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Comparing quality profiles in Human-Robot Collaboration: empirical evidence in the automotive sector

Gervasi, R.[1)], Digiaro, F.N.[1)], Mastrogiacomo, L.[1)], Maisano, D.A.[1)] and Franceschini, F.[1)]

[1)] Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Turin, Italy

STRUCTURED ABSTRACT

Purpose- Human-Robot Collaboration (HRC) is a paradigm that is gradually consolidating in the industrial field. The goal of this paradigm is to combine human and robot skills to make production more flexible. An effective implementation of HRC requires a careful analysis of its different aspects, related to both robots and humans. For this reason, the development of a tool able to consider all HRC aspects to evaluate the collaboration quality is a real practical need.

Design/methodology/approach- In a previous work, Gervasi et al. (2020) proposed a multidimensional framework to evaluate HRC quality. This framework has been tested on a real industrial HRC application in the automotive sector. Two different alternatives of the same assembly task were analyzed and compared on the quality reference framework.

Findings- The comparison between the two alternatives of the same assembly task highlighted the framework's ability to detect the effects of different configurations on the various HRC dimensions. This ability can be useful in decision making processes and in improving the collaboration quality.

Social implications- The framework considers the human aspects related to the interaction with robots, allowing to effectively monitor and improve the collaboration quality and operator satisfaction.

Originality/value- This paper extends and shows the use of the HRC evaluation framework proposed by Gervasi et al. (2020) on real industrial applications. In addition, an HRC application implemented in an important automotive company is described and analyzed in detail.

Keywords: Human-Robot Collaboration, HRC evaluation framework, Automotive industry.

Paper type: Research paper

INTRODUCTION AND LITERATURE REVIEW

The sharing of workspace and the physical interaction between humans and robots in manufacturing processes are no longer a futuristic utopia, but a reality that has been consolidating in recent years. Unlike traditional robotic systems, collaborative robots represent a promising solution to meet the needs arising from the increasingly pressing demand for production based on “mass customization” (Mateus et al., 2019; Pine, 1993).

Collaborative robots represent one of the fundamental elements of Industry 4.0, as enabling technologies of adaptive systems based on flexibility, reconfigurability and production efficiency (Cohen et al., 2019; Mateus et al., 2019). At the same time, they provide an important opportunity for technological development in many areas where robotics is almost unfamiliar (Huang et al., 2020; Wang et al., 2019).

The main idea of Human-Robot Collaboration (HRC) is combining the capabilities of humans with those of robots. On the one hand, humans have innate flexibility, intelligence, dexterity, and problem-solving skills; on the other hand, robots provide precision, power, and repeatability (ISO/TS 15066:2016, 2016). The implementation of HRC introduces several issues related mainly to safety (Robla-Gómez et al., 2017; Vicentini et al., 2020), robot programming (Argall et al., 2009; Huang et al., 2020), task organization (Raatz et al., 2020), and human-related aspects (Salm-Hoogstraeten and Müsseler, 2020).

For an effective implementation of collaborative robot systems it is necessary to consider all aspects concerning HRC (Franceschini et al., 2019; Gervasi et al., 2019; Goodrich and Schultz, 2007). The evaluation methods currently available in the literature focus only on certain HRC aspects (Beer et al., 2014; Bröhl et al., 2016; Vicentini et al., 2020) or on the analysis of specific tasks or situations (Gualtieri et al., 2020; Rabbani et al., 2020; Rifinski et al., 2020). However, the attempt to build a general evaluation framework for HRC, able to consider all its aspects, seems to be less explored.

In a previous work, Gervasi et al. (2020) proposed a multidimensional conceptual framework to evaluate HRC, with some preliminary metrics. The aim of this paper is to extend this framework to real industrial HRC applications, focusing on the automotive sector. With reference to a specific HRC application, the evaluation framework will be also used to compare different design alternatives.

The paper is organized as follows. In the next section, a short summary of the HRC evaluation framework proposed by Gervasi et al. (2020) is provided. Afterwards, the methodology for collecting information on the real industrial HRC application is described. The subsequent section contains an in-depth description and analysis of a real industrial HRC application in the automotive sector. Next, a hypothetical variant of the application is analyzed and compared with the original one. Afterwards, a discussion of the obtained results is presented. Finally, the concluding section explores limitations and future research directions.

HRC EVALUATION FRAMEWORK

Gervasi et al. (2020) proposed a reference framework to evaluate HRC applications considering several characterizing aspects, both related to humans and robots. The framework was developed to allow the comparison and analysis of different HRC applications. Moreover, it can support decision making, highlighting HRC aspects that need to be improved. Below follows a brief description of the latent dimensions and sub-dimensions of the HRC evaluation framework (Gervasi et al., 2020), also summarized in Table 1:

- *Autonomy* represents the robot capabilities of sensing the surroundings, planning and acting according to the environment and other entities. Note that, in the HRC context, higher robot autonomy enables more advanced and complex interactions (Goodrich and Schultz, 2007; Thrun, 2004).
- *Information Exchange* represents the way information is exchanged between robot and human. It is composed of two sub-dimensions, namely *Communication format* and *Communication medium*, which refer to the senses involved in the communication and how communication takes place, respectively.
- *Team Organization* considers the organization of the agents involved in the collaboration. It is composed of *Structure of the team*, which refers to the number of robots and humans in the team, and *Role of members*, which represents to the role of each team member.
- *Adaptivity and Training* latent dimension concerns robot adaptivity and instruction as well as human training, and it is characterized by three sub-dimensions. *Robot adaptivity* represents the ability to accomplish a given task despite unexpected situations. *Robot training method* refers to the methods for instructing the robot to perform a certain task. *Operator training* indicates the effort in training the operators involved in a collaborative task.
- *Task* dimension contains information on the task to be performed, and it is composed of five sub-dimensions. *Field of application* refers to the field in which the task takes place. *Task organization* refers to the assignation of individual operations to each team member. *Performance* refers to the evaluation of the outcome of the collaborative task. *Safety* concerns

the identification of the risks and hazards involved in the task and the related safety measures implemented.

- *Human Factors* dimension concerns the understanding of interactions among human and robot to optimize human well-being and overall system performance (ISO 26800:2011, 2011). It is composed of five sub-dimensions. *Workload* refers to the effort of the human operators during a task. *Trust* is the attitude that an agent will help to achieve an individual's goal in a situation characterized by uncertainty and vulnerability (Charalambous et al., 2015). *Robot morphology* refers to the evaluation of the morphology and design of the collaborative robot. *Physical ergonomics* addresses the anatomical, anthropometric, and biomechanical characteristics of humans in relation to physical activity. *Usability* sub-dimension represents the evaluation and design of the interaction between human and robot that is supposed to take place.
- *Ethics* represents the common understanding of the principles that constrain and guide human behavior (BS 8611:2016, 2016). *Social impact* refers to the consequences of introducing a collaborative robotic system within a community. *Social acceptance* indicates the perception of the collaborative robotic system within a community.
- *Cybersecurity* is the process of protecting information by preventing, detecting, and responding to attacks (NIST, 2018). It is composed of five sub-dimensions. *Identification* represents the actions related to the understanding of policies, cybersecurity risks, and priorities relevant for managing cybersecurity risks. *Protection* concerns activities related to the development and implementation of safeguards to protect infrastructure services and to train staff. *Detection* includes activities related to the development and deployment of appropriate detection activities to identify cybersecurity events. *Response* represents activities related to the development and implementation of appropriate plans to act regarding a detected cybersecurity event. *Recovery* involves activities related to the development and implementation of appropriate plans to recover from cybersecurity events.

