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EXECUTIVE SUMMARY

This deliverable summarises the early multi-human-multi-robot (MH–MR) evaluation of the SOPRANO prototypes across three use cases: KUKA, CRF, and E-TERRY. The assessment examined how workers experience collaboration with these robotic platforms during operational scenarios, focusing on key human factors such as workload, emotional responses, safety perception, comfort, and trust.

Despite differences in context and functionality, the results show a consistent trend: robot behaviours that are predictable, transparent, and well-paced support smoother interaction, higher perceived safety, and lower cognitive demand. In contrast, fast or insufficiently communicative behaviours increased effort, frustration, and perceived risk.

The insights gained will guide the next development phase by informing improvements to robot autonomy, communication cues, and shared control mechanisms. Overall, the results provide a strong foundation for advancing safe, efficient, and user-centred multi-human–multi-robot collaboration within the SOPRANO project.

LIST OF ACRONYMS

BIM	Building Information Modelling
CRF	Centro Ricerche Fiat
HMI	Human-Machine Interface
GUI	Graphical User Interface
MH-MR	Multi Human-Multi Robot
NASA-TLX	NASA Task Load Index
SAM	Self-Assessment Manikin
SART	Situation Awareness Rating Technique
SUS	System Usability Scale
UI	User Interface
UR	Universal Robot
WS	Workstation

1. INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This deliverable examines the SOPRANO robotic platforms through the lens of human experience, focusing on how workers interact with and respond to the robots during shared tasks. The evaluation explores well-being, satisfaction, and the perceived fluency and effectiveness of teamwork, as these factors strongly influence overall system performance in multi-human–multi-robot (MH-MR) environments.

The evaluation covers three use cases: residential building renovation led by KUKA, vehicle door disassembly coordinated by CRF, and symbiotic farming carried out by E-TERRY. Each case is first introduced by outlining its main human–robot interaction features and the use case scenarios considered during early prototype testing. This is followed by an overall assessment of sociotechnical design requirements defined in deliverable *D1.3 Early Prototype Framework Requirements for MH-MRs*, evaluating the extent to which they are currently fulfilled.

In addition, quasi-experiments tailored to each use case's needs and technical potentials were designed and implemented to empirically examine the influence of various robotic aspects on human users. These aspects include the usability of the current robotic platforms, and configurations regarding speed and distance, which affect human experience, trust, cognitive workload, and situation awareness, ultimately contributing to human well-being in these interactive systems.

The results of these evaluations, together with the assessment of sociotechnical requirements, provide the foundation for recommendations that guide the human-centred development of the SOPRANO robotic platforms toward the final prototype.

It should be noted that this deliverable does not include a dedicated safety analysis. Safety is a fundamental factor for human well-being; however, it has been addressed in *D5.3 Use Case Evaluation I* under the technical component of the Safety Tools (DSA and RSA) and will be addressed in more detail in *D3.3 Technologies for Safety Analysis and Testing of MH-MR Systems II*. In this deliverable, safety is considered only in terms of subjective perception and its relation to broader human-related factors.

1.2 INTENDED READERSHIP

This deliverable *D5.4 Analysis of MH-MR Collaboration in Early Prototype Evaluations* is a public document. Foremost, it is intended for the technical project partners within the SOPRANO project to ease and guide technological development in a human-centred manner. Therefore, aiming to improve human well-being and performance through robot- and AI-driven collaboration in socio-technical systems. Additionally, the document is intended for a public readership especially for academia and relevant industries that are interested in human-robot collaboration in diverse industry sectors.

1.3 RELATIONSHIP TO OTHER DELIVERABLES

This deliverable builds on deliverable *D5.3 Use Cases Evaluation I*, which focused on the technical implementation of components and their integration into early prototypes,

by examining how these components and the current configuration of the robotic platforms affect human users and their interaction with robots. It also continues the work of *D1.3 Early Prototype Framework Requirements for MH-MRs* by evaluating the fulfilment status of the sociotechnical requirements defined therein.

1.4 OVERVIEW

This document is organised into three main sections, each corresponding to one SOPRANO use case. For each use case, the structure guides the reader based on the flowchart presented in Figure 1.

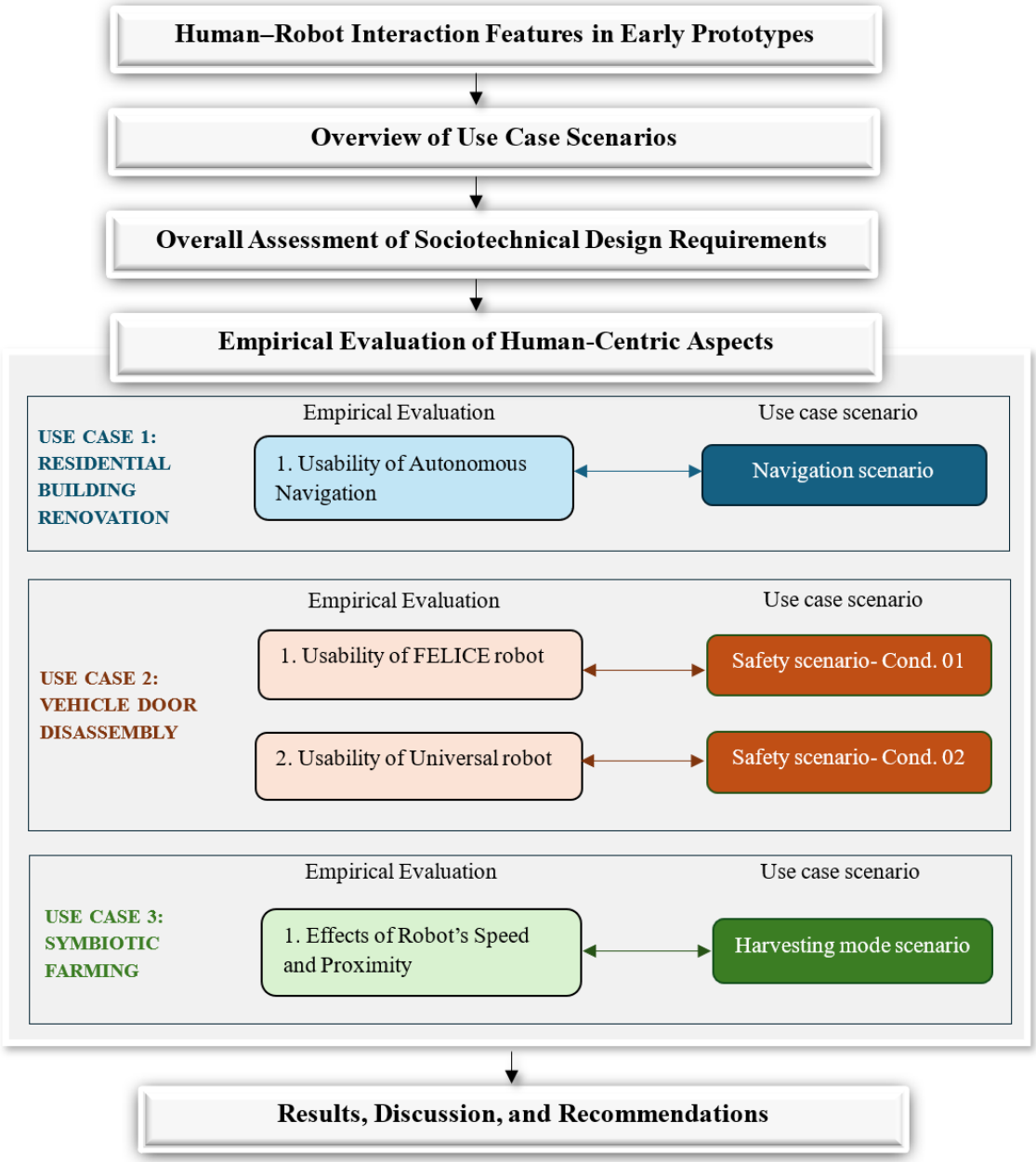


Figure 1: The structure of the evaluation for each use case

2. ANALYSIS OF MH-MR COLLABORATION FOR USE CASE 1: RESIDENTIAL BUILDING RENOVATION

KUKA has developed a flexible robotic platform designed for building renovation, capable of partially or fully automating tasks such as measuring, drilling, and milling. As part of the SOPRANO project, the robotic platform is being applied specifically to support the installation of electrical cables in collaboration with human workers.

The platform features a compact crawler vehicle equipped with an interchangeable end effector. A human operator positions the robot inside the building and defines task parameters through a Human-Machine Interface (HMI). Once configured, the robot can autonomously navigate between rooms, performing complementary tasks that support the human worker. The collaboration follows a sequential workflow, demanding high spatial and temporal awareness from both the human and the robot to optimize efficiency. While the human can move freely around the robot, effective coordination remains critical to ensure safety and maintain productivity.

In the early prototype evaluation phase, the focus is on three scenarios: Localization, Navigation, and Data Handling (see deliverable *D5.3 Use Case Evaluation I*), each defined by specific robotic capabilities and modes of human-robot interaction, as detailed in Table 1 and the following subsections.

Table 1: Human–robot main interaction features in the early prototype for the KUKA use case

Team composition	One human - One robot Note: In the initial evaluation, based on the examined scenarios, the human-robot interaction involves one human and one robot. However, the KUKA use case generally features a setup with multiple humans and a single robot, where one human supervises the robot while others act as "bystanders" working in the shared environment with the robot.
Robot capabilities	- Localization - Object detection (humans, walls, and obstacles) - Autonomous navigation - Communicating with operators via GUI, auditory signals, and LED - Integrated safety mechanisms (safety button and safety stop mechanism)
Human roles	- Supervisor
Interaction	**Supervisor** The supervisor monitors the robot, provides task instructions, and intervenes when the robot fails. Responsibilities include: - Providing first-level support - Moving the robot to the starting position - Entering the BIM data file - Configuring the systems and initiating autonomous operation - Intervening in the event of a robot failure during operation - Remotely controlling the robot when necessary

2.1 EARLY PROTOTYPE EVALUATION SCENARIOS

2.1.1 Scenario 1: Localization

The renovation robot uses advanced sensors and cameras to scan the environment and support precise localization. It processes this data to understand the room's dimensions, layout, and object placement. By analysing this information, the robot can determine its exact position within the room. A human supervisor monitors the process and intervenes if localization is unsuccessful.

2.1.2 Scenario 2: Navigation

The renovation robot is designed for autonomous navigation within indoor environments. It can detect and follow predefined paths, moving from room to room while avoiding obstacles. This capability is essential for meeting safety requirements in collaborative settings, where shared workspaces and sequential workflows require reliable and human-centric design.

2.1.3 Scenario 5: Data Handling

Robot configuration begins with importing Building Information Modelling (BIM) data, which offers a comprehensive overview of the construction project requirements. BIM data, along with additional information such as log files and system status, is accessible through a web client. An efficient user interface (UI) is essential to ensure both functionality and ease of use. It should provide a clear data overview, enable fast data processing, and support the visualization of relevant maps.

2.2 EVALUATION APPROACH

2.2.1 Overall Assessment of Sociotechnical Design Requirements

This section evaluates the fulfilment status of the 20 requirements defined for the KUKA use case in *D1.3 Early Prototype Framework Requirements for MH-MRs*. The analysis considers the scenarios and components examined during the early evaluation phase, with each requirement classified as: 'Completely fulfilled', 'Partially fulfilled', or 'Not fulfilled at this stage'. Table 2 presents the results.

Table 2: Overall Assessment of Sociotechnical Design Requirements for the KUKA use case

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
K.01	The user should easily read and understand the BIM-based information prior to the start of the overall working task.	SHOULD	- Advanced Visualization (AVT)	Partially fulfilled	
K.02	Any manipulation should provide feedback on the successful execution of the action	SHOULD	- Advanced Visualization (AVT)	Not fulfilled at this stage	
K.03	The user should be able to easily switch on the robot as a preparation for human-robot collaborative operations.	SHOULD	- KUKA robot capability**	Completely fulfilled	
K.04	The system should provide a clear indicator of its state (i.e., power on)	SHOULD	- Advanced Visualization (AVT)	Completely fulfilled	Through GUI and LEDs
K.05	The user should easily control the robot to the designated position for autonomous robot execution	SHOULD	- KUKA robot capability	Completely fulfilled	Through the joystick and the remote control
K.06	The system shall clearly indicate which entity (human or robot) has control over the task execution and signal any transition of authority.	SHALL	- Advanced Visualizations [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
K.07	The user shall be aware of the position of the robot during autonomous route execution/navigation	SHALL	- Advanced Visualizations [AVT]	Completely fulfilled	
K.08	Robot and human users sharing a common working space shall be mutually aware of the dynamic positioning, monitor proximity limits	SHALL	- Safety Tools (DSA & RSA)	Partially fulfilled	Risks were modelled with hazards, causes, and mitigations during the design phase; monitoring and integrating mitigation actions at runtime are ongoing and planned for the final prototype.
K.09	The robot shall communicate (unintentional) proximity violations/conflicts.	SHALL	- Safety Tools [RSA & DSA]	Completely fulfilled	Through the LED on the robot
K.10	The robot shall inform the user for the need to relocate to meet the task execution positioning	SHALL	- Advanced Visualizations [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
	requirements		- Mapping Robotic Capabilities [MRC]		
K.11	The user shall control/change the mounted end-effector in accordance with the planned task.	SHALL	-		
K.12	The robot may support the user in their decision, e.g., by warning if an unsuitable tool is selected	MAY	- Object Perception [OBP]	Not fulfilled at this stage	
K.13	The robot shall indicate task completion and notify the user for the time for the quality control check.	SHALL	- Advanced Visualizations [AVT] - MH-MR Task Allocation [CTA]	Partially fulfilled	Currently, the status of the task is displayed in GUI.
K.14	The robot shall cease any operations after the notification during the necessary user approach to and dwell at to the working object for the purpose of quality control/manual post-processing.	SHALL	- Safety Tools [RSA & DSA] - MH-MR Task Allocation [CTA] - Mapping Robotic Capabilities (MRC)	Completely fulfilled	
K.15	User shall approve the transition to the next working object/working zone with the workspace (or back to the start position if autonomous navigation) after performing the quality control task	SHALL	- Advanced Visualizations [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
K.16	Robot should indicate the next working object /working zone or return to the starting point	SHOULD	- Advanced Visualization (AVT)	Partially fulfilled	
K.17	The system shall be designed to minimize the operator's mental workload during collaborative tasks (e.g., avoid excessive alarms; clear prioritization of warnings).	SHALL	- Advanced Visualizations [AVT]	Not fulfilled at this stage	
K.18	The robot shall notify the user in the face of detected problems during task execution	SHALL	- Advanced Visualizations [AVT]	Completely fulfilled	Through KUKA's GUI and LEDs
K.19	The robot should notify the user when returning to the start/shut down position.	SHOULD	- Advanced Visualization (AVT)	Not fulfilled at this stage	
K.20	The robot may indicate when the power is off.	MAY	- Advanced Visualization (AVT)	Completely fulfilled	

* The main components whose outputs directly affect the fulfilment of the requirement are considered. The supporting components are not included here.
** KUKA robot capability refers to functionalities that are not provided by the SOPRANO components.

