Task	*Field of application*	Manufacturing	Manufacturing
	Performance	L1 (Medium)	L2 (High)
	Safety	L3 (Very high)	L3 (Very high)
Human Factors	*Workload*	L1 (High)	L2 – Medium
	Trust	L2 (High)	L2 (High)
	Robot morphology	Functional (single arm)	Functional (single arm)
	Physical ergonomics	L1 (Yellow)	L2 (Green)

	Usability	L1 (Marginal)	L2 (Acceptable)
Ethics	*Social impact*	L2 (Light)	L2 (Light)
	Social acceptance	L2 (High)	L2 (High)
Cybersecurity	*Identification*	L1 (Risk informed)	L1 (Risk informed)
	Protection	L1 (Risk informed)	L1 (Risk informed)
	Detection	L1 (Risk informed)	L1 (Risk informed)
	Response	L1 (Risk informed)	L1 (Risk informed)
	Recovery	L1 (Risk informed)	L1 (Risk informed)

Since communication between cobot and operator takes place through a display, that show the cobot's status, and a push-button when the operator wants the cobot to proceed with its action, *communication medium* and *communication format* were evaluated L2 and L1, respectively.

Robot adaptivity was assessed L1, as the cobot can stop if the force limit is reached, mainly for ensuring safety. The cobot can be instructed by manual programming or teach-pendant, which allows PbD (i.e., a classical automatic programming technique), therefore *robot training method* was rated L1. The operator training mainly focuses on safety during HRC, task operations, and the use of the teach pendant, leading *operator training* to be rated L2 (Medium).

Performance of the collaborative task was rated L1 (Medium), as in terms of efficiency and efficacy no improvement were noticed compared to a classical manual setting according to the team of expert. *Safety* was rated L3 (Very high) through a risk-assessment based on the list of hazards contained in ISO 10218-2 standard and the risk matrix proposed in ISO/TR 14121-2. The risk score obtained was 18/90 (less than 25% of the maximum score), since for the most likely mechanical hazards, mainly due to accidental contact with the cobot during its operations (i.e., "impact", “drawing-in/trapping” and "friction/abrasion"), the harm severity was rated as moderate.

Workload was assessed using the NASA-TLX, obtaining a score of 46/100, leading to the rating L1 (High). *Trust* was evaluated L2 (High), since a trust score of 34/50 was obtained. Concerning *physical ergonomics*, it was rated L1 (Yellow) since the score obtained by the EAWS was of 41 (>25 and <50) due to the having to work standing and manually tighten all the screws. *Usability* was rated L1 (Marginal), since the cobot's contribution to the achievement of the task's objectives was not perceived to be fundamental, although the interaction with the cobot was acceptable.

Social impact was rated L2 (Light), as the cobot was introduced to support the operator and did not involve resignation or a task change. The introduction of the cobot was accompanied by an appropriate level of propensity to collaborate with it, leading to L2 (High) for *social acceptance*.

Concerning *Cybersecurity*, the sub-dimensions *identification*, *protection*, *detection*, *response*, and *recovery* were all evaluated L1 (Risk informed) due to the presence of dedicated cybersecurity staff who intervene when necessary.

Moving into the *Analysis* phase of DMAIC, some critical issues emerged in the current HRC setup. The *performance* level of the assembly was not satisfactory, as with the introduction of a second agent (i.e., the cobot) the cycle time would have been desired to be reduced. In addition, from the operator's point of view, the level of *workload*, *physical ergonomics*, and *usability* emerged to be not particularly adequate. The main reason lied in the screwing operations, which were found to be particularly tedious and repetitive for the operator.

Having identified the causes of the problems, appropriate solutions were introduced in the *Improve* phase. With the goal of parallelizing operations to reduce cycle time and to enable the cobot to perform at least some of the tightening operations, it was necessary to enhance the cobot's capabilities. A tool exchanger was introduced for the UR5e, so that it can change end-effectors independently during the process, switching from the gripper to an electric screwdriver and vice versa. In addition, a vision system was also introduced to enable the cobot to locate the screws to be tightened. These changes resulted in an increase in the cobot's *Autonomy* and *robot adaptivity*, bringing them to L4 (Decision support) and L2, respectively.

The allocation of operations was changed, assigning the most tedious screwing operations to the cobot, namely the screwing of the screws V2, V3, and V4. The new list of operations is summarized as follows (compared to the previous list, modified operations are in italics):

1. The cobot brings the flanges F1 and F2 and the diaphragm D1 close to the operator. Meanwhile the operator wedges them together, the cobot changes the gripper with the electric screwdriver.*

2. The operator inserts the three screws V2 into the holes of D1 and lets the cobot tighten them.*

3*. Meanwhile, the operator takes the cover C and inserts the diaphragm D2 and fixes the pressure switch PS through the two screws V5.

4. The operator places the cover C on the flange F2, inserts the three screws V3 and lets the cobot tighten them (subassembly SA1).*

5. Meanwhile, the operator places the engine block EB in front of themself.*

6*. The operator picks up the rubber support RF, places it on EB, and secures it with the two screws V1 using a screwdriver.

7. The operator places EB vertically.*

8*. The operator inserts the ring R in EB, takes subassembly SA1 and inserts it into the rotor shaft of EB.

9. The operator inserts the three screws V3 into the holes of SA1 and lets the cobot tighten them, fixating SA1 with EB.*

10*. The operator takes the filter adapter FA1 and the filter FIL and screws them together.

11*. The operator screws FIL and the filter adapter FA2 into the threaded housings of C.

The new configuration led to the expected improvements (Table 2). By parallelizing some operations, the cycle time was reduced considerably, bringing *performance* to the level L2 (High). By leaving the more tedious screwing operations to the cobot, the perceived workload decreased to 33/100 according to the NASA-TLX, bringing *Workload* to the level L3 (Medium). *Physical ergonomics* improved considerably by relieving the operator of several screwing operations, reaching L2 (Green) due to an EAWS score of 20 (<25). By participating in screwing operations, the cobot's contribution was perceived as more important, therefore *Usability* increased to level L2 (Acceptable). Although the introduction of the electric screwdriver as cobot's end-effector introduced new risks for the operator's safety, through risk-assessment a level L3 (Very high) for *Safety* was maintained thanks also to the use of personal safety devices such as cut-resistant gloves.

To make sure that the improvements achieved were maintained, a monthly routine was established for the *Control* phase to re-evaluate the process and discuss with the operators involved to obtain feedback on their experience.

5. Discussion and conclusions

This chapter outlined a methodology that combines an HRC evaluation framework proposed by Gervasi et al. (2020) with the DMAIC method in order to achieve continuous quality improvement in HRC processes. Implementing a holistic approach in HRC evaluation is essential to fully exploit its benefits and improve its quality. The case study highlighted the framework's ability to detect critical areas that need intervention, supporting practitioners especially in the measurement and analysis phase. In the improvement phase, the framework can also be used to compare various scenarios by integrating multiple-criteria decision analysis methods (Gervasi et al., 2022b). In the control phase, it becomes essential to introduce processes for monitoring various HRC aspects over the long term. In addition to periodic checks, tools for continuous monitoring can also be considered, such as vision systems for defect control and noninvasive biosensors to track the psychophysical state of operators during HRC (Gervasi et al., 2024).

In conclusion, by implementing the proposed methodology, organizations can systematically improve the synergy between humans and cobots. As HRC continues to evolve, the proposed methodology provides a reliable and versatile tool to guide and support advancements, ensuring that both human and robotic elements work harmoniously together toward shared goals.

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