Table 1 – Summary of HRC evaluation framework with latent dimensions, sub-dimensions, and evaluation methods (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 between sigh, hearing, and touch involved– (L2) Two senses between sigh, hearing, and touch involved– (L3) Sight, hearing, and touch involved
	Communication format	4-level scale	(L0) No means – (L1) Only control panel/displays – (L2) A human-natural communication mean implemented – (L3) At least two human-natural communication means 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 (Krüger et al., 2017)	(L0) No adaptivity – (L1) No flexible adaptivity – (L2) Adaptiity – (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 organitation	List of operations	-
	Performance	4-level scale	(L0) Low – (L1) Medium – (L2) High – (L3) Very High
	Safety	Risk Assessment (ISO 10218-2:2011, 2011; ISO/TR 14121-2:2012, 2012)	(L0) Low – (L1) Medium – (L2) High – (L3) Very High

Table 1 – (continued)

Dimension	**Sub-dimension**	**Evaluation method**	**Scale levels**
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., 2015)	(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		(L0) Partial – (L1) Risk informed – (L2) Repeatable – (L3) Adaptive
	Detection		(L0) Partial – (L1) Risk informed – (L2) Repeatable – (L3) Adaptive
	Response		(L0) Partial – (L1) Risk informed – (L2) Repeatable – (L3) Adaptive
	Recovery		(L0) Partial – (L1) Risk informed – (L2) Repeatable – (L3) Adaptive

DATA COLLECTION AND METHODOLOGY

The HRC evaluation framework has been used to analyze a real industrial HRC application, which will be discussed in next sections. Evaluations were carried out by a team of experts based on the information collected. Data were acquired through direct observations of the production process, semi-structured interviews with managers, and questionnaires administered to operators working with collaborative robots.

In order to evaluate the sub-dimensions *Workload*, *Trust*, *Usability*, and *Social acceptance*, a single questionnaire has been created summarizing the ones proposed in the HRC evaluation framework (Gervasi et al., 2020) (see Appendix A). Although this choice may have led to a light degradation of the evaluation for these sub-dimensions, it was necessary to administer a questionnaire easy to use, immediately understandable and not too intrusive for operators.

CASE STUDY: PARKING PAWL ASSEMBLY TASK

The industrial HRC application considered concerns an assembly task in an important automotive company. The task consists of assembling a mechanical component, called "parking pawl", in the gearbox for vehicles in the U.S. market.

The workstation is managed by three agents: a robotic system and two human operators. The robot and the operators share the same workspace without physical or virtual safety barriers.

The robot system is composed of a single-arm collaborative robot UR10/CB3 (Universal Robots, 2019) and three end devices installed on the robot flange: an electromagnetic gripper to take screws from a box, a vision system (SensoPart Visor V20 2D) and a collaborative gripper (Robotiq 2F-85).

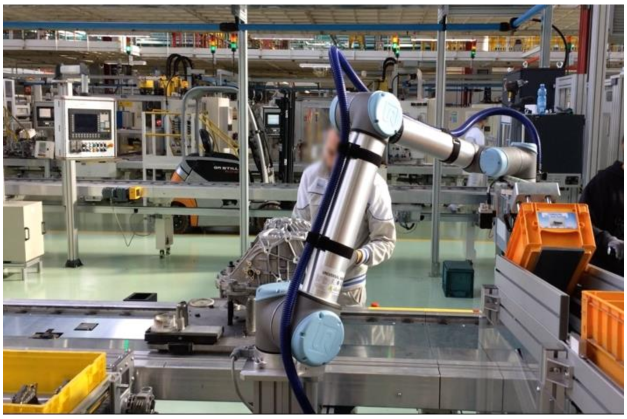
Table 2 shows the list of operations of the parking pawl assembly task, organized in four phases:

- First phase: a logistics staff operator sets up the workpieces in the appropriate boxes, also checking their correct position (Figure 1a).
- Second phase: the robot takes six screws from the workpiece box, through the electromagnetic gripper, and hands them to the operator (Figure 1b).
- Third phase: the robot takes with the gripper the parking pawl and hands it to the operator in an ergonomic position (Figure 1c).
- Fourth phase: the operator inserts the parking pawl into the gearbox and screws it in with a screwdriver (Figure 1d).

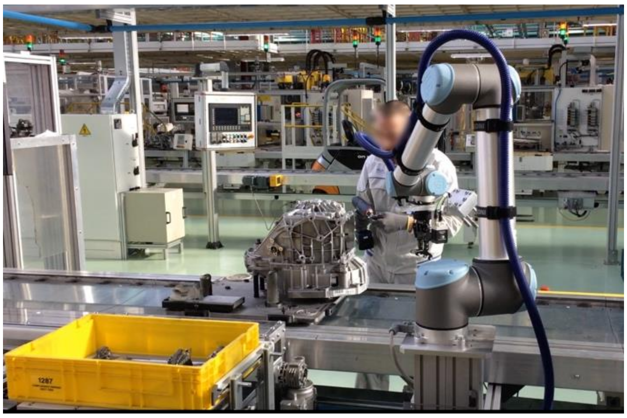
Table 2 – List, allocation and description of operations of the parking pawl assembly task.

Phase	Operation	Operation allocation	Description
0	**Parking pawl assembly** *1. Components setup* *2. Screws feeding* *3. Pawl feeding* *4. Pawl screwing*	**Humans - Robot** *Human (2)* *Human (1) - Robot* *Human (1) - Robot* *Human (1)*	Portion of gearbox assembly process performed by an operator in collaboration with a robot.
1.	*1. Components Setup* 1.1 Placing components into the box 1.2 Checking components in the box	*Human (2)* Human (2) Human (2)	Logistics staff sets up workpieces in the dedicated boxes, checking that they are correctly positioned.
2.	*2. Screws feeding* 2.1 Screws picking 2.2 Screws moving 2.3 Screw release	*Human (1) - Robot* Robot Robot Human (1) - Robot	The robot approaches the box containing the screws and picks them up via the dedicated gripper. The robot brings the screws closer to the operator, who extracts them.
3.	*3. Pawl feeding* 3.1 Pawl picking 3.2 Pawl moving 3.3 Pushbutton drive 3.4 Pawl releasing	*Human (1) - Robot* Robot Robot Human (1) Human (1) - Robot	The robot approaches the box containing the pawl and picks it up via the dedicated gripper. The robot brings the pawl closer to the operator. The operator presses the pushbutton to enable pawl release and extracts it.
4.	*4. Pawl screwing* 4.1 Pawl handling 4.2 Pawl insertion 4.3 Screwdriver load 4.4 Pawl tightening	*Human (1)* Human (1) Human (1) Human (1) Human (1)	The operator inserts the pawl into the appropriate seat. Afterwards, he sets each screw for insertion and tightens them with a screwdriver.