2.2.2 Empirical Evaluation of Human-Centric Aspects

The following sections present an empirical evaluation examining the usability of the robot's autonomous navigation (Table 3). To address this aim, one field experiment was conducted in a near-realistic construction environment. In this experiment, participants collaborated with the KUKA renovation robot, primarily during the localization and navigation processes involved in electrical cabling. This setup enabled the collection of empirical data to evaluate how different modes of robotic support influence user experience.

Table 3: Main Characteristics of KUKA's Empirical Evaluation

Empirical Evaluation 1: Usability Assessment of the Robot's Autonomous Navigation				
Objective	**Conditions**	**KUKA robot tasks**	**Human tasks**	**Measures**
Usability of Autonomous Navigation	1. Remote control (baseline) 2. Autonomous navigation	Navigation	Supervisor: • Monitor status, • Detect failures. • Joystick control (Only in Cond. 1)	• Workload • Situation awareness • Affective state • Trust • System usability

2.3 EMPIRICAL EVALUATION: USABILITY ASSESSMENT OF THE ROBOT'S AUTONOMOUS NAVIGATION

The empirical evaluation of the KUKA use case was conducted to examine the effects of autonomous navigation on the human supervisor within the Navigation scenario. The evaluation aimed to assess the impact of robotic autonomy on usability, human trust, workload, and situation awareness.

Experimental Setup

This experiment involved the KUKA robot and human participants assigned to the role of supervisors. A between-subjects design was used, with four participants performing the task under remote control and three participants performing it under autonomous navigation.

(I) Condition 1 (Remote control-baseline): Robot operated via remote control

(II) Condition 2 (Autonomous navigation): Robot operated with autonomous navigation

Procedure

Prior to the experiment, participants received a general overview of the study, informing them that they would either supervise the KUKA robot or control it, depending on their assigned condition (remote control vs. autonomous navigation). To avoid bias, they were not informed about the specific purpose of the experiment or the detailed measures at this stage.

Before starting the main trials, participants completed a 5-minute training session. This included instructions on how to monitor the robot's behavior and system states, as well

as how to operate the robot using a joystick. A short familiarization trial was conducted to ensure participants felt confident with the setup.

At the beginning of each condition, the examiner positioned the robot at its initial location, performed the required configurations, and activated the respective mode (autonomous or remote control) before initiating the task. The navigation path comprised a 6 m distance from the start zone to point A, a 2 m distance from point A to point B, and a 4 m distance from point B back to the start zone (Figure 2). In the remote control condition (Condition 1), participants were instructed to manually guide the robot along a predefined navigation path using a joystick. In the autonomous navigation condition (Condition 2), participants were asked to monitor the robot's actions, remain aware of its system states, and identify any failures and their possible causes. They were not expected to configure the system or troubleshoot problems.

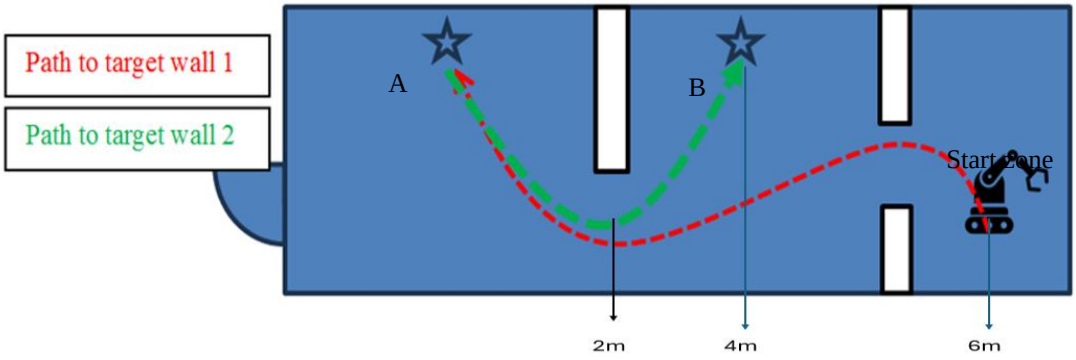


Figure 2: Path of the KUKA robot during navigation scenario

Each condition included two work cycles (i.e., navigating the robot from the start zone to multiple socket locations). After completing each condition, participants provided subjective ratings of workload, situation awareness, trust, and perceived system usability. The overall procedure of the empirical experiments is illustrated in Figure 3.

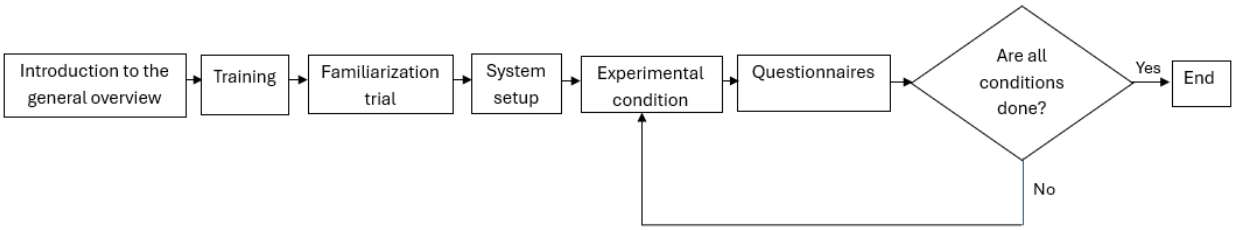


Figure 3: Procedure of the empirical experiment

Measures

- **Travel time** quantified how long the robot required to travel predefined distances under each control mode.
- **Human workload** was assessed using the NASA Task Load Index (NASA-TLX), which captures perceived workload across multiple subscales (Hart & Staveland, 1988).

- **Situation awareness** was assessed using the Situation Awareness Rating Technique (SART), which reflects attentional demand, available attentional resources, and understanding of the situation (Taylor, 2017).
- **Emotional state** was assessed using the Self-Assessment Manikin (SAM), measuring valence, arousal, and dominance through graphical rating scales (Bradley & Lang, 1994).
- **Trust in the robot** was assessed using the Trust Perception Scale–HRI, capturing perceived reliability, predictability, and supportiveness of the robot during task execution (Schaefer, 2016).
- **System usability** was assessed using the System Usability Scale (SUS), reflecting aspects such as ease of use, learnability, and user confidence across ten subscales (Brooke, 1996).

Controlled Variables

To ensure consistency across both conditions, the following variables were held constant across the conditions:

- The robot's path of movement and the targets
- The robot's speed

Participants

Seven engineers (six male and one female) participated in the KUKA robot experiment, all serving as supervisors. Their average age was 48 years (*SD* = 12.6), and 71% reported prior experience working with robots.

2.4 EMPIRICAL EVALUATION RESULTS AND DISCUSSION

2.4.1 Travel time

For each predefined distance, two runs were completed under both the remote control and autonomous navigation conditions. The average times for all trajectories are summarized in Table 4.

Table 4: Navigation time measurements under remote control and autonomous conditions

Distance (m)	Remote Control Time (sec)	Auto Navigation Time (sec)
6 m (start zone ==> A)	30.65	42.82
2 m (A ==> B)	9.41	13.38
4 m (B ==> start zone)	18.91	25.73

As illustrated in Figure 4, autonomous navigation consistently required more time than remote control across all distances, suggesting that further efficiency improvements may be needed for the autonomous mode in the final prototype.

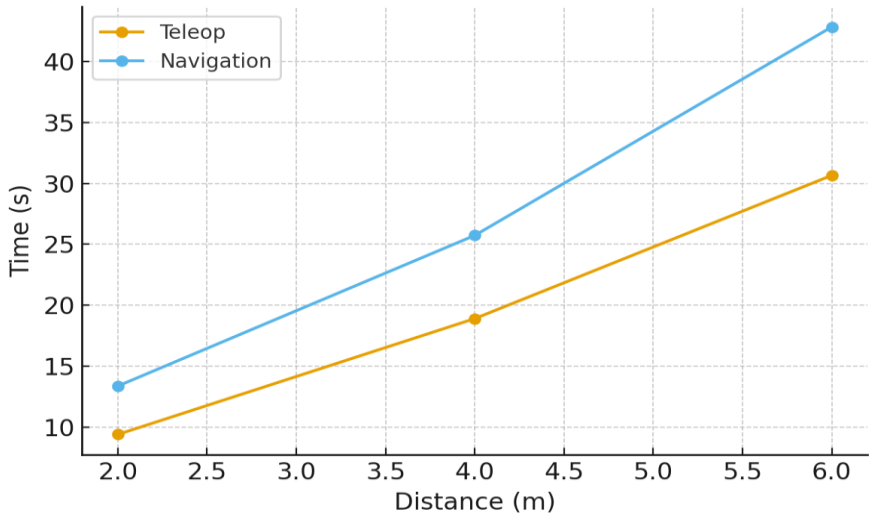


Figure 4: Comparison of travel time under remote control (orange) and autonomous navigation (blue)

Table 5: Summary of the human-factor results for KUKA use case

Measures	1 (Remote control) Mean (SD)	2 (Auto Navigation) Mean (SD)	T-test (Significant difference?) (alpha= 0.1)	Main findings
Workload (out of 100):				
Mental Demand	30 (18.71)	18.33 (2.89)	**No** (t (3) = 1.22, p =.31)	There were no significant differences between remote control and autonomous navigation in mental demand, physical demand, or temporal demand, whereas autonomous navigation resulted in poorer perceived performance (a stronger sense of not meeting the task requirements) and substantially higher frustration
Physical Demand	16.25 (7.5)	16.67 (7.64)	**No** (t (4) = -0.07, p =.95)	
Temporal Demand	22.5 (6.45)	18.33 (2.89)	**No** (t (4) = 1.15, p =.31)	
Performance	12.5 (5)	48.33 (7.64)	**Yes** (t (3) = -7.07, p =.01)	
Effort	20 (10.80)	20 (10)	**No** (t (5) = 0, p = 1)	
Frustration	16.25 (11.09)	56.67 (12.58)	**Yes** (t (4) = -4.42, p =.01)	
Emotional state (out of 5):				
Valence	4.5 (0.58)	3.67 (0.58)	**No** (t (4) = 1.89, p =.13)	Emotional state measures did not differ significantly between the two conditions, indicating that valence, arousal, and dominance were largely unaffected by the mode of robot operation.
Arousal	1.75 (0.96)	2 (0)	**No** (t (3) = -0.52, p =.64)	
Dominance	4.5 (0.41)	2.83 (1.44)	**No** (t (2) =1.94, p =.19)	
Trust- HRI (out of 100):	64.29 (4.21)	33.57 (2.14)	**Yes** (t (3) = 12.59, p < .001)	Participants reported significantly lower trust in the robot during autonomous navigation, with trust scores significantly reduced compared to the remote-control condition.
Usability (out of 5):	4.4 (0.22)	3.83 (0.06)	**Yes** (t (4) = 5.01, p =.01)	Autonomous navigation led to significantly lower perceived usability compared to remote control, reflecting reduced user satisfaction and ease of use in this mode.
Situation awareness (out of 7):				
Demand on Attentional Resources	7.25 (0.96)	11.33 (2.52)	**No** (t (2) = -2.67, p =.12)	Autonomous navigation significantly enhanced situation awareness, with higher scores in attentional resource supply and situation understanding, although attentional demand did not differ between conditions.
Supply of Attentional Resources	15.50 (1.91)	18.17 (0.76)	**Yes** (t (3) = -2.53, p =.06)	
Understanding of the Situation	8.75 (0.96)	13.5 (2.60)	**Yes** (t (2) = -3.02, p =.09)	

2.4.2 Workload

The NASA-TLX was used to assess how demanding it was for participants to supervise the KUKA robot under manual and autonomous navigation. Lower scores indicate that participants experienced the task as less demanding, reflecting a smoother and more efficient interaction with the robot. As illustrated in

Figure 5, the “Performance” and “Frustration" ratings increased significantly in the autonomous navigation condition, suggesting that participants felt less successful in accomplishing the task and experienced higher levels of insecurity, discouragement, irritation, stress, or annoyance during this condition.

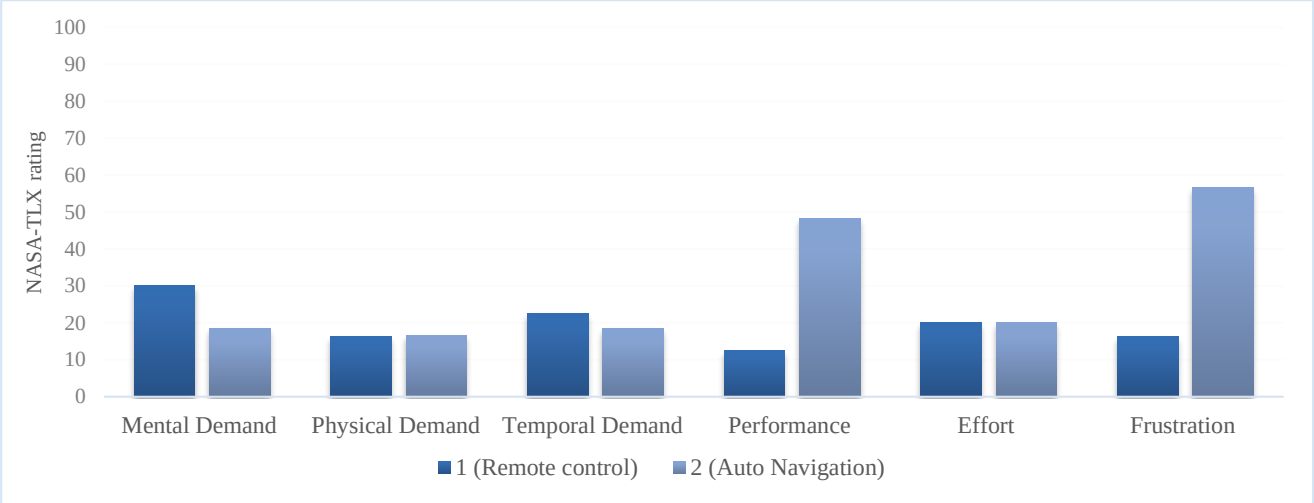


Figure 5: NASA-TLX rating scales for remote control and autonomous navigation modes

2.4.3 Emotional state

Emotional states were assessed using the SAM, which captures how pleasant, arousing, and controllable the experience felt while supervising the robot under manual and autonomous navigation conditions (Figure 6). Higher scores reflect more positive emotions (i.e., positive valence), greater excitement (i.e., arousal), and a stronger sense of control (i.e., dominance). As shown in Table 5, these emotional state measures were largely unaffected by the mode of robot operation.