The following sub-sections describe the results of the analysis performed by a team of experts for each sub-dimension of the HRC evaluation framework. Table 3 provides a summary of the evaluations of the team of experts.

(a) (b)

(c) (d)

Figure 1 – Sequence of operations of the parking pawl assembly task: (a) Components setup; (b) Screws feeding; (c) Pawl feeding; (d) Pawl screwing.

Autonomy

Thanks to the vision system and the force sensor of the gripper, the robot is able to collect environmental data for the execution of the task and to support the operator in the execution of the planned task. The task planning is exclusive to the human. For these reasons, *Autonomy* was rated L3 ("Batch Processing") according to the evaluation scale based on LORA taxonomy (Beer et al., 2014; Gervasi et al., 2020).

Information Exchange

Communication between human and robot takes place through a teach pendant, displaying information about robot's status, and a button on the robot flange, used to order the robot to release workpieces. Since touch and sight senses are involved in communication, but no human-natural communication modality is implemented, *communication medium* and *communication format* were evaluated L2 and L1, respectively.

Team Organization

The *Team structure* is composed by 1 robot and 2 humans. The workstation is mainly composed of the robot and an operator, who carry out the assembly task; periodically, a second operator from the logistics area loads the workpieces into the appropriate boxes.

As for *Member roles*, the workstation operator is the master of process (L2), since he performs the assembly task and controls the task execution, the logistics staff operator is an assistant (L1), who provides support for task, and the robot is just an executor of the task instructions (L0).

Adaptivity and Training

The robot, thanks to the vision system, can identify the contour of objects to adjust its position and perform a correct grip. If the operation fails, the robot tries again three more times, after which it stops. Since the robot does not have the ability to learn from experience, but apply a fixed policy, *Robot adaptivity* was rated L1.

The robot was instructed using both offline programming and online programming via teach pendent. Since these methods are automatic programming methods, *Robot training method* was evaluated L1.

Operators involved in HRC task attended a training course organized by the robot manufacturer's academy. This course covered safety setting and teach pendant use. Thus, *Operator training* was evaluated L2 (Medium).

Task

Performance dimension was assessed L2 (High), based on information from interviews with managers and observations of the collaborative task.

Safety was evaluated through a risk-assessment based on a list of hazards contained in ISO 10218-2 standard (see Appendix B). The risk assessment was carried out considering the severity and probability of occurrence of harm, both evaluated on a 4-level scale. The assessment considered the risk reduction due to the implementation of protective measures, i.e. safety functions configured in the robot. These functions consisted of reducing the speed in the interaction zone and preventing unwanted movements or positions. This affected the probability of occurrence and the severity of harms. Regarding mechanical hazards, the most likely risks were "impact", "friction/abrasion" and "cutting/severing", due to the possibility of touching the robot and moving workpieces. However, the severity of harm of each of these risks was “Moderate” (L1), as the robot safety functions significantly reduced the damage and the possible contact regions were not vital organs. The other mechanical hazards (“entanglement”, “crushing”, “shearing”, “drawing-in/trapping”, “stabbing/puncture”) and hazards of other categories were evaluated with a “Serious” (L2) severity but “Remote” (L0) or

"Unlikely" (L1) probability of occurrence. Some hazards were assessed as "Not Available" (N/A) since potential harm was completely excluded. The final risk score obtained was 22/90, meaning that the *Safety* level is "Very High" (L3) according to the scale proposed in the HRC framework.

Human factors

Workload was rated "Medium" (L2), based on the results of the questionnaire and the adapted evaluation scale of the HRC framework (see Appendix A).

The responses collected by the operators revealed a high level of trust in the robot, with a final score of 19/20 (see Appendix A). Thus, *Trust* has been rated "Very High" (L3).

Physical ergonomics has been rated "Green" (L2), i.e. no risk or low risk for the operator. The task involves a low biomechanical load on the operator, as it requires the handling of low load objects and the application of low forces while maintaining a non-fatiguing posture. This is confirmed by the EAWS score of 15.5 (< 25), which indicates a low risk of biomechanical overload. For further details on the evaluation, see Appendix C.

Usability has been rated "Marginal" (L1). From the answers to the questionnaire (see Appendix A) the operators do not believe that the various functions of the robot are well integrated into the system.

Ethics

The implementation of the collaborative robot led to a significant reconfiguration of the assembly task. Previously, the assembly of the parking pawl was done in a dedicated off-line station. This operation was performed continuously and manually by one operator, on average for two shifts per day. Currently, this task has been integrated directly into the production line, resulting in a redeployment of personnel. Therefore, according to the scale proposed in the HRC framework (Gervasi et al., 2020), *Social impact* has been rated "Medium" (L1).

Social acceptance has been rated "High" (L2), based on the answers to the questionnaire (see Appendix A).

Cyber security

Identification, Protection, Detection, Response, and *Recovery* have been all evaluated "Risk informed" (L1) (Dedeke, 2017). The management of cybersecurity is part of the company's activities and is carried out by a specific and qualified personnel.

Table 5 – Evaluation summary of the parking pawl assembly task by the team of experts.

Dimension	Sub-dimension	Evaluation
Autonomy	-	L3 (Batch processing)
Information Exchange	Communication medium Communication format	L2 L1
Team Organization	Team structure Member role	2 Humans, 1 Robot Human (1) L2 (Master) Human (2) L1 (Assistant) Robot L0 (Executor)
Adaptivity and Training	Robot adaptivity Robot training method Operator training	L1 L1 L2 (Medium)
Task	Field of application Performance Safety	Manufacturing (automotive) L2 (High) L3 (Very High)
Human Factors	Workload Trust Robot morphology Physical ergonomics Usability	L2 (Medium) L3 (Very High) Functional (Single arm) L2 (Green) L1 (Marginal)
Ethics	Social impact Social acceptance	L1 (Medium) L2 (High)
Cybersecurity	Identification Protection Detection Response Recovery	L1 (Risk informed) L1 (Risk informed) L1 (Risk informed) L1 (Risk informed) L1 (Risk informed)

COMPARISON OF DESIGN ALTERNATIVES BY HRC FRAMEWORK

As pointed out in the introduction, the HRC evaluation framework (Gervasi et al., 2020) can also be used in the design phase as a tool to compare different alternatives of the same task. To show this use, a hypothetical alternative HRC scenario of the parking pawl assembly task was developed, evaluated, and compared with the original one by a team of experts.

As in the original HRC scenario, the workstation is managed by three agents: a robotic system and two human operators. The robotic system is equipped with an electromagnetic gripper, a vision system, and a collaborative screwdriver.

The operations of the hypothetical alternative HRC scenario are organized in four phases, which are the following:

- First phase: a logistics staff operator sets up the workpieces in the appropriate boxes.