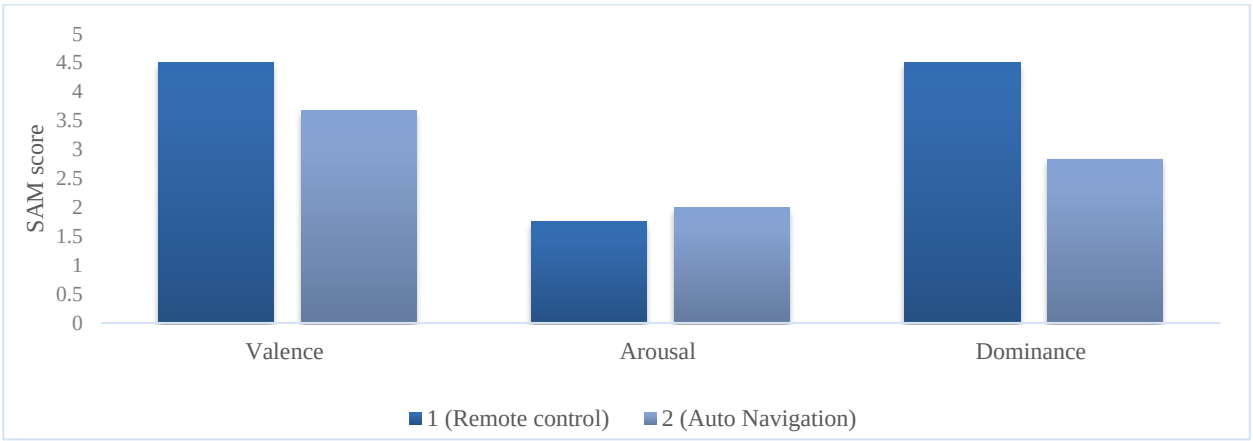


Figure 6: SAM scores for remote control and autonomous navigation modes

2.4.4 Trust

Trust in the robot was assessed using the Trust Perception Scale–HRI, which measures the extent to which users perceived the robot as dependable, predictable, and supportive during task execution. Higher scores indicate stronger trust in the robot's performance and behaviour. Participants reported significantly lower trust in the robot during autonomous navigation (Figure 7). Apart from the 'Provide feedback' item where autonomous navigation received a higher rating, trust scores decreased across all other items in this condition.

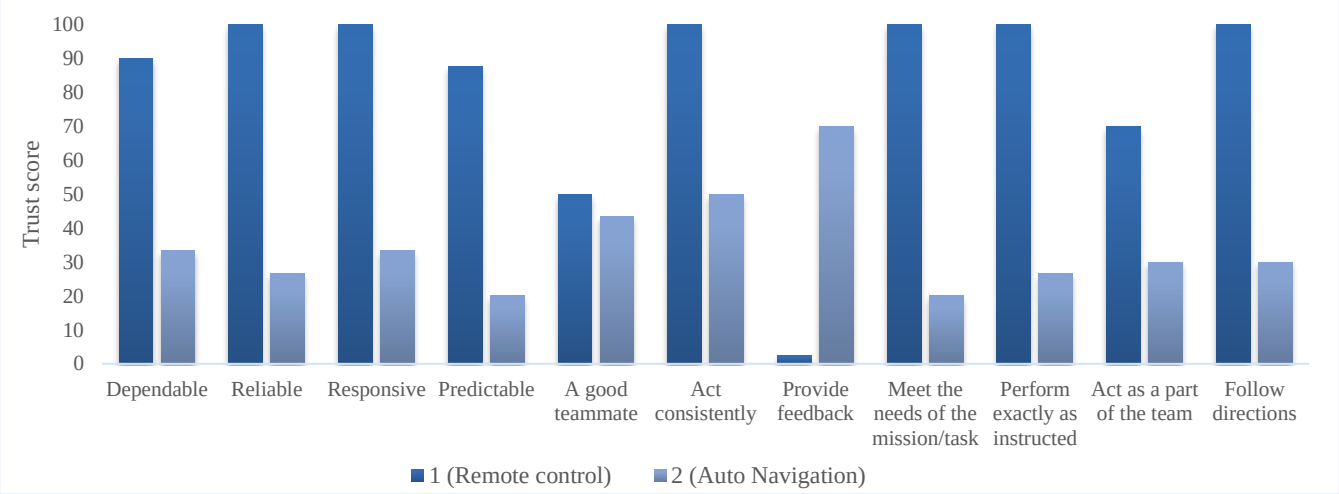


Figure 7: Trust scores for remote control and autonomous navigation modes

2.4.5 Usability

Perceived usability, assessed using the SUS, reflects how easy and efficient it was for participants to supervise and interact with the KUKA robot during manual and autonomous navigation. Higher scores indicate that participants found the system more intuitive, straightforward to operate, and satisfactory to use. As shown in Table 5, autonomous navigation led to significantly lower perceived usability compared to remote control, particularly in aspects related to system consistency and user confidence (Figure 8). These findings align with the trust results presented in Figure 7.

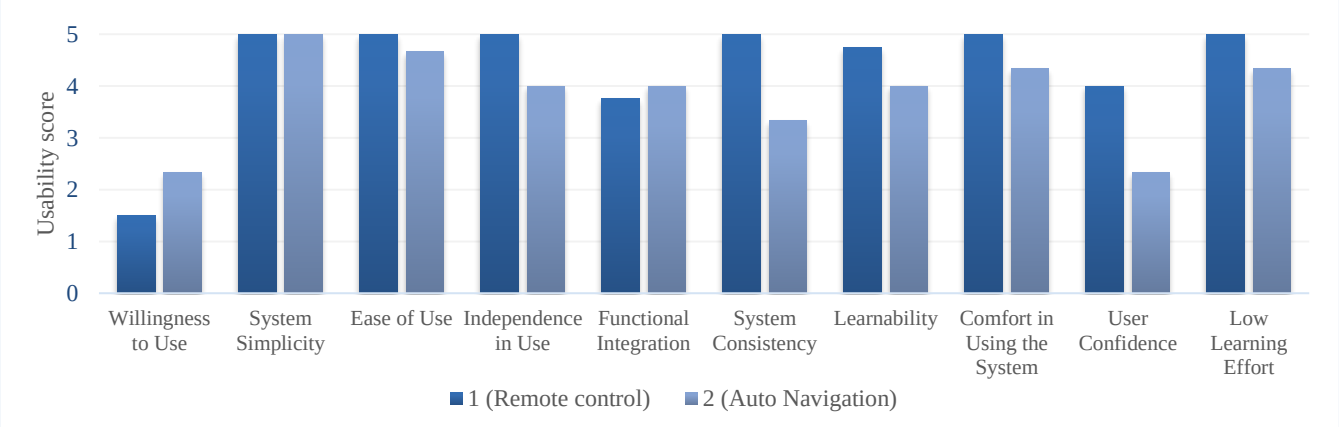


Figure 8: Usability scores for remote control and autonomous navigation modes

2.4.6 Situation Awareness

Participants' situation awareness, assessed using the SART, reflects how well they could follow and understand the robot's behaviour during manual and autonomous navigation. The measure captures how demanding the task was in terms of attention, how effectively participants could allocate their mental resources, and how well they understood the robot's state and upcoming actions. Based on Table 5, autonomous navigation significantly enhanced situation awareness, with higher scores in attentional resource supply and situation understanding (includes the scales from "Arousal" through "Familiarity"). Although attentional demand did not differ between conditions, the increased score for "Instability of situation" during autonomous navigation suggests that participants perceived this mode as more changeable and dynamic (Figure 9).

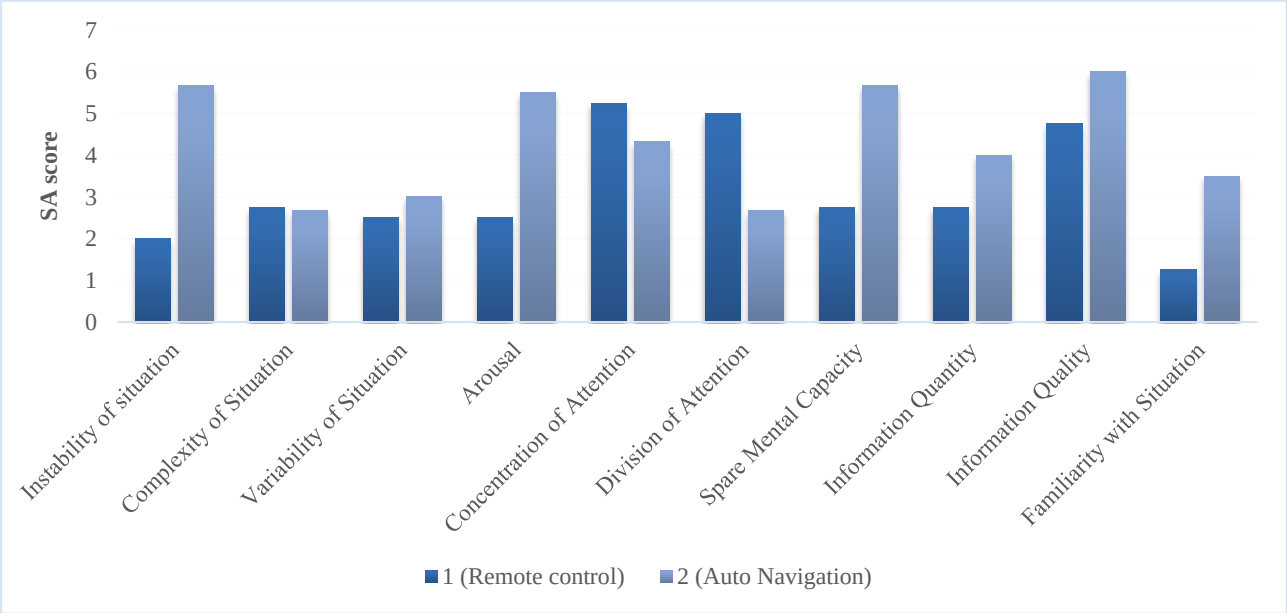


Figure 9: SA scores for remote control and autonomous navigation modes

2.5 SUMMARY OF FINDINGS

The early MH-MR evaluation of the KUKA use case provides an overview of how human supervisors experienced the robot under remote control and autonomous navigation. The findings highlight several strengths of the current prototype and identify aspects requiring refinement. The recommendations below focus on improving the overall quality of human-robot interaction and user experience in the final prototype.

Reduce frustration and improve perceived task success

The significant increase in frustration during autonomous navigation, together with lower perceived task success, suggests a mismatch between system operation and user expectations. Improving the consistency of system motion and responses, as well as providing clearer confirmation of task progress and completion, can help improve the overall interaction experience.

Increase user confidence and trust in autonomy

Trust and usability scores were significantly lower in the autonomous condition. This indicates a need to strengthen the perceived reliability of autonomous navigation, particularly by ensuring predictable and consistent behaviour across similar task executions.

Support situation awareness and system stability
Autonomous navigation significantly improved attentional resource supply and situation understanding. However, the higher perceived instability indicates that future designs should aim to preserve these awareness benefits while improving the stability of system operation.

Overall, the results indicate that the current autonomous navigation provides a solid foundation for supervisory interaction but requires further refinement to better align system operation with user expectations. Addressing these aspects in future development can support more reliable, acceptable, and effective human–robot interaction in real-world construction environments.

3. ANALYSIS OF MH-MR COLLABORATION FOR USE CASE 2: VEHICLE DOOR DISASSEMBLY

Centro Ricerche Fiat (CRF), the research and innovation centre of the automotive manufacturing company Stellantis, aims to leverage the advantages of MH–MR collaboration to support the development of highly flexible manufacturing processes. The particular focus in SOPRANO lays on the car door disassembly process. The target system consists of disassembly workstations dedicated to removing gaskets, carriers, rearview mirrors, glass panels, screws, and door panels. It incorporates two robots: FELICE, an autonomous mobile robot developed by ACCREA (https://accrea.com), and a six-axis Universal Robot (UR). These robots collaborate with human workers at two workstations (WS) to support component assembly/disassembly, and material transport.

The FELICE robot, equipped with an interactive head that displays information to users and collects video data from the environment, can grasp and release objects within the industrial settings. Within the SOPRANO project, it is responsible for handing over and receiving the tools required for the disassembly process. The UR is integrated with a DEPRAG Screwdriver Function Module end effector for automated unscrewing of the carrier, along with a camera and a machine vision algorithm to manage this phase. Effectively coordinating multiple robots and human workers is critical for optimizing assembly line efficiency.

The initial evaluation phase concentrates on the Safety and Reconfiguration scenarios (see deliverable *D5.3 Use Case Evaluation I*), each defined by specific robotic functionalities and human-robot interaction characteristics, as presented in Table 6 and the subsequent subsections.

Table 6: Human–robot main interaction features in the early prototype for the CRF use case

Team composition	Multi humans - Multi robots
Robot capabilities	FELICE robot: - Human behavioral modeling - Object detection (tools and doors) - Obstacle detection - Autonomous navigation - Handover - Communicating with operators through GUI and the LED - Integrated safety mechanisms UR10: - Object detection (screws and door) - Unscrewing - Communicating with operators through GUI - Integrated safety mechanisms (only a stop button and a stop mechanism for static objects)
Human roles	- Collaborator with the FELICE robot (Human Operators at WS 10) - Cooperator with the UR (Human operator at WS 20)
Interaction	**Human operator at WS 10** The human operator at WS 10 collaborates with the FELICE robot in handing over and receiving tools (i.e., screwdrivers) during the disassembly process.
	Human operator at WS 20 The human operator at WS 20 monitors the UR10 and disassembles the same door that the UR10 is working on, while maintaining a safe distance. Note: In the early prototype, based on the examined scenarios, the interaction involved one human and one robot at WS 20. In the final evaluation, however, this workstation features a setup with multiple robots, FELICE and UR10, and a single human operator. The operator at WS 20 monitors the UR10 and disassembles the same door that the UR10 is working on, while simultaneously collaborating with the FELICE robot to hand over and receive tools during the disassembly process.