- Second phase: the robot takes six screws from the workpiece box, through the electromagnetic gripper, and hands them to the operator.
- Third phase: the operator takes the parking pawl, inserts it into the gearbox and places the screws into the slots.
- Fourth phase: the robot performs the screwing with the collaborative screwdriver.

Figure 2 shows a comparison between the quality profiles of the original HRC application and the alternative one. *Autonomy*, *Information Exchange*, *Team Organization*, *Adaptivity and Training*, *Ethics,* and *Cybersecurity* have not undergone any changes compared to the original HRC scenario.

Regarding *Performance*, an increase from "High" (L2) to "Very High" (L3) has been hypothesized. Assigning the screwing operation to the robot could improve the quality of the product, reducing the risk of over-tightening and always having the correct tension, thanks to the robot precision and repeatability. *Safety* has been evaluated “High” (L2), suffering a decrease compared to the original HRC scenario. This is due to the presence of a screwdriver on the robot, which increases the risks of “crushing” and “stabbing/puncture”. *Workload* has been rated “High” (L1), since an increase in “frustration” is likely due to the new task allocation, although a slight decrease in “physical demand” is expected. The presence of a screwdriver as an end-effector may reduce the operator's trust, as well as the perception of safety, towards the robot. Therefore, *Trust* has been degraded from “Very High” (L3) to “High” (L2). Both *Physical ergonomics* and *Usability* have remained unchanged in the evaluations.

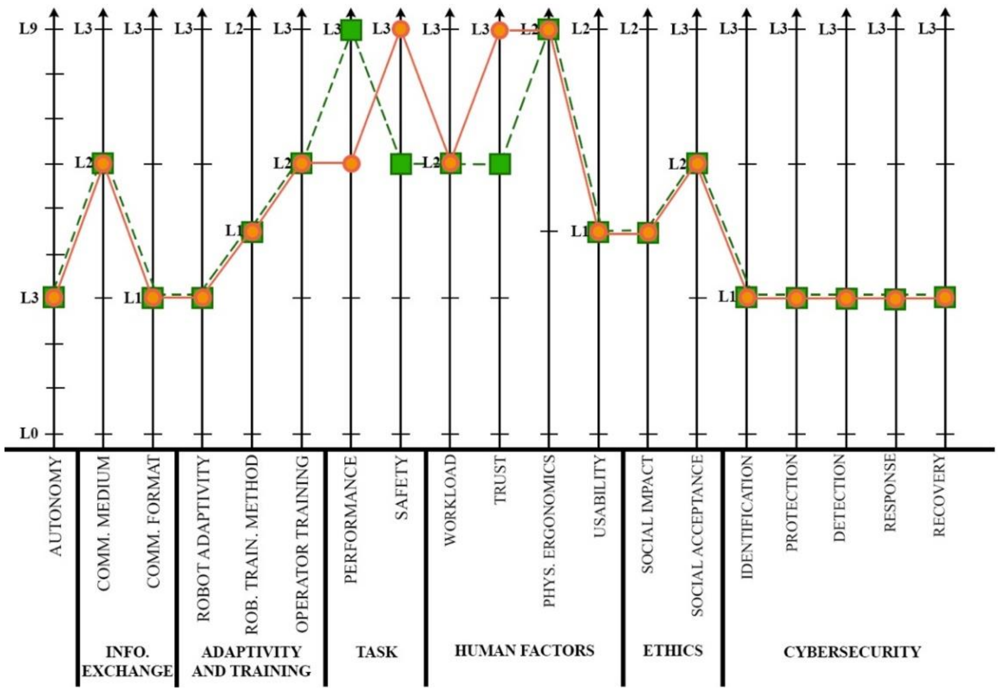


Figure 2 – Graphical comparison between the HRC quality profiles of the original parking pawl assembly task (orange) and the hypothetical alternative one (green).

DISCUSSION

The HRC reference framework proposed by Gervasi et al. (2020) , through the evaluation of each dimension, provides an extended and detailed representation of a collaborative task. This representation is focused on aspects related to each agent, their synergistic interaction, and the application context. Moreover, this representation allows to make considerations on the quality of the collaboration. For instance, in the industrial HRC application previously analyzed, it can be noted that the sub-dimensions *Safety*, *Trust*, and *Physical ergonomics* obtained quite high evaluations, indicating a good task design. However, *Autonomy* and *Communication format* were not particularly high, implying some limitation in the interaction.

Another use of the HRC evaluation framework consists in comparing different scenarios of the same application. For example, by varying the assignment of a task operation between operator and robot, a group of experts can understand which are the most suitable configurations. In order to show this possible exploitation, a hypothetical variant of the parking pawl assembly task was introduced. Once evaluated through the HRC framework, this variant was compared with the original HRC application. Looking at the evaluation profiles (Figure 2), it can be noted that the original HRC application outclasses the hypothetical one in almost all sub-dimensions. This result may suggest that the level of collaboration of the original HRC scenario is higher than that of the variant. Moreover, the comparison highlighted how changing certain aspects of a task can influence different HRC dimensions.

Further investigation to understand how to take advantage of the information provided by the HRC evaluation framework is needed. The creation of a global indicator that synthesizes the level of collaboration between human and robot is rather challenging, due to the heterogeneity of the aspects that influence it. However, one idea could be trying to identify benchmark profiles to define different collaboration levels. By examining a large sample of collaborative tasks and evaluating each of them through the HRC framework, it could be possible to cluster similar profiles. This process may lead to the identification of the most common collaboration profiles, which can constitute the benchmark levels of a potential HRC scale. However, during this operation, it has to be taken into account that the sub-dimensions of the HRC evaluation framework are not independent from each other (Gervasi et al., 2019).

CONCLUSIONS

A multidimensional HRC evaluation framework proposed by Gervasi et al. (2020) was examined and tested on an industrial HRC application in the automotive sector. Each framework dimension was evaluated by a team of experts supported by technical information provided by managers, process observations, and operators' feedback. By using the scales proposed in the reference framework, a structured description of the application with an evaluation profile was obtained.

A variant of the HRC application was also hypothesized and evaluated qualitatively. Some considerations were drawn from the comparison between the original HRC scenario and the alternative one. This procedure highlighted the framework's ability to detect the effects of different configurations on various HRC dimensions, which is useful in decision making processes and in improving the quality of collaboration and finished products.

Future investigations will concern the design of more agile questionnaires to evaluate some HRC dimensions (e.g., the possibility of using fuzzy scale rating to design questionnaire forms). Other future activities will focus on analyzing in depth the relationships between the different dimensions of the framework and on building benchmark profiles in order to create a unidimensional HRC scale.

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APPENDIX A - SYNTHETIC QUESTIONNAIRE

A synthetic questionnaire to evaluate *Workload*, *Trust*, *Usability*, and *Social acceptance* has been created. Table 4 shows the questionnaire items for each sub-dimension with their respective median scores for the parking pawl assembly task. Each item is evaluated on a five-point Likert scale, and, for each sub-dimension, the item scores are summed up to provide a final score. The final scores of each sub-dimension are interpreted using the respective evaluation scales proposed in the HRC evaluation framework, adapting them to the new scoring ranges.

Table 4 – Questionnaire to evaluate *Workload*, *Trust*, *Usability*, and *Social acceptance*. Negative items are indicated with " * " and scores are already correctly converted.

Dimension	Item	Median Score (0 to 4)	Interquartile range
Workload	How much mental and perceptual activity was required?	1	1
	How much physical activity was required?	2	2
	How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?	1	3
	How successful were you in performing the task? *	2	1
	Total	**6/16**	
Usability	I thought the system was easy to use	3	2
	I would imagine that most people would learn to use this system very quickly	3	1
	I found the system very cumbersome to use *	3	2
	I found the various functions in this system were well integrated	1	3
	Total	**10/16**	
Trust	The size of the robot did not intimidate me	4	1
	I was comfortable the robot would not hurt me	4	2
	I felt safe interacting with the robot	4	2
	The robot gripper did not look reliable *	3	3
	The way the robot moved made me uncomfortable *	4	2
	Total	**19/20**	
Social acceptance	People in my organization who use the robot have more prestige than those who do not	3	1
	I fear that I lose the contact to my colleagues because of the robot *	3	2
	I fear that I will lose my job because of the robot *	4	2
	Using the robot improves my performance in my job	2	3
	Total	**12/16**	

APPENDIX B - SAFETY DIMENSION EVALUATION

Safety has been evaluated through a risk-assessment based on a list of hazards contained in ISO 10218-2. Table 5 contains the evaluation results for the parking pawl assembly task, while Table 6 the risk matrix proposed in ISO/TR 14121-2 used for the evaluation.

Table 5 – Risk-assessment for the parking pawl assembly task

Type of risk	Risk	Probability	Severity	Risk indicator
Mechanical hazards	crushing	L0	L2	Low (1)
	shearing	L0	L2	Low (1)
	cutting or severing	L2	L1	Medium (2)
	entanglement	L1	L1	Low (1)
	drawing-in or trapping	L0	L2	Low (1)
	impact	L2	L1	Medium (2)
	stabbing or puncture	L0	L2	Low (1)
	friction, abrasion	L2	L1	Medium (2)
	high-pressure fluid/gas injection or ejection	N/A	N/A	N/A
Electrical hazards	electrocution	L0	L2	Low (1)
	shock	L0	L2	Low (1)
	burn	L0	L2	Low (1)
	projection of molten particles	N/A	N/A	N/A
Thermal hazards	burn (hot or cold)	L0	L2	Low (1)
	radiation injury	L0	L2	Low (1)
Noise hazards	loss of hearing	N/A	N/A	N/A
	loss of balance	N/A	N/A	N/A
	loss of awareness, disorientation	N/A	N/A	N/A
	any other	N/A	N/A	N/A
Vibration hazards	fatigue	L1	L1	Low (1)
	neurological demage	L0	L2	Low (1)
	vascular disorder	L0	L2	Low (1)
	impact	L0	L2	Low (1)
Radiation hazards	burn	N/A	N/A	N/A
	demage of eyes and skin	N/A	N/A	N/A
	releted illnesses	N/A	N/A	N/A
Material/substance hazard	sensitization	L0	L2	Low (1)
	fire	L0	L2	Low (1)
	chemical burn	L0	L2	Low (1)
	inhalation illness	N/A	N/A	N/A
Combinations of hazards	combinations of hazard	N/A	N/A	N/A

Table 6 – Risk matrix proposed in ISO/TR 14121-2.

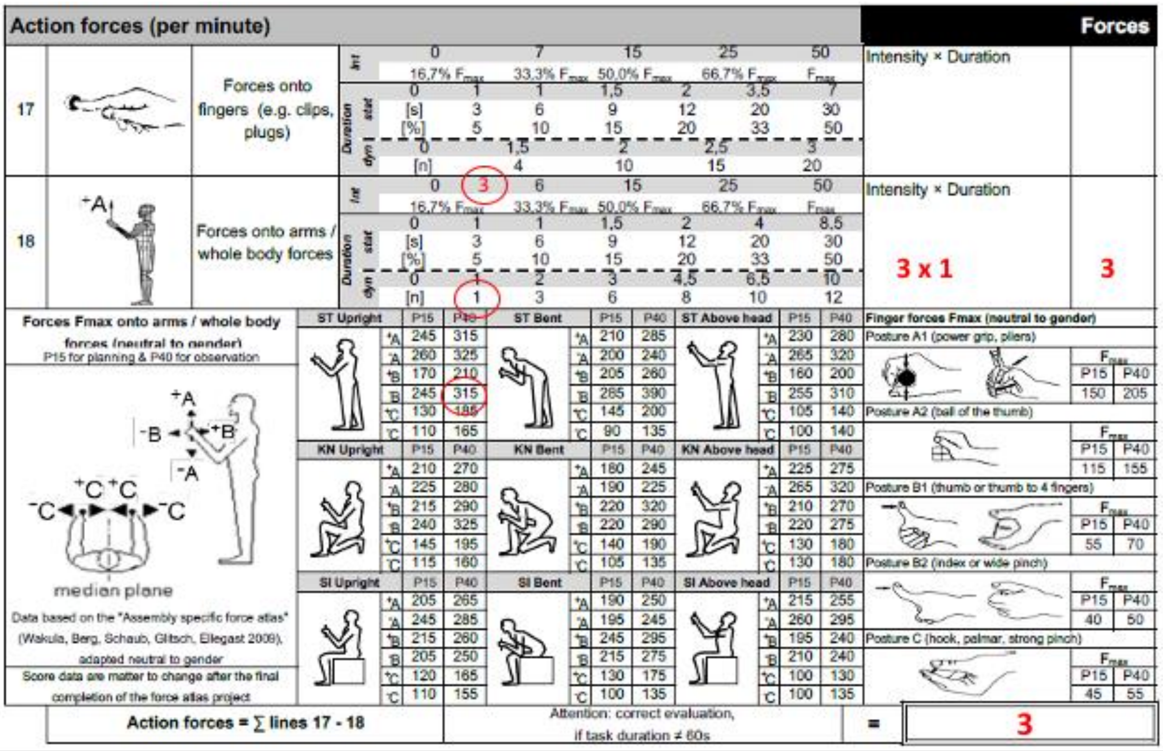
	Severity of harm			
Probability of occurrence	(L3) Catastrophic	(L2) Serious	(L1) Moderate	(L0) Minor
(L3) Very likely	High (3)	High (3)	High (3)	Medium (2)
(L2) Likely	High (3)	High (3)	Medium (2)	Low (1)
(L1) Unlikely	Medium (2)	Medium (2)	Low (1)	Negligible (0)
(L0) Remote	Low (1)	Low (1)	Negligible (0)	Negligible (0)

APPENDIX C – PHYSICAL ERGONOMICS EVALUATION

EAWS (Schaub et al., 2013) has been used to evaluate *Physical ergonomics* sub-dimension. EAWS is divided in two macro-sections: Whole body and Upper limbs. The Whole-body macro-section is composed of four sections: Extra Points, Body Posture, Action forces and Manual material handling. The Upper limbs macro-section is composed of only one section, i.e. Upper limb load in repetitive tasks. Figures 3,4,5,6,7 and 8 show the evaluation of each EAWS section for the parking pawl assembly task.