3.1 EARLY PROTOTYPE EVALUATION SCENARIOS

3.1.1 Scenario 1: Safety

Within the Safety scenario, several sub-scenarios were defined to examine safety-related challenges in human–robot collaboration. These sub-scenarios for the early prototype evaluation are as follows:

1. Multi- human[1] collaboration with FELICE robot in WS 10
2. Multi- human collaboration with UR10 in WS 20

[1] The robot interacts with one human but can also monitor or pay attention to other humans at other WSs.

3.1.2 Scenario 2: Reconfiguration

This scenario reflects situations that may occur during real-world operation of the production system, involving workflow deviations such as tools being missing or not in their expected positions as detected by the robot, as well as components absent from the door that are identified by the human operator and reported to the system.

3.2 EVALUATION APPROACH

3.2.1 Overall Assessment of Sociotechnical Design Requirements

This section is dedicated to assessing how well the 36 requirements proposed for the CRF use case in deliverable *D1.3 Early Prototype Framework Requirements for MH-MRs* have been implemented, based on the scenarios and components examined during the early evaluation, using the scales: ‘Completely fulfilled’, ‘Partially fulfilled’, and ‘Not fulfilled at this stage’. The results are presented in Table 7.

Table 7: Overall Assessment of Sociotechnical Design Requirements for the CRF use case

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
C.01	The robot shall perform the tool handover and take back the tool with high reliability.	SHALL	- Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.02	Tools should not be dropped.	SHOULD	- FELICE robot capability**	Completely fulfilled	
C.03	Tools should be handed over in such a way that the user can grip them comfortably.	SHOULD	- Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.04	The robot shall indicate readiness to initiate the handover (approach phase).	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	It can also be done through LED indicators in addition to the GUI.
C.05	The robot should select and transfer the correct tools and parts.	SHOULD	- Object Perception [OBP] - Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.06	The robot may recognize when an unexpected tool or part is returned to the robot.	MAY	- Object Perception [OBP] - Robotic Capabilities Implementation [RCI]	Not fulfilled at this stage	
C.07	The user shall always have the authority and the ability to determine or even reject, if necessary, the actions.	SHALL	- Advanced Visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.08	The robot shall keep up with the speed and timing of the users' work elements and actions to not interrupt the user unnecessarily. At the same time, the user should not have to wait for the robot.	SHALL	- MH-MR Task Allocation [CTA]	Partially fulfilled	
C.09	The operator shall be trained to effectively hand over and take back tools or parts from the robot.	SHALL	-		
C.10	The user shall be informed who is responsible for the performance of the robot, especially in terms of error and failure mode handling.	SHALL	- Safety tools [RSA & DSA] - MH-MR Task Allocation [CTA]	Partially fulfilled	The mitigation actions are defined but are not integrated into CTA at the early prototype.

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
C.11	The user should be able to stop the robot upon its arrival at the workstation and go into standby mode.	SHOULD	- Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA] - Safety tools [RSA & DSA]	Partially fulfilled	It is addressed at DSA by identifying arrival at workstation scenarios requiring a monitored stop or standby state. RSA monitors arrival conditions and can issue safety or emergency stop signals, but the physical stop and transition to standby are executed by the robotic control layer.
C.12	The robot's body should not move in an unpredictable manner during handover.	SHOULD	- Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.13	The robot should not abandon the collaborative task until it has been performed and completed.	SHOULD	- Robotic Capabilities Implementation [RCI] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.14	The robot should provide meaningful warnings in failure and error cases using its display.	SHOULD	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA] - Robotic Capabilities Implementation [RCI]	Not fulfilled at this stage	
C.15	The workflow of the task and, therefore, the timing of when the robot is coming and handing over a specific tool or receives a part shall follow the same scheduling for every instance of collaboration at the given workstation.	SHALL	- MH-MR Task Allocation [CTA]	Completely fulfilled	
C.16	The user shall be able to monitor the behaviour of the robot at the workstation and the shop floor.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Partially fulfilled	The requirement is fully met for the FELICE robot (through GUI), but not for the UR10
C.17	The workflow shall not foster any authority-responsibility mismatches. For every step in the workflow, this must be clearly described and provided to the user, for instance, by training.	SHALL	- MH-MR Task Allocation [CTA]	Not fulfilled at this stage	

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
C.18	The process of information distribution on workflow and operator metrics should be coherent, accessible to all collaborative elements in the work system, and easy to understand, e.g., by symbols.	SHOULD	- Advanced visualization [AVT]	Partially fulfilled	The requirement is fully met for the FELICE robot (through GUI), but not for the UR10
C.19	A message signalling the intent of the robot shall be displayed and congruent/fit to the current joint activity.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Partially fulfilled	The requirement is met for the FELICE robot (through GUI), but not for the UR10
C.20	The robot shall indicate to the user that it is ready for tool handover after completing the arm movement.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.21	The handover completion shall be indicated immediately after the user receives the tool.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.22	The departure of the robot shall be indicated after handover completion and before departure.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Completely fulfilled	
C.23	The current state of the robot shall always be visible throughout the joint activity, but also in the approach and departure of the robot.	SHALL	- Advanced visualization [AVT]	Partially fulfilled	The requirement is fully met for the FELICE robot (through GUI), but not for the UR10
C.24	The information about the approach of the robot to the workstation shall be provided in good time before the robot enters the workstation.	SHALL	- Advanced Visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.25	The cues shall be designed such that additional (i.e., interaction-related) workload for the human is kept to a minimum by taking multiple resources theory into account, thus considering as well auditory signals.	SHALL	- Advanced Visualization [AVT]	Partially implemented	Different visualizations (LED and GUI) for the FELICE robot. Only one communication channel for UR10 (GUI)
C.26	The cues shall be designed to be redundant in joint activity during handing over the tool or the part at the workstation, hence visual and auditory, or visual and haptic, or haptic and auditory.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA] - FELICE robot capability	Completely fulfilled	During handover, the system provides visual feedback via the GUI.

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
C.27	The user shall at any given time be able to abort the handover.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.28	The user shall be able to reject the robot's handover request before the handover is initiated at the workstation.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.29	The user shall be able to call the robot to provide a tool during disassembly.	SHALL	- Advanced visualization [AVT]	Completely fulfilled	
C.30	The user shall be able to override intended actions throughout the process.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.31	The user shall be able to reject the robot for the given activity at any given time during work at the workstation.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.32	The user shall be able to request the robot to return the component at any time while being on the workstation.	SHALL	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
C.33	A spatial separation zone between the UR and FELICE robot should be set up (programmed) so that interference is inhibited. The separation zone can be marked on the ground by colour zones.	SHOULD	- Safety Tools [RSA & DSA]	Not fulfilled at this stage	
C.34	A signalling of potential conflicting spatial proximities shall be integrated.	SHALL	- Safety Tools [RSA & DSA]	Not fulfilled at this stage	
C.35	The robot's behaviour model shall be clearly described and communicated to the user.	SHALL	- Advanced Visualization [AVT] - MH-MR Task Allocation [CTA]	Partially fulfilled	A prospective view (what the robot is planned to do) and a real-time view (what the robot is currently doing): this requirement is partially met for the FELICE robot but not yet for the UR10.
C.36	Emergency shut-offs for the user shall be included.	SHALL	- Safety Tools [RSA & DSA] - FELICE robot capability	Partially fulfilled	For the FELICE robot, emergency shut off is

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
			- Robotic Capabilities Implementation [RCI]		provided at the hardware level (i.e., FELICE robot capability). For the UR10, emergency stop buttons are available on the teach pendant and via a physical button near the robot; integration into RCI is pending.

* Main components whose outputs directly affect the fulfilment of the requirement are considered. The basic components are not included here.
** FELICE robot capability refers to functionalities that are not provided by the SOPRANO components.

3.2.2 Empirical Evaluation of Human-Centric Aspects

The following sections examine the impact of integrating the FELICE and UR robots into the disassembly process and how they support human operators at WS 10 and 20. Two empirical evaluations were conducted at these workstations to assess the usability of the FELICE and UR robots, respectively (Table 8). The evaluations consisted of two experiments carried out in the CRF assembly/disassembly area under near-realistic conditions for task performance. Participants collaborated with the FELICE and UR robots during the car door disassembly process, enabling the collection of empirical data to assess the effects of robotic support on human performance and experience.

Table 8: Main Characteristics of CRF's Empirical Evaluations

Empirical Evaluation 1: Usability Assessment of the FELICE robot at WS 10					
Objective	**Conditions**	**FELICE robot tasks**	**UR10 tasks**	**Human tasks**	**Measures**
Assess the impact of integrating the FELICE robot at WS10 on the human operator	1. Manual (baseline) 2. With the FELICE robot's support	Handing over and receiving tools	-	Disassembly based on the defined workflow (Figure 11)	• Usability • Workload • Perceived safety • Emotional states • Trust • Team fluency (Cycle time, Human/robot idle times, Interaction time)
Empirical Evaluation 2: Usability Assessment of the UR10 at WS 20					
Objective	**Conditions**	**FELICE robot tasks**	**UR10 tasks**	**Human tasks**	**Measures**
Assess the impact of integrating the UR10 robot at WS 20 on the human operator	1. Manual (baseline) 2. With the UR10's support	-	Unscrewing	Disassembly based on the defined workflow (Figure 17)	• Usability • Workload • Emotional states • Trust • Team fluency (Cycle time, Interaction time)

The experiments took place at the Melfi Campus facilities of Stellantis, where new solutions for improving automotive production processes are tested. The assembly/disassembly area was used for this purpose. This area closely replicates a real production line segment, featuring two workstations and a moving line (Figure 10). It is also fully equipped with the tools and components required for the assembly and disassembly of automotive parts**.**



Figure 10: CRF's assembly area

3.3 EMPIRICAL EVALUATION 1: USABILITY ASSESSMENT OF THE FELICE ROBOT AT WS 10

In the first empirical evaluation, the objective was to examine how integrating the FELICE robot at WS 10 influenced the human operator under the first sub-scenario of the **Safety Scenario** (mentioned in Section 3.1). The evaluation focused on the robot's usability from the human's perspective, as well as its influence on team fluency, the operator's cognitive workload, emotional state, and perceived safety.

Experimental Setup

This experiment was conducted at WS 10 and involved **a human operator** collaborating with the **FELICE robot**. It comprised two conditions, which were presented in randomized order:

(I) Condition 1 (Manual- baseline): Disassembly without the FELICE robot's support

(II) Condition 2 (FELICE-supported): Disassembly with the FELICE robot's support

Procedure

Prior to the experiment, participants received a general overview of the study, explaining that they would perform the disassembly task at WS 10 with or without support from the FELICE robot, which was introduced as not fully reliable. To avoid bias, they were NOT informed about the specific purpose of the experiment or the detailed measures at this stage.

At the beginning of each condition, the experimenter carried out the necessary configurations, including positioning the robot and activating it when required (Condition 2), before initiating the process. Participants were instructed to begin the disassembly task at WS 10, following the defined sequence of actions.

In the baseline condition (Condition 1), participants performed the entire task sequence manually (e.g., unscrewing and removing car door parts) without receiving any support from the FELICE robot. This condition corresponds to a single-agent (human-only) workplace design.

In Condition 2, participants collaborated with the FELICE robot for specific auxiliary tasks, such as receiving and handing over a screwdriver required for subsequent work activities. Beyond the disassembly tasks, participants in this condition also had to monitor and interpret specific aspects of the robot's state related to tool transfer, including readiness for handover, handover completion, and the appropriateness of the tool. After completing the handover, the FELICE robot moved away from the participant's position and navigated to the tool stand to place the tool there. Each condition included three work cycles (i.e., working on different doors to be disassembled).

Measures

After each condition, data were collected through objective measures (calculated by the experimenter) and subjective questionnaires (completed by participants):

- **Team performance and fluency** assessed the performance and fluency of human–robot collaboration and was measured using (Hoffman, 2019):
  - Cycle time: the time required for disassembling of one door.
  - Human idle time: the percentage of the total task time (i.e., cycle time) that the human was not active.
  - Robot idle time: the percentage of the total task time (i.e., cycle time) that the robot was not perceivably active and waiting for the human to complete an action.
  - Interaction time: the percentage of time out of the total task time (i.e., cycle time), during when human and robot are both actively contributing together to the completion of a task.
- **Human workload** was assessed using the NASA Task Load Index (NASA-TLX), which captures perceived workload across six subscales (Hart & Staveland, 1988).
- **Emotional state** was assessed using the Self-Assessment Manikin (SAM), measuring valence, arousal, and dominance through graphical rating scales (Bradley & Lang, 1994).
- **System usability** was assessed using the System Usability Scale (SUS), reflecting key aspects of ease of use, learnability, and user confidence across ten subscales (Brooke, 1996).
- **Perceived Safety and Comfort** were assessed using the questionnaire by Lasota and Shah (Lasota & Shah, 2015) and were collected only in the FELICE-supported disassembly condition; the results will be used to compare the early and final robot versions.
- **Trust in the robot** was assessed using the trust scale questionnaire (Charalambous et al., 2016) and was collected only in the FELICE-supported disassembly condition; the results will be used to compare the early and final robot versions.

Participants

Six males from the CRF company, participated in the FELICE robot experiment as operators of WS 10. Their average age was 39 years (*SD* = 2.1), and none of them had prior experience working with robots.

3.4 EMPIRICAL EVALUATION 1: RESULTS AND DISCUSSION

3.4.1 Team Performance and fluency

Team performance and fluency reflect how smoothly and efficiently the human operator and the FELICE robot work together during the disassembly task at WS 10. It was assessed through the timing of actions, focusing on human and robot idle times and periods of active joint contribution. These measures were extracted from 18 cycles, in which six participants each performed the disassembly task three times with the FELICE robot. Figure 11 illustrates the human–robot workflow at WS 10, based on the average human timing extracted from video recordings and the robot timing extracted from the system log.

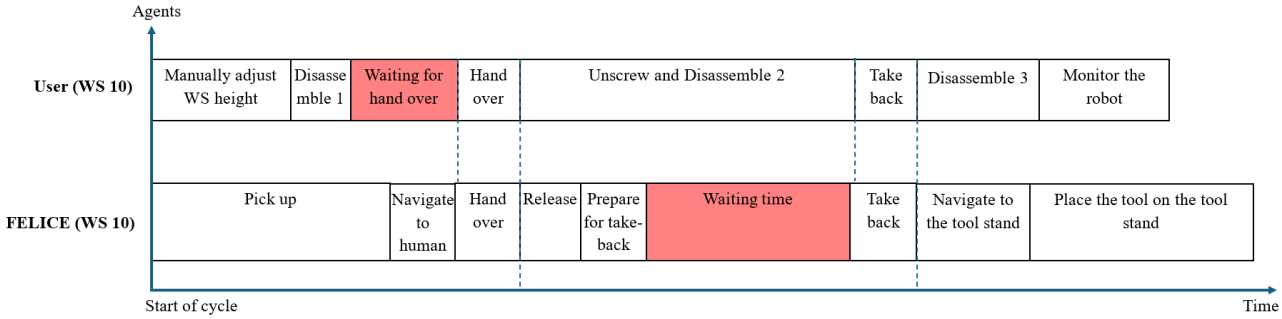


Figure 11: Human-robot workflow at WS 10

The cycle time measurements are presented in Table 9. The cycle time with FELICE support is significantly higher than in the manual condition (t (27) = -3.51, p = .002), indicating the need for further improvements and, to a certain extent, adaptation of the human–robot work cycle to achieve higher productivity. For example, keeping the robot next to the human to directly provide and retrieve tools, would eliminate repeated trips to the tool stand. This is expected to reduce human waiting time and result in shorter disassembly cycles.

Table 9: Cycle time measurements at WS 10

Conditions	Average (*SD*) (min)
Manual cycle	2.6 (0.4)
FELICE-supported cycle	3.26 (0.62)

The average values of the team fluency measures at WS 10 are summarised in Table 10, providing insight into the distribution of interaction and idle times between the human operator and the FELICE robot. These average measures serve as baseline indicators and will be used for comparison with the final prototype to assess improvements in coordination and fluency.

Table 10: Team fluency measures at WS 10

Team fluency measures	Value (sec)
Human-robot interaction time	14 (7% of cycle time)
Human idle time	23 (12% of cycle time)
Robot idle time	49.90 (25% of cycle time)

3.4.2 Usability

Usability, assessed with the SUS, reflects how easy and efficient it was for participants to collaborate with the FELICE robot during the disassembly task at WS 10. Higher scores indicate a more intuitive and satisfactory interaction. As presented in Table 11, overall usability did not differ significantly between conditions. However, the "Independence in Use" scale decreased meaningfully with FELICE support, indicating that users felt a greater need for technical assistance when operating the system (Figure 12).

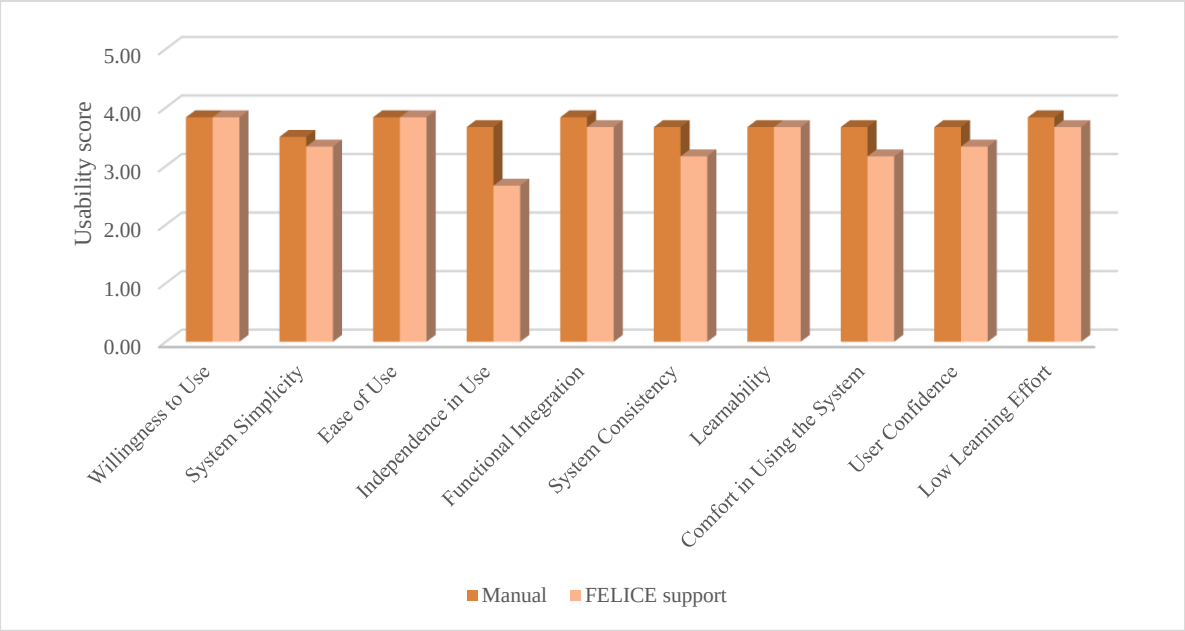


Figure 12: Usability scores for manual and FELICE-supported disassembly

Table 11: Summary of human-factor results of the FELICE usability experiment at WS 10

Measures	**Cond.1 (**Manual**)** **Mean (SD)**	**Cond. 2 (**FELICE-supported) **Mean (SD)**	**T-test-Significant difference? (alpha= 0.1)**	**Effect size (Cohen's d)**	**Main findings**
Usability (out of 5)	3.75 (0.54)	3.43 (0.7)	No (t (5) = 0.73, p = .5)	Small (Cohen's d: -0.3)	Usability was generally similar between conditions, with only small, non-conclusive differences.
Independence in Use	3.67 (0.82)	2.67 (0.52)	**Yes** (t (5) = 2.24, p = .07)	Large (Cohen's d: -0.91)	However, users felt less able to use the system without help when working with the FELICE robot, and this decrease in independence was statistically meaningful.
Workload (out of 100):					
Mental Demand	49.17 (22.68)	45 (10.95)	No (t (5) = 0.50, p = .64)	Small (Cohen's d: -0.2)	No NASA-TLX scales showed significant differences. Most workload dimensions decreased slightly with FELICE support, while Effort and Frustration were higher when using the robot.
Physical Demand	39.17 (28)	30.83 (24.17)	No (t (5) = 1.13, p = .31)	Medium (Cohen's d: -0.46)	
Temporal Demand	35.83 (21.31)	30.83 (24.98)	No (t (5) = 0.66, p = .53)	Small (Cohen's d: -0.27)	
Performance	29.17 (23.76)	28.33 (25.82)	No (t (5) = 0.24, p = .82)	Very small (Cohen's d: -0.097)	
Effort	33.33 (23.80)	46.67 (32.04)	No (t (5) = -0.93, p = .39)	Small (Cohen's d: 0.38)	
Frustration	20 (17.61)	33.33 (35.02)	No (t (5) = -1.4, p = .22)	Medium (Cohen's d: 0.57)	
Emotional state (out of 5)					
Valence	3.67 (0.52)	4 (0.63)	No (t (5) = -1.58, p = .17)	Medium (Cohen's d: 0.64)	Valence and Arousal showed a small increase with FELICE support compared to manual, but these differences were not significant. However, Dominance dropped significantly with FELICE support, indicating that users felt less in control when working alongside the robot.
Arousal	2.67 (1.21)	3.17 (1.17)	No (t (5) = -1, p = .36)	Medium (Cohen's d: 0.41)	
Dominance	4.33 (0.82)	3.5 (1.04)	**Yes** (t (5) = 2.08, p = .09)	Large (Cohen's d: -0.84)	
Perceived safety and comfort (out of 4)	-	3.23 (0.69)	-	-	Results will be compared with the final prototype.
Trust (out of 5)	-	3.37 (0.9)	-	-	Results will be compared with the final prototype.

3.4.3 Workload

Workload was evaluated using the NASA-TLX to determine how demanding the disassembly task was for participants when working with the FELICE robot compared to performing it manually. Lower scores indicate that the task required less effort and was easier to manage. As shown in the table, none of the NASA-TLX scales showed significant differences across the two disassembly conditions. Most workload dimensions decreased slightly with FELICE support, while "Effort" and "Frustration" were higher when using the robot, indicating that users found it harder to achieve their desired level of performance and felt more insecure, discouraged, irritated, stressed, or annoyed during the disassembly task when working with the FELICE robot.

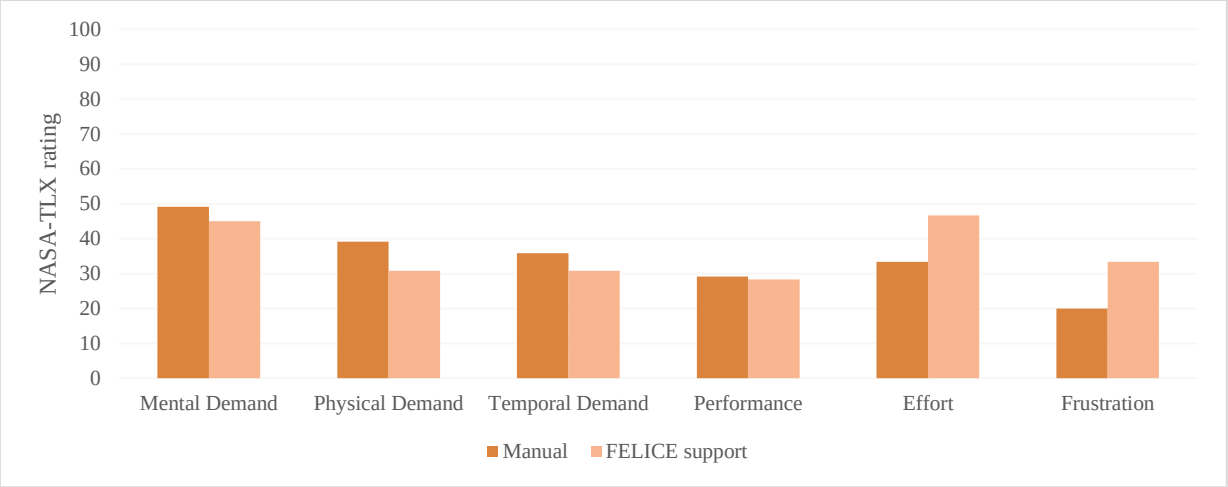


Figure 13: NASA-TLX scores for manual and FELICE-supported disassembly

3.4.4 Emotional state

Participants' emotional experience across valence, arousal, and dominance was captured using the SAM. Higher scores represent more positive valence (positive emotions), greater arousal (excitement), and a stronger sense of dominance (control). As shown in Table 11, valence and arousal were unaffected by the mode of disassembly. However, participants perceived less control over the process in the FELICE-supported disassembly, which significantly reduced the level of dominance in this condition Figure 14.

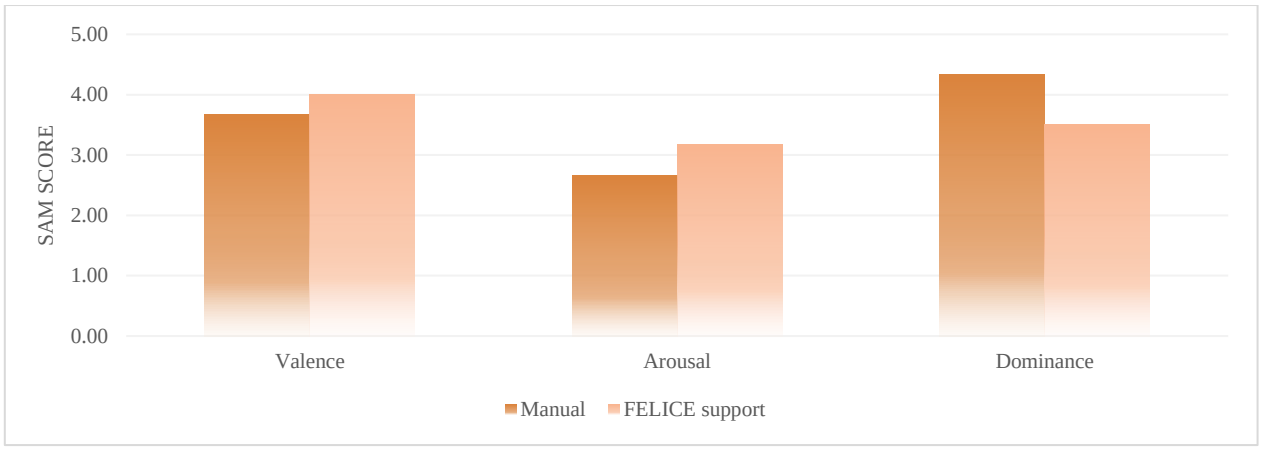


Figure 14: SAM scores for manual and FELICE-supported disassembly

3.4.5 Perceived safety and comfort

Participants' sense of safety and comfort was evaluated while collaborating with the FELICE robot during the disassembly task. These results serve as a baseline for comparison with the final version of the robot. Based on Figure 15, showing the average scores for perceived safety and comfort in the FELICE-supported disassembly, factors such as "Trust in Robot's Actions", "Teamwork Quality", and "Perceived Safety" indicate areas where improvements may be needed in the final prototype.

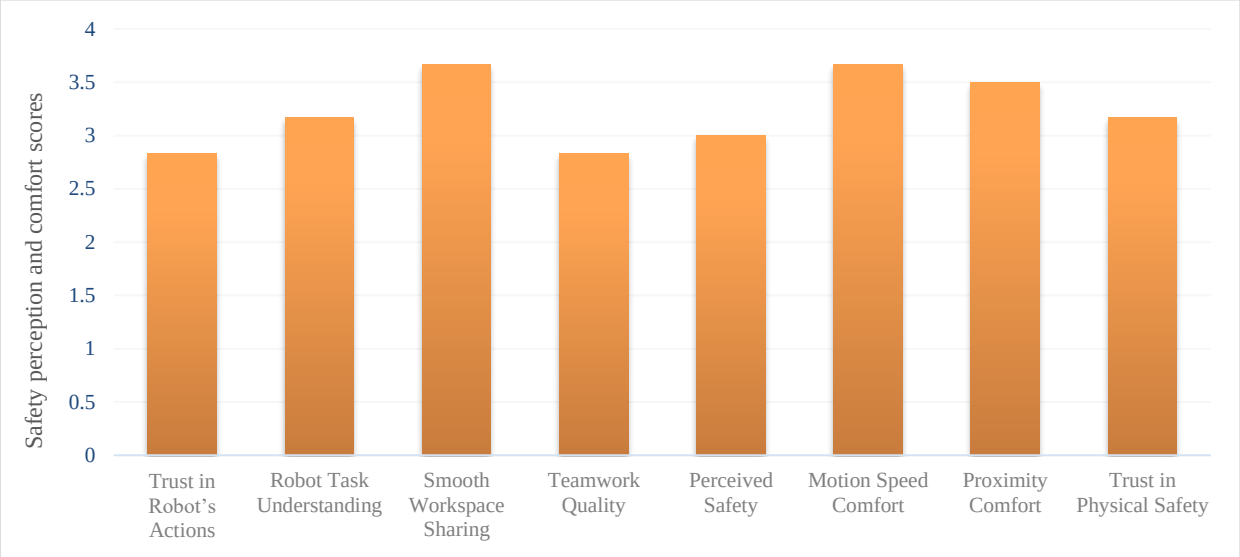


Figure 15: Safety perception and comfort scores for the FELICE-supported disassembly

3.4.6 Trust

Participants' trust in the FELICE robot was assessed during the disassembly task to understand how confidently they relied on its actions and support. These results will be compared with the final evaluation to track changes in trust. Nevertheless, "Gripper Hold Reliability" received the lowest trust ratings, indicating a key area for improvement in the final prototype (Figure 16).