Extra points "Whole body" (per minute / shift)									Extra points
0a	Adverse effects by working on moving objects	0 none		3 middle	8 strong		15 very strong		Intensity **3**
0b	Accessibility (e.g. entering motor or passenger compartment)	0 good		2 complicated	5 poor		10 very poor		Status **/**
0c	Countershocks, impulses, vibrations	0 light		1 visible	2 heavy		5 very heavy		Intensity × frequency **1 x 3 = 3**
		0 [n]	1 1 - 2	2,5 4 - 5	3 6	4 8 - 10	6 18 - 20	8 > 20	
0d	Joint position (especially wrist)	0 neutral		1 ~ 1/3 max	3 ~ 2/3 max		5 maximal		Intensity × duration or frequency **/**
		0 [s] [n] [%]	2 3 1 5	2,5 10 8 17	4 20 11 33	6 40 16 67	8 60 20 100		
0e	Other physical work load (please describe in detail)	0 none		5 middle	10 strong		15 very strong		Intensity **/**
	Extra = ∑ lines 0a – 0e	Attention: Max. score = 40 (line 0c, 0d); Max. score = 15 (line 0a, 0e); Max. score = 10 (line 0b)			Attention: correct evaluation, if duration of evaluation ≠ 60 s				= **6**
	Lines 0a-b mainly relate to the Automotive Industry, for other sectors additional elements may be necessary. For details see the EAWS manual.								

Figure 3 – Extra Points section of EAWS. Evaluations for the task are provided in red.



Action forces (per minute) — **Forces**

No.	Load		Points / values							Intensity × Duration	Forces
17	Forces onto fingers (e.g. clips, plugs)	Int	0	7	15	25	50			Intensity × Duration	
			16,7% F_{max}	33,3% F_{max}	50,0% F_{max}	66,7% F_{max}	F_{max}				
		Duration stat	0	1	1	1,5	2	3,5	7		
		[s]		3	6	9	12	20	30		
		[%]		5	10	15	20	33	50		
		dyn	0	1,5	2	2,5	3				
		[n]		4	10	15	20				
18	Forces onto arms / whole body forces	Int	0	3	6	15	25	50		Intensity × Duration	
			16,7% F_{max}	33,3% F_{max}	50,0% F_{max}	66,7% F_{max}	F_{max}			3 x 1	3
		Duration stat	0	1	1	1,5	2	4	8,5		
		[s]		3	6	9	12	20	30		
		[%]		5	10	15	20	33	50		
		dyn	0	1	2	3	4,5	6,5	10		
		[n]		1	3	6	8	10	12		

Forces Fmax onto arms / whole body forces (neutral to gender)
P15 for planning & P40 for observation

	ST Upright P15	ST Upright P40	ST Bent P15	ST Bent P40	ST Above head P15	ST Above head P40
+A	245	315	210	285	230	280
-A	260	325	200	240	265	320
+B	170	210	205	260	160	200
-B	245	315	265	390	255	310
+C	130	185	145	200	105	140
-C	110	165	90	135	100	140

	KN Upright P15	KN Upright P40	KN Bent P15	KN Bent P40	KN Above head P15	KN Above head P40
+A	210	270	180	245	225	275
-A	225	280	190	225	265	320
+B	215	290	220	320	210	270
-B	240	325	220	290	220	275
+C	145	195	140	190	130	180
-C	115	160	105	135	130	180

	SI Upright P15	SI Upright P40	SI Bent P15	SI Bent P40	SI Above head P15	SI Above head P40
+A	205	265	190	250	215	255
-A	245	285	195	245	260	295
+B	215	260	245	295	195	240
-B	205	250	215	275	210	240
+C	120	165	130	175	100	130
-C	110	155	100	135	100	135

Data based on the "Assembly specific force atlas" (Wakula, Berg, Schaub, Glitsch, Ellegast 2009), adapted neutral to gender

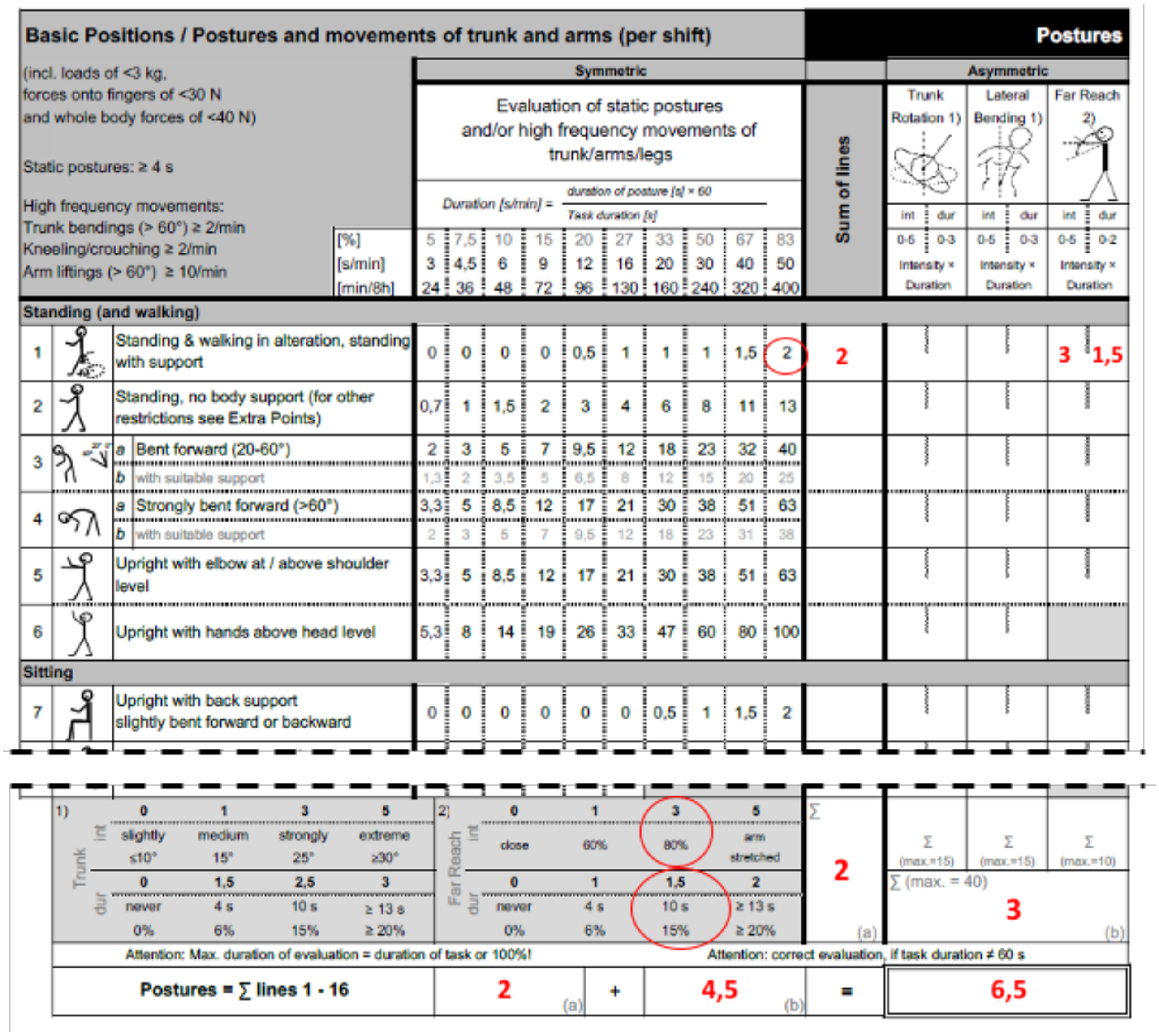
Score data are matter to change after the final completion of the force atlas project