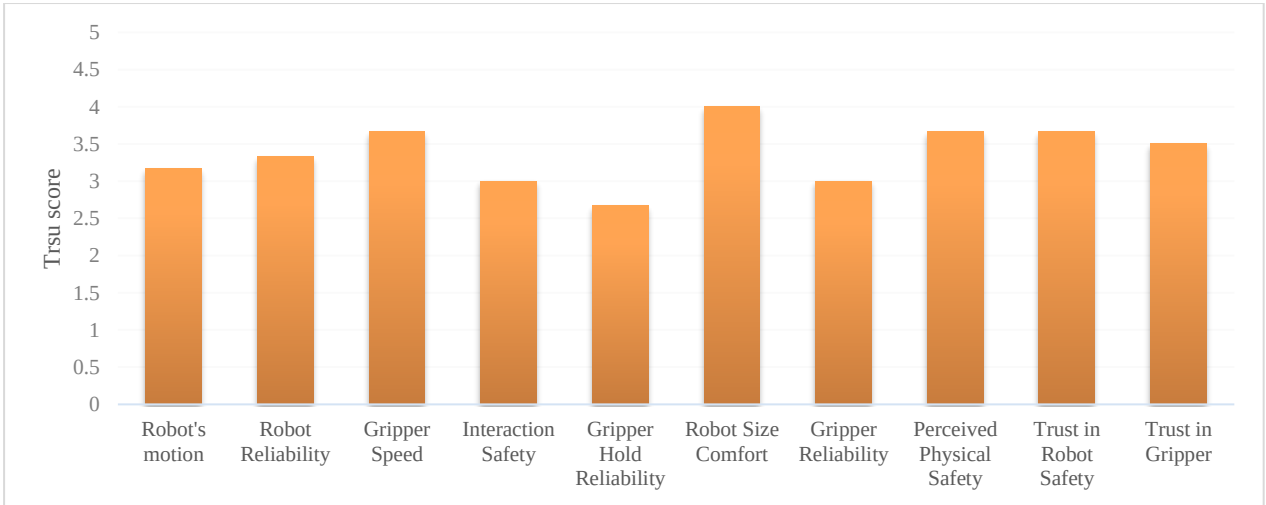


Figure 16: Trust scores for the FELICE-supported disassembly

3.5 EMPIRICAL EVALUATION 2: USABILITY ASSESSMENT OF UR10 AT WS 20

Empirical evaluation 2 aimed to assess the integration of the UR10 robot at WS 20 and its impact on the human operator under the second sub-scenario of the **Safety Scenario** (mentioned in Section 3.1). The evaluation addressed the robot's usability and its impact on team fluency, human's cognitive workload, affective state, and trust.

Experimental Setup

This experiment was conducted at WS 20 and involved **a human operator** collaborating with the **UR10 robot**. It includes two conditions, which were presented in randomized order:

(I) Condition 1 (Manual-baseline): Disassembly without the UR10 robot's support

(II) Condition 2 (UR10- supported): Disassembly with the UR10 robot's support

Procedure

Prior to the experiment, participants received a general overview of the study. They were informed that they would perform the disassembly task at WS 20 either alone or in combination with the UR10 robot. The robot was introduced as not operating with full reliability. To avoid bias, participants were NOT informed about the specific purpose of the experiment or the detailed measures at this stage.

After the briefing, in the baseline condition (Condition 1), participants performed the entire task sequence manually (e.g., unscrewing and removing car door parts) without receiving any support from the UR10 robot. This condition corresponds to a single-agent (human-only) workplace design.

In Condition 2, at the beginning of the session, the experimenter prepared the robot for operation. Participants then cooperated with the UR10 robot. This robot supported the unscrewing of the carrier screws, while participants handled the remaining manual disassembly tasks and managed the screwdriver. Each condition lasted 2 work cycles (i.e., disassembly of different car doors).

However, after two disassembly cycles with one participant, the UR10 robot encountered hardware issues that made it impossible to continue, as the repair required support from the manufacturer of the UR10 and would take considerable time. Therefore, the experimental approach was changed to a video-based study (Cha et al., 2013). In this approach, participants watched the recorded disassembly cycles performed with the UR10 robot and reported their perceptions of the collaboration by completing the questionnaires.

Measures

- **Team performance and fluency** assessed the performance and fluency of human–robot teaming, measured by cycle time and human–robot interaction time. These data were calculated based on the only two cycles where real interaction occurred between a participant and the UR10 robot.

The following measures were collected from participants' perceptions while watching the disassembly video of the UR10.

- **Human workload** was assessed using the NASA Task Load Index (NASA-TLX), which captures perceived workload across six subscales (Hart & Staveland, 1988).
- **Emotional state** was assessed using the Self-Assessment Manikin (SAM), measuring valence, arousal, and dominance through graphical rating scales (Bradley & Lang, 1994).
- **System usability** was assessed using the System Usability Scale (SUS), reflecting key aspects of ease of use, learnability, and user confidence across ten subscales (Brooke, 1996).
- **Trust in automation** was assessed using the scale by Jian et al. (2000), capturing trust-related perceptions across different system features, such as reliability and predictability.

Participants

Twelve participants, ten men and two women, with an average age of 44 years (*SD* = 8.9) from the CRF company, took part in this video-based experiment. Among them, only one woman had prior experience working with robots.

3.6 EMPIRICAL EVALUATION 2: RESULTS AND DISCUSSION

3.6.1 Team Performance and fluency

Team performance and fluency was assessed through the timing of actions, focusing on cycle time and human–robot interaction time. Figure 17 presents the human–robot workflow at WS 20, based on the average timing extracted from video recordings of two cycles.

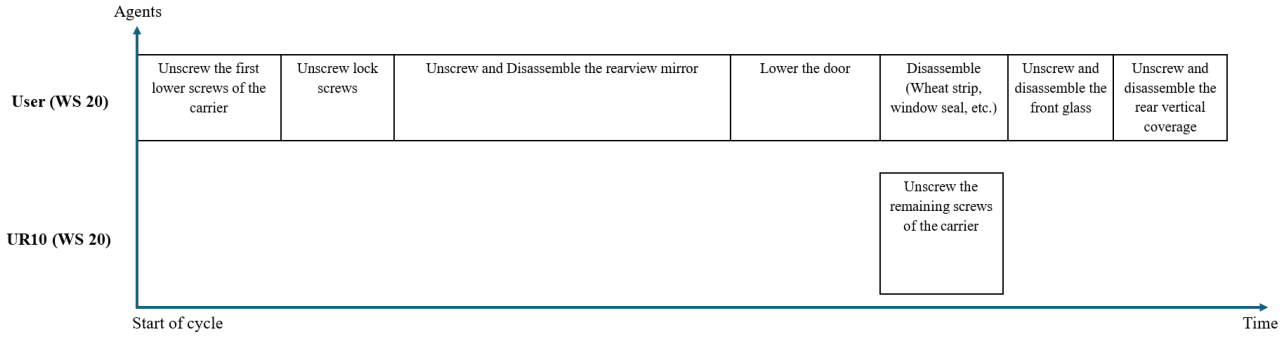


Figure 17: Human-robot workflow at WS 20

The average human–robot interaction time across the two cycles was 32 seconds, corresponding to approximately 13% of the total cycle time. The average cycle times calculated from these two cycles are presented in Table 12.

Table 12: Cycle time measurements at WS 20

Conditions	Average (*SD*) (min)
Manual cycle	4 (0.71)
UR10-supported cycle	4.08 (0.35)

3.6.2 Human factor measures

According to the results presented in Table 13, participants reported moderately high usability, indicating that the disassembly process with the UR10 robot appeared intuitive and manageable from the user's perspective. Workload ratings across all NASA-TLX dimensions were generally low, suggesting that the task was not perceived as mentally, physically, or temporally demanding, nor did it create notable strain or frustration. Emotional state scores showed positive valence, moderate arousal, and a strong sense of dominance, implying that participants felt comfortable, engaged, and in control when imagining themselves performing the task with the robot. Additionally, trust levels were relatively high, indicating that participants perceived the UR10 as dependable and capable within the context of the disassembly workflow.

Table 13: The human-factor results of the UR10 usability experiment at WS 20

Human Factor Measures	Mean (*SD*)
Usability (out of 5)	3.97 (0.47)
Workload (out of 100):	
Mental Demand	35 (21.32)
Physical Demand	37.08 (21.05)
Temporal Demand	23.33 (16.83)
Performance	26.25 (24.13)
Effort	31.25 (14.32)
Frustration	14.58 (7.82)
Emotional state (out of 5)	
Valence	3.83 (0.83)
Arousal	2.5 (1)
Dominance	4.17 (0.58)
Trust (out of 7)	5.28 (1.44)

3.7 SUMMARY OF FINDINGS

The early MH-MR evaluation of the CRF vehicle door disassembly use case provides a clear picture of how operators experienced robot support at WS 10 (FELICE) and WS 20 (UR10). The findings highlight key aspects of the current prototypes that support the task, as well as several areas that require refinement to achieve improved human–robot collaboration in the final stage.

3.7.1.1 WS 10 – FELICE Robot

At WS 10, the FELICE robot automated tool handover and retrieval, but its current behaviour occasionally introduced delays, which contributed to a longer cycle time compared to manual operation. While overall usability remained acceptable, participants reported reduced independence, higher effort and frustration, and lower trust in the gripper's ability to hold tools securely. They also felt less in control during the FELICE-supported disassembly compared to manual operation. These outcomes point to several improvement needs:

Increase human authority and controllability
Participants reported reduced feeling of control and a stronger dependency on technical support when performing disassembly with the FELICE robot. To address this, users should be given more authority to intervene in the process, such as the ability to stop or pause the robot at any time, open the gripper, or adjust individual steps of the workflow.

Improve trust in the FELICE robot's placing ability
Users expressed insufficient trust in the robot's ability to securely place the objects back. Suggestions regarding potential improvements are described in deliverable *D5.3 Use Case Evaluation I.*

Training
The reliability of tool placement into the tool stand is affected not only by the robot but also by how the human positions the tool within the gripper during taking back. Instructing workers on how to correctly position the tool within the robot's gripper during the take-back action can improve the robot's placement reliability and, consequently, increase user trust.

In addition, training users on the robot's actions, their available authority, and the functions they can monitor or perform through the interface can strengthen their sense of control, enhance trust, improve awareness, and support more efficient task execution

Reduce effort and frustration during robot-assisted disassembly
Although increases in perceived effort and frustration were small to moderate with FELICE support, these aspects can be improved in the final prototype. Providing operators with clearer visibility into the robot's actions even when the robot is away from the operator, such as installing a monitor at WS10 and giving them more authority to adjust or intervene in the workflow can help reduce uncertainty and make the process easier to manage.

3.7.1.2 WS 20 – UR10 Robot

Due to a hardware failure after two cycles, the UR10 could not be fully evaluated through real human-robot interaction. Participants instead watched recorded cycles and imagined themselves performing the task. Based on this perception-based evaluation, participants reported good usability, low workload, positive emotional responses, and generally high trust in the UR10's behaviour. Although these findings may not fully reflect actual interaction, they provide a useful baseline for future improvements, guiding what users expect from the final prototype.

Overall, the CRF use case evaluation shows that both FELICE and UR10 have the potential to support the vehicle door disassembly task, but further refinement is required

to improve human–robot collaboration in the final prototype. At WS 10, improvements should focus on increasing operator control, strengthening trust in the robot's placing performance, and reducing effort and frustration. At WS 20, the perception-based results provide an initial reference for usability, workload, emotional response, and trust. Together, these findings offer clear guidance for design and interaction improvements in the next development stage.

4. ANALYSIS OF MH-MR COLLABORATION FOR USE CASE 3: SYMBIOTIC FARMING

The agriculture sector is currently facing a 20% labour shortage, while up to 30% of farm workers' efforts are spent on crop transportation. To address these challenges, E-TERRY, an AgTech start-up based in Erfurt, Germany, has developed an autonomous farming robot aimed at promoting sustainable agriculture on a large scale through automation and AI. The robotic platform is built on a highly agile carrier system with adjustable height and track width, enabling it to adapt to various crop types and growth stages.

Within the SOPRANO project, the E-TERRY robot is designed to support field workers during the harvesting process. Specifically, it transports harvested crops to a central unloading location, where workers manually empty and reload the boxes. Once the unloading is complete, the robot autonomously returns to the previously processed row to continue its task. Effective interaction between field workers and the robotic platform is essential for increasing agricultural productivity, reducing manual labour, and minimizing delays, objectives that align closely with E-TERRY's goals within the SOPRANO project.

In the early evaluation stage, the focus is on the **Harvesting** and **Unloading** modes (see deliverable *D5.3 Use Case Evaluation I*), each with distinct robotic capabilities and human-robot collaboration features, as outlined in Table 14 and the following subsections.

Table 14: Human–robot main interaction features in the early prototype for the E-TERRY use case

Team composition	Multi humans - One robot
Robot capabilities	- Object detection (humans and boxes) - Autonomous navigation - Remote operation - Integrated safety mechanisms
Human roles	- Supervisor - Bystander (field worker) - Cooperator (unloading workers)
Interaction	**Supervisor** The supervisor monitors the robot, provides task instructions, and intervenes when the robot fails. Responsibilities include: - Providing first-level support - Moving the robot to the starting position - Launching autonomous operation / Change operation mode (early evaluation)

	- Transferring the robot between fields - Intervening in case of robot failure during the operation - Remotely controlling the robot when necessary
	Field workers Field workers act mainly as bystanders, working in the same shared workspace and at a safe distance from the robot, without controlling or manipulating its behaviour. However, they do interact with the robot by loading E-TERRY with full boxes. As a result, this role still requires a mental representation of the robot and its behaviour to avoid potential collisions.
	Unloading workers Unloading workers act as cooperator, as they remove the full boxes while the robot is stopped and communicate with it to get back to the field and enter Harvesting Mode.