Finger forces Fmax (neutral to gender)

Posture	F_{max} P15	F_{max} P40
Posture A1 (power grip, pliers)	150	205
Posture A2 (ball of the thumb)	115	155
Posture B1 (thumb or thumb to 4 fingers)	55	70
Posture B2 (index or wide pinch)	40	50
Posture C (hook, palmar, strong pinch)	45	55

Action forces = ∑ lines 17 - 18 — Attention: correct evaluation, if task duration ≠ 60s — = 3

Figure 4 – Action forces section of EAWS. Evaluations for the task are provided in red.



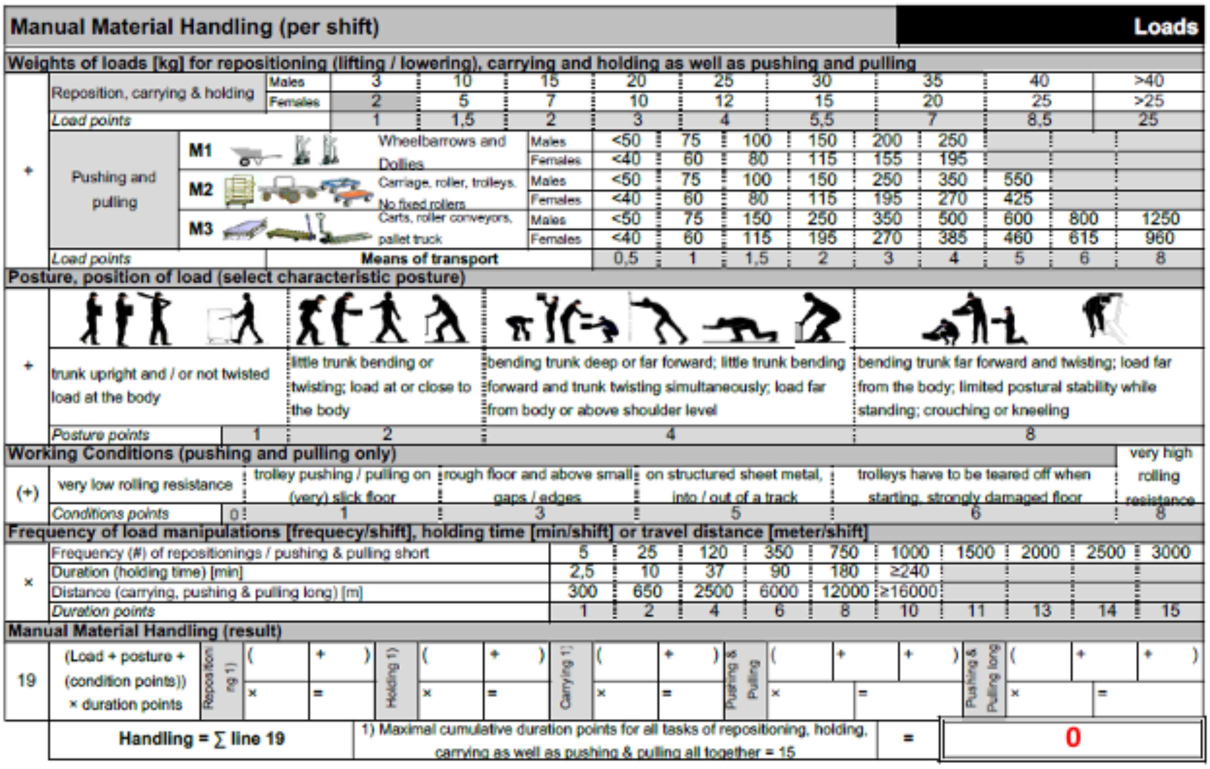
Basic Positions / Postures and movements of trunk and arms (per shift)														Postures		
(incl. loads of <3 kg, forces onto fingers of <30 N and whole body forces of <40 N) Static postures: ≥ 4 s High frequency movements: Trunk bendings (> 60°) ≥ 2/min Kneeling/crouching ≥ 2/min Arm liftings (> 60°) ≥ 10/min		Symmetric: Evaluation of static postures and/or high frequency movements of trunk/arms/legs. Duration [s/min] = duration of posture [s] × 60 / Task duration [s]											Sum of lines	Asymmetric: Trunk Rotation 1)	Lateral Bending 1)	Far Reach 2)
	[%]	5	7,5	10	15	20	27	33	50	67	83		int 0-5, dur 0-3	int 0-5, dur 0-3	int 0-5, dur 0-2
	[s/min]	3	4,5	6	9	12	16	20	30	40	50		Intensity × Duration	Intensity × Duration	Intensity × Duration
	[min/8h]	24	36	48	72	96	130	160	240	320	400				
Standing (and walking)															
1 Standing & walking in alteration, standing with support		0	0	0	0	0,5	1	1	1	1,5	2	2			3 1,5
2 Standing, no body support (for other restrictions see Extra Points)		0,7	1	1,5	2	3	4	6	8	11	13				
3 a Bent forward (20-60°)		2	3	5	7	9,5	12	18	23	32	40				
3 b with suitable support		1,3	2	3,5	5	6,5	8	12	15	20	25				
4 a Strongly bent forward (>60°)		3,3	5	8,5	12	17	21	30	38	51	63				
4 b with suitable support		2	3	5	7	9,5	12	18	23	31	38				
5 Upright with elbow at / above shoulder level		3,3	5	8,5	12	17	21	30	38	51	63				
6 Upright with hands above head level		5,3	8	14	19	26	33	47	60	80	100				
Sitting															
7 Upright with back support slightly bent forward or backward		0	0	0	0	0	0	0,5	1	1,5	2				

1) Trunk	0	1	3	5	2) Far Reach	0	1	3	5	∑			
int	slightly ≤10°	medium 15°	strongly 25°	extreme ≥30°	int	close	60%	80%	arm stretched	2 (a)	∑ (max.=15)	∑ (max.=15)	∑ (max.=10)
	0	1,5	2,5	3		0	1	1,5	2		∑ (max. = 40) 3 (b)		
dur	never 0%	4 s 6%	10 s 15%	≥ 13 s ≥ 20%	dur	never 0%	4 s 6%	10 s 15%	≥ 13 s ≥ 20%				

Attention: Max. duration of evaluation = duration of task or 100%! Attention: correct evaluation, if task duration ≠ 60 s

Postures = ∑ lines 1 - 16	2 (a)	+	4,5 (b)	=	6,5

Figure 5 – Body Postures section of EAWS. Evaluations for the task are provided in red.