4.1 EARLY PROTOTYPE EVALUATION SCENARIOS

4.1.1 Scenario 1: Harvesting mode

The primary operational mode for E-TERRY is Harvesting Mode. In this mode, the robot moves in a stop-and-go pattern, maintaining a safe distance while autonomously following the field workers. Harvesting Mode remains active until the loading area beneath E-TERRY reaches full capacity.

4.1.2 Scenario 2: Unloading mode

When the loading platform is full, the unloading mode is activated. The E-TERRY drives autonomously to the loading point where all the full boxes are collected. Here, the E-TERRY stops until all the boxes have been unloaded. After the field worker at the loading point gives the E-TERRY the signal to move on via a button on the internal E-TERRY HMI, the E-TERRY moves back to the same row as before to the field worker's position. Harvesting mode is then resumed.

4.2 EVALUATION APPROACH

4.2.1 Overall Assessment of Sociotechnical Design Requirements

The objective of this section is to assess the extent to which the 34 requirements proposed for the E-TERRY use case in *D1.3 Early Prototype Framework Requirements for MH-MRs* have been implemented, based on the scenarios and components examined during the early evaluation. Each requirement is evaluated using the scales ‘Completely fulfilled’, ‘Partially fulfilled’, and ‘Not fulfilled at this stage’. The results are presented in Table 15. For requirements that require further clarification, additional explanations and recommendations are provided.

Table 15: Overall Assessment of Sociotechnical Design Requirements for the E-TERRY use case

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
E.01	The system should provide information on the current position of the worker	SHOULD	- Human Monitoring [HMO] - Advanced visualization [AVT]	Partially fulfilled	The current positions of multiple workers are provided by HMO in real-time.
E.02	The system should provide information on its current location on demand	SHOULD	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.03	The system shall provide information on that it is currently following the worker	SHALL	- Advanced visualization [AVT	Not fulfilled at this stage	It can be done using LEDs to represent the robot's status.
E.04	The system should provide information if it cannot follow the worker due to the environmental conditions or crop topology	SHOULD	- Object Perception [OBP]/ Human Monitoring [HMO] - Advanced visualization [AVT] - E-TERRY robot capability**	Partially fulfilled	Currently, the existing GUI provides log information that can partially meet this requirement. In addition, auditory feedback such as sound alarms could further support this communication
E.05	The system should inform about any sensor-based problem and provide remedies on how to act (be it informing the co-worker in charge of the robot)	SHOULD	- Context Extraction Module [CEM] - Safety Tools [RSA & DSA] - Advanced visualization [AVT]	Not fulfilled at this stage	
E.06	The robot shall keep an acceptable distance to the worker, adhering to safety standards	SHALL	- Safety Tools [RSA & DSA]	Completely fulfilled	There are three emergency stop buttons and a speed-and-separation monitoring mechanism to guarantee functional safety
E.07	The system should provide information about the status of crops carried, and the type of crops	SHOULD	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.08	The system shall release physical load from the worker	SHALL	- Human Monitoring [HMO]	Partially fulfilled at this stage	Although the 3D body pose of the closest worker is estimated and tracked, physical ergonomics are not evaluated in this UC.
E.09	The system should allow the human operator to always direct it during operation.	SHOULD	- MH-MR Task Allocation [CTA]	Completely fulfilled	Equipped with a joystick and the remote control
E.10	The robot shall provide a set of clearly defined gestures to communicate	SHALL	- Human Monitoring [HMO]	Not fulfilled at this stage	Hand gestures scenario
E.11	The robot shall provide feedback if the worker who interacts is detected in the “interaction field of view.”	SHALL	- Human Monitoring [HMO] - Advanced visualization [AVT] - E-TERRY robot capability	Not fulfilled at this stage	Hand gestures scenario

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
E.12	The robot shall give feedback on the recognized gesture command	SHALL	- Human Monitoring [HMO] - Advanced visualization [AVT] - E-TERRY robot capability	Not fulfilled at this stage	Hand gestures scenario
E.13	The robot shall provide a UI on the smartphone that is reliable in use	SHALL	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.14	The robot shall provide a UI that is user & task-friendly, providing only relevant information to control the robot	SHALL	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.15	The system shall provide a clear possibility to change the authority of operators namely transitions of control	SHALL	- MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
E.16	The system shall clearly provide information who is responsible for the smooth operation	SHALL	- MH-MR Task Allocation [CTA] - Advanced visualization [AVT]	Not fulfilled at this stage	
E.17	The system shall provide redundant means of directing and controlling the robot.	SHALL	- E-TERRY robot capability	Partially fulfilled	Currently, there is only a joystick
E.18	The system shall be stoppable at any given time, also by the worker not in charge	SHALL	- Safety Tools [RSA & DSA] - MH-MR Task Allocation [CTA]	Partially fulfilled	There are three stop buttons. A virtual button with the same functionality needs to be added to the interface.
E.19	The system shall provide information on the status of loading to the worker in charge and the workers around	SHALL	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.20	The system should provide information on the start and completion of the loading process, such as started and completed	SHOULD	- MH-MR Task Allocation [CTA] - Advanced visualization [AVT]	Not fulfilled at this stage	
E.21	The system shall display the current operation mode	SHALL	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.22	The system should provide information on how to change modes of operation	SHOULD	- Advanced visualization [AVT] - E-TERRY robot capability	Not fulfilled at this stage	
E.23	The system should provide information on the modes available	SHOULD	- Advanced visualization [AVT]	Not fulfilled at this stage	

Id.	Requirement Description	Priority	Main Associated Component*	Overall Evaluation	Evaluation notes/ Recommendation
E.24	The robot should provide information on which worker is monitored and detected; this applies only to those ones in close vicinity of the system	SHOULD	- Human Monitoring [HMO] - Advanced visualization [AVT]	Partially fulfilled	
E.25	The system should provide access to current movement and location on demand (App)	SHOULD	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.26	The system should indicate the next movement direction or changes in movement direction	SHOULD	- Advanced visualization [AVT] - MH-MR Task Allocation [CTA]	Not fulfilled at this stage	
E.27	The robot should be able to communicate with a specific worker and with multiple workers	SHOULD	- Human Monitoring [HMO] - Advanced visualization [AVT]	Not fulfilled at this stage	Communication with the field worker will be possible through gestures
E.28	The robot should communicate who it is attending to	SHOULD	- E-TERRY robot capability	Not fulfilled at this stage	
E.29	The robot shall indicate its readiness for communication/interaction	SHALL	- Advanced visualization [AVT]	Not fulfilled at this stage	
E.30	The robot should provide flexible ways to communicate	SHOULD	- Advanced visualization [AVT] - E-TERRY's components	Partially fulfilled	Currently, there is a GUI (which needs improvement), a joystick, and a physical button
E.31	The robot should inform about the current and next actions	SHOULD	- MH-MR Task Allocation [CTA] - Advanced visualization [AVT]	Not fulfilled at this stage	
E.32	The robot should provide information on the distance and the space where communication is possible	SHOULD	- Advanced visualization [AVT] - E-TERRY robot capability	Not fulfilled at this stage	Hand gestures scenario
E.33	The robot should confirm the correct initialization	SHOULD	- E-TERRY robot capability - Advanced visualization [AVT]	Not fulfilled at this stage	
E.34	The system should give the opportunity to provide set-up instructions	SHOULD	- Advanced visualization [AVT]	Not fulfilled at this stage	

* Main components whose outputs directly affect the fulfilment of the requirement are considered. The basic components are not included here.
** E-TERRY robot capability refers to functionalities that are not provided by the SOPRANO components.

4.2.2 Empirical Evaluation of Human-Centric Aspects

The following sections focus on evaluating how the specific design and configuration of the robotic platform affect humans, particularly field workers. One empirical evaluation was conducted, examining the effects of the robot's speed and proximity on human behaviour and interaction within the collaborative setting (Table 16). To achieve this, one field experiment was conducted involving participants who worked with the E-TERRY robot in a real test environment, allowing for the collection of empirical data to assess the effects of the robot on human performance and experience.

Table 16: Main Characteristics of E-TERRY's Empirical Evaluation

Empirical Evaluation 1: Assessing the Effects of Robot's Speed and Proximity				
Objective	**Conditions**	**E-TERRY robot tasks**	**Human tasks**	**Measures**
Assessing the Effects of the Robot's Speed and Proximity	1. Close & Fast 2. Close & Slow 3. Far & Fast 4. Far & Slow	Follow humans with safety considerations – Harvesting mode	Field workers: • Collect items and place them in the box • Load full boxes on the carrier	• Affective state • Anxiety • Perceived safety • Workload

The experiment was conducted in a controlled field setting at the University of Applied Sciences Erfurt, Germany. The designated test area comprised a vegetable plot measuring 10 m × 100 m, structured into two parallel rows to resemble typical field conditions. To simulate manual field labour, a minimum of three participated in each trial, assuming the role of field workers. The robotic system was supervised and operated by an E-TERRY engineer to ensure safe and consistent execution of tasks.

Since the focus of the study was not on actual crop harvesting due to seasonal constraints, strawberries were not cultivated in the test field. Instead, the harvesting process was emulated using lightweight balls, which were collected and transported into a designated container to replicate the workflow of fruit gathering and deposition. The unloading area was positioned at the end of the field, approximately 5 m beyond the cultivation rows, where all harvested items were transferred to a collection box.

4.3 EMPIRICAL EVALUATION: ASSESSING THE EFFECTS OF ROBOT'S SPEED AND PROXIMITY

In the empirical evaluation 1, the objective was to assess the effects of the robot's speed and distance on human operators and other field workers within the **Harvesting mode**. The evaluation focused on identifying the impacts of the robotic platform's configuration on humans' perception of safety, comfort, and mental load.

Experimental Setup

This study investigated human-robot collaboration using the **E-TERRY robot** and human participants acting as **field workers**. A 2 (speed: low-high) × 2 (distance: close-far) within-subjects design was employed with two independent variables. The values of these variables were defined based on proximity zones and the robot's speed limit (Section 4.2.5 of deliverable *D5.3 Use Case Evaluation I*).

Robot distance:	▪ Close (4 m): It means that the robot operates at 4 m from the field workers and stops at 3 m. ▪ Far (6 m): It means that the robot operates at 6 m from the field worker and stops at 4 m.
Robot speed:	▪ Low (0.19 m/s) ▪ High (0.33 m/s)

The design yielded four experimental conditions, representing all combinations of distance and speed:

(I) Condition 1: Close & fast

(II) Condition 2: Close & slow

(III) Condition 3: Far & fast

(IV) Condition 4: Far & slow

Each participant completed all four conditions. The order of presentation was randomized to control for sequence effects

Procedure

At the beginning of each trial, the examiner positioned the robot at its designated starting point, carried out the necessary configurations, and initiated the run. Participants were instructed to collect designated items (i.e., lightweight balls) in the field, place them into a box, and, once full, load the box onto the robot's carrier. Each condition covered one cycle in which the robot completed its full automated sequence.

Following each condition, participants provided subjective evaluations of their perceived comfort, anxiety, sense of safety, and mental load in relation to the robot's behaviour. Depending on the field setup, multiple participants could work simultaneously in different areas of the field under the same conditions.

Measures

At the end of each experimental condition, participants completed the following questionnaires to assess their affective experience and mental load during the session:

- **Anxiety** was assessed using the State-Trait Anxiety Inventory (STAI) which consists of 20 items measuring participants' momentary anxiety in response to the experimental conditions (e.g., feelings of tension, worry, calmness, and confidence) (Spielberger et al., 1971).
- **Perceived Safety and Comfort** were assessed using the questionnaire by Lasota and Shah (2015), which measures participants' perceptions of safety, comfort, and satisfaction with the robot as a teammate during interaction.
- **Human workload** was assessed using the NASA Task Load Index (NASA-TLX), which captures perceived workload across multiple subscales (Hart & Staveland, 1988).
- **Emotional state** was assessed using the Self-Assessment Manikin (SAM), measuring valence, arousal, and dominance through graphical rating scales (Bradley & Lang, 1994).

Controlled Experimental Conditions

To ensure consistency across all four conditions, the following variables were held constant:

- The robot's path of movement
- The robot's level of autonomy
- The assigned location of each participant within the field

Participants

Six participants**,** five males and one female**,** from the E-TERRY company took part in this experiment, with an average age of 29 years (*SD* = 3.5). Half of the participants had prior experience working with robots**.**

4.4 EMPIRICAL EVALUATION RESULTS AND DISCUSSION

4.4.1 Anxiety

A modified State-Trait Anxiety Inventory was used to assess how the robot's speed and distance influenced field workers' momentary anxiety, covering a broad range of feelings such as tension, worry, discomfort, and reduced calmness and confidence. Results, presented in Table 17, revealed a statistically significant effect of the robot's behaviour on anxiety levels. The "Close & Fast" condition produced the highest anxiety (Figure 18), reflected in stronger reports of not feeling calm, not self-confident, and unsatisfied. The remaining three conditions showed similarly low anxiety levels and did not differ from one another.



Figure 18: Anxiety scores for different robot's speed and proximity conditions

4.4.2 Perceived Safety and Comfort

A safety and comfort questionnaire adapted from Lasota and Shah (2015) was used to assess how the robot's speed and proximity influenced participants perceived safety and comfort during interaction. Results (Table 17) showed a statistically significant effect of the robot's behavior on these perceptions. Post-hoc inspection indicated that the "Close & Fast" condition produced the lowest safety and comfort ratings.

As illustrated in Figure 19, when comparing the scale results of two opposite conditions ("Close & Fast" vs. "Far & Slow"), the differences in "Smooth Workspace Sharing", "Teamwork Quality", and even "Proximity Comfort" are not as large as expected.