Manual Material Handling (per shift) — **Loads**

Weights of loads [kg] for repositioning (lifting / lowering), carrying and holding as well as pushing and pulling

+	Reposition, carrying & holding	Males	3	10	15	20	25	30	35	40	>40
		Females	2	5	7	10	12	15	20	25	>25
	Load points		1	1,5	2	3	4	5,5	7	8,5	25

+	Pushing and pulling	M1 Wheelbarrows and Dollies	Males	<50	75	100	150	200	250			
			Females	<40	60	80	115	155	195			
		M2 Carriage, roller, trolleys. No fixed rollers	Males	<50	75	100	150	250	350	550		
			Females	<40	60	80	115	195	270	425		
		M3 Carts, roller conveyors, pallet truck	Males	<50	75	150	250	350	500	600	800	1250
			Females	<40	60	115	195	270	385	460	615	960
	Load points	Means of transport		0,5	1	1,5	2	3	4	5	6	8

Posture, position of load (select characteristic posture)

+	trunk upright and / or not twisted load at the body		little trunk bending or twisting; load at or close to the body	bending trunk deep or far forward; little trunk bending forward and trunk twisting simultaneously; load far from body or above shoulder level	bending trunk far forward and twisting; load far from the body; limited postural stability while standing; crouching or kneeling
	Posture points	1	2	4	8

Working Conditions (pushing and pulling only)

(+)	very low rolling resistance		trolley pushing / pulling on (very) slick floor	rough floor and above small gaps / edges	on structured sheet metal, into / out of a track	trolleys have to be teared off when starting, strongly damaged floor	very high rolling resistance
	Conditions points	0	1	3	5	6	8

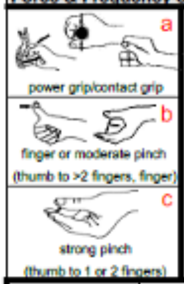
Frequency of load manipulations [frequecy/shift], holding time [min/shift] or travel distance [meter/shift]

×	Frequency (#) of repositionings / pushing & pulling short	5	25	120	350	750	1000	1500	2000	2500	3000
	Duration (holding time) [min]	2,5	10	37	90	180	≥240				
	Distance (carrying, pushing & pulling long) [m]	300	650	2500	6000	12000	≥16000				
	Duration points	1	2	4	6	8	10	11	13	14	15

Manual Material Handling (result)

19	(Load + posture + (condition points)) × duration points	Repositioning 1)	(+) × =	Holding 1) (+) × =	Carrying 1) (+) × =	Pushing & Pulling (+ +) × =	Pushing & Pulling long (+ +) × =
	Handling = ∑ line 19		1) Maximal cumulative duration points for all tasks of repositioning, holding, carrying as well as pushing & pulling all together = 15		=	0	

Figure 6 – Manual materials handling section of EAWS. Evaluations for the task are provided in red.



Upper limb load in repetitive tasks		Upper Limbs
Force & Frequency & Grip (FFG)	Basis: number of real actions per minute or percent static actions (analyze only the most loaded limb)	
a power grip/contact grip	%SA = Percentage of Static Actions	%DA = 100% - %SA
b finger or moderate pinch (thumb to >2 fingers, finger)	FDS = Force-Duration Static	FFD = Force-Frequency Dynamic
c strong pinch (thumb to 1 or 2 fingers)	GS' = Modified Grip Points Static (Grip x %SA)	GD = Grip Points Dynamic
Legend	%FLS = Percentage of Static Actions at force level	%FLD = Percentage of Dynamic Actions at force level
	SC = Static Contribution	DC = Dynamic Contribution
	FDGS = Sum of Static Contributions	FFGD = Sum of Dynamic Contributions

Force [N]	Calc Stat FDS	GS'	%FLS	SC	Static actions (s/min) ≥45	30	20	10	5	3	Grip 0	2	4	Dynamic actions (real actions/min) 2-5	10	15	20	25	30	35	≥40	Calc Dyn FFD	GD	%FLD	DC
0 – 5					1	1	0	0	0	0	abc			0	0	0	1	2	3	4	7	7	0	48	3,4
> 5 – 20	2,2	0,2	14	0,3	4	2	1	1	0	0	ab	bc		0	0	1	2	3	4	6	9	9	0,3	12	1,1
> 20 – 35	3,2	0	86	2,7	7	5	3	2	1	1	ab	b	c	0	1	2	3	4	6	8	12				
> 35 – 90					11	8	5	3	2	1	a	b	b	1	2	3	5	7	9	12	18				
> 90 – 135					16	11	7	4	3	2	a	ab	b	2	3	5	7	9	12	15	24				
> 135 – 225					21	14	10	6	4	3	a	a	b	4	5	6	8	11	14	20	32				
> 225 – 300					28	18	12	8	5	4	a	a	b	5	6	7	9	12	16	26	40				

20a FDGS = ∑ SC$_i$ (100%) **3** | FFG = FDGS + FFGD **7,5** FFG | %DA = ΣFLD$_i$ FFGD = ∑ DC$_i$ (%DA) **4,5**

Hand / arm / shoulder postures (use duration for worst case of wrist / elbow / shoulder)
Wrist (deviaton, flex./extens.) > 15° > 20° > 45° | Elbow (pron, sup, flex./extens.) 60° | Shoulder (flexion, extension, abduction) 45° If shoulders are involved close to or above shoulder 80°

20d Work Organization Points	0		1				2		
Breaks (≥ 8 min) [#/shift]	0	1	2	3	4	5	6	≥7	
Break points cycle time ≤ 30 s	3	2	1	0	-1	-2	-3	-4	+
cycle time > 30 s	0		-0,5		-1		-1,5	-2	
Duration Points									= DP

Upper limb load in repetitive tasks								
20	(a) Force & Frequency & Grip (**7,5** FFG	+	(b) Postures **0** PP	+	(c) Additional factors **0** AF)	×	(d) Duration **0** DP	= Upper Limbs **7,5**

Figure 7 – Manual materials handling section of EAWS. The evaluations for the task are provided in red.

Result of overall evaluation:

☑ green ☐ yellow ☐ red	WHOLE BODY	=	Postures	+	Forces	+	Manual handling	+	Extra	UPPER LIMBS
	15,5	=	6,5	+	3	+	0	+	6	7,5

EAWS evaluation		
0-25 Points	green	Low risk: - recommended; no action is needed
26-50 Points	yellow	Possible risk: – not recommended; redesign if possible, otherwise take other measures to control the risk
>50 Points	red	High risk:– to be avoided; action to lower the risk is necessary

Figure 8 – Overall score of EAWS. The evaluations for the task are provided in red.