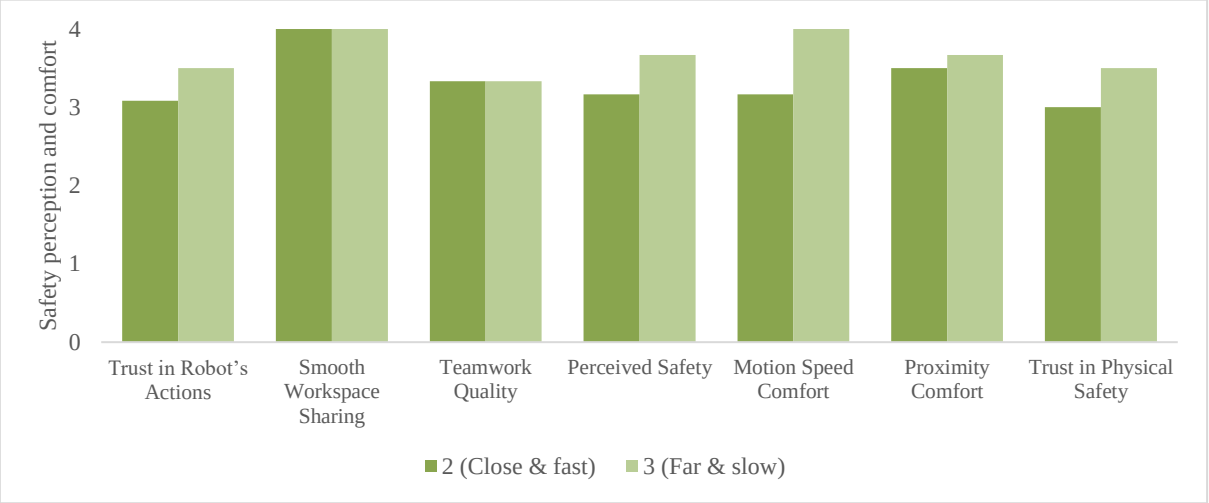


Figure 19: Comparison of safety perception and comfort subscale scores between 'Close & Fast' and 'Far & Slow' conditions

4.4.3 Workload

The NASA-TLX was applied to assess the perceived workload associated with supervising the E-TERRY robot under different combinations of speed and proximity. This measure captures how demanding it was for participants to work with the robot and maintain safe coordination as it operated at varying distances and motion speeds. Most workload factors remained consistent across the four conditions; however based on the results presented in Table 17, the "Close & Fast" configuration notably increased participants' feelings of "Effort", how hard they needed to work to maintain adequate performance and "Frustration", reflecting feelings of insecurity, irritation, stress, or discouragement relative to all other robot behaviours (Figure 20).

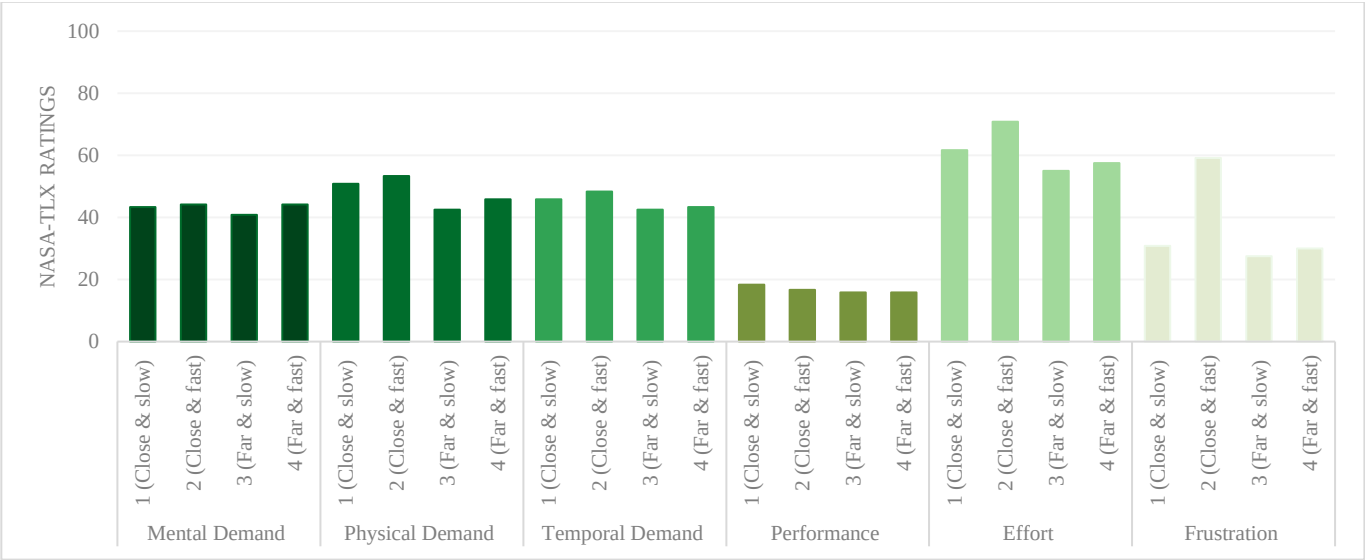


Figure 20: Comparison of NASA-TLX subscale scores across proximity and speed conditions

4.4.4 Emotional state

Emotional states were assessed using the SAM, which captures how pleasant, arousing, and controllable the experience felt while working alongside the robot at different combinations of speed and proximity. Higher scores reflect more positive emotions (positive valence), greater excitement or alertness (arousal), and a stronger sense of control (dominance).

The robot's behaviour had a clear impact on these emotional dimensions (Table 17). Across all three SAM scales, the "Close & Fast" condition consistently resulted in less positive emotional responses, higher arousal, and a reduced sense of control compared to the other three conditions (Figure 21).

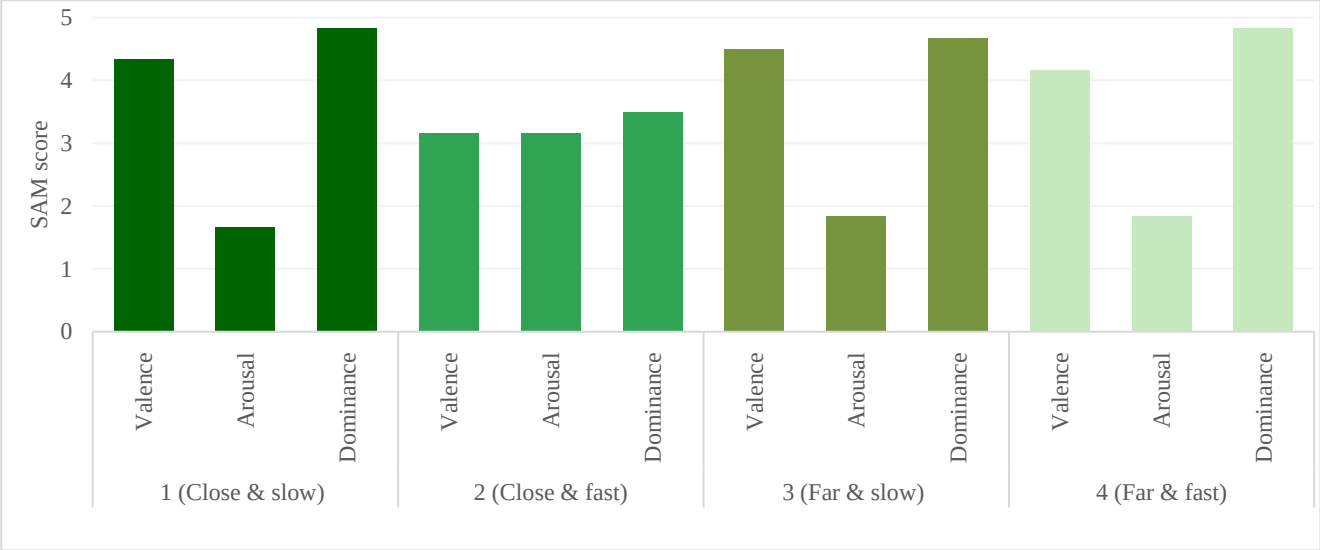


Figure 21: Comparison of SAM subscale scores across proximity and speed conditions.

Table 17: Summary of the human-factor results for E-TERRY use case

Measures	1 (Close & slow) Mean (SD)	2 (Close & fast) Mean (SD)	3 (Far & slow) Mean (SD)	4 (Far & fast) Mean (SD)	Repeated-Measures ANOVA- (Significant difference?) (alpha= 0.1)	Main findings
Anxiety (out of 100)	38.75 (10.34)	52.92 (9.93)	38.13 (9.83)	38.75 (10.98)	**Yes** (F (3,15) = 4.60, p = .02)	Results revealed a statistically significant effect of robot's speed and proximity on participant anxiety scores. The results showed that "Close & Fast" condition produced substantially higher anxiety compared to all other conditions, while the remaining three conditions did not differ from each other.
Perceived safety and comfort (out of 4)	3.67 (0.38)	2.98 (0.55)	3.67 (0.38)	3.57 (0.52)	**Yes** (F (3,15) = 8.43, p < 0.01)	There was a statistically significant effect of the robot's speed and proximity on participants' safety perception and comfort levels. The results showed that the "Close & Fast" condition resulted in noticeably lower safety and comfort ratings, compared to the other three conditions,
Workload (out of 100):						
Mental Demand	43.33 (39.71)	44.17 (39.17)	40.83 (41.88)	44.17 (38.65)	No (F (3,15) = 0.9, p = .46)	Most workload factors stayed consistent across conditions, but the "Close & Fast" configuration significantly increased users' effort and frustration levels compared to all other robot behaviors
Physical Demand	50.83 (26.91)	53.33 (24.83)	42.50 (34.02)	45.83 (30.24)	No (F (3,15) = 1.37, p = .29)	
Temporal Demand	45.83 (27.46)	48.33 (31.25)	42.50 (30.78)	43.33 (29.78)	No (F (3,15) = 0.33, p = .80)	
Performance	18.33 (9.31)	16.67 (11.25)	15.83 (11.58)	15.83 (11.58)	No (F (3,15) = 0.91, p = .46)	
Effort	61.67 (22.51)	70.83 (13.57)	55 (32.40)	57.50 (38.94)	**Yes** (F (3,15) = 2.82, p = .07)	
Frustration	30.83 (19.60)	59.17 (18.82)	27.5 (23.18)	30 (20.49)	**Yes** (F (3,15) = 4.60, p = .02)	
Emotional state (out of 5):						
Valence	4.83 (0.41)	3.5 (1.38)	4.67 (0.82)	4.83 (0.41)	**Yes** (F (3,15) = 5.13, p =.01)	The robot's speed and proximity had a clear impact on participants' emotional states. Across Valence, Arousal, and Dominance, the "Close & Fast" condition consistently led to less positive emotions, higher arousal, and reduced sense of control compared to the other three
Arousal	1.67 (0.52)	3.17 (0.98)	1.83 (0.75)	1.83 (0.75)	**Yes** (F (3,15) = 4.41, p =.02)	
Dominance	5.50 (1.76)	4.17 (2.64)	5.33 (1.97)	5.50 (1.76)	**Yes** (F (3,15) = 3.46, p =.04)	

4.5 SUMMARY OF FINDINGS

The early MH–MR evaluation of the E-TERRY use case provides a clear picture of how field workers interact with the robot while operating in a shared workspace during harvesting activities. The findings highlight key aspects of the current prototype that support human–robot collaboration, as well as areas where targeted improvements can enhance human experience in the final prototype.

Adjust robot speed and proximity
Robot speed and operating distance should be carefully tuned when humans and the robot operate in a shared workspace. Lower speeds and/or increased operating distances are recommended to reduce anxiety, effort, and frustration, and to support perceived safety, emotional comfort, and a stronger sense of control for field workers.

Strengthen communication and feedback mechanisms
Based on the overall assessment, several requirements related to communication, feedback, and system transparency are not yet implemented at this stage, with the corresponding components planned for integration in the next development phase. Strengthening feedback about the robot's current state, intentions, and upcoming actions is recommended to support user understanding, reduce cognitive workload, and foster trust during operation.

Overall, the results indicate that appropriate tuning of robot behaviour and improved communication are essential for supporting comfortable and acceptable human–robot collaboration in agricultural field environments.

5. CONCLUSIONS AND OUTLOOK

The early evaluation of the MH–MR prototypes across the three use cases (KUKA, CRF, and E-TERRY) provides a first comprehensive picture of how human workers experience collaboration with the early prototype robotic platforms. Despite differences in the application domain (e.g., construction, automotive, farming), the task structure and the interaction demands, a consistent pattern emerged: robot behavior that is predictable and transparent, for humans, enhances user experience and supports efficient collaboration. Contrastingly, behavior that is too fast, vague in intention, or insufficiently coordinated with human timing of tasks increases cognitive effort, frustration, and perceived risk. The results also underline the importance of designing robotic systems that align with human expectations, preserve situational awareness, and minimize unnecessary workload induced by robots. Eventually, these factors directly affect human performance and, consequently, overall system efficiency.

For the KUKA use case, the early evaluation highlights the potential of autonomous navigation to support supervisory interaction and enhance situation awareness during renovation tasks. At the same time, increased frustration, lower perceived task success, and reduced trust observed in the autonomous mode indicate that further refinement is required. Future development should focus on improving the consistency and stability of autonomous behaviour and strengthening feedback about task progress and system state. Preserving the observed benefits for situation awareness, particularly in attentional resource supply and situation understanding, while reducing perceived

instability will be key to improving acceptance and usability in real construction environments.

In the CRF use case, the findings show that both the FELICE and UR10 robots can effectively support disassembly tasks, but that different challenges arise depending on the workstation and interaction role. At WS 10 during collaboration with the FELICE robot higher operator dependency on robot capacities, increased effort and frustration, and lower trust in specific robot capabilities, particularly tool placement were observed. Future development activities should therefore prioritise improving transparency of robot actions through appropriate, clear and comprehensible signifiers of robot activity, and strengthening trust through more reliable and controllable interaction mechanisms. At WS 20, the perception-based evaluation of the UR10 provided a rather positive baseline in terms of usability, workload, emotional response, and trust, which should be validated and extended through real interaction in the final prototype

In the E-TERRY use case, the early evaluation demonstrates that robot speed and operating distance have a strong influence on field workers' anxiety, emotional state, perceived safety, and workload in shared agricultural workspaces. Configurations combining high speed with shorter distances were consistently associated with less favorable human experience, while slower and/or more distant operation supported comfort and acceptance. In addition, the overall assessment revealed that many communication, feedback, and transparency requirements are not yet implemented at this stage. Future development should therefore focus on careful adjusting of robot behavior in shared spaces and on strengthening cues that communicate robot state, intentions, and upcoming actions to support user understanding and trust.

Future enhancements should therefore focus on strengthening human authority and controllability across all use cases, improving visual communication and feedback cues, and enhancing the stability and reliability of robot behavior to better align with human support needs and expectations. Extending the evaluations to more diverse operational scenarios will deepen the understanding of MH–MR collaboration and help ensure that the final systems are robust, scalable, and well aligned with real-world demands. Ultimately, the early insights gained here provide a solid foundation for advancing efficient, safe, and human-centered multi-human–multi-robot teamwork within the SOPRANO project.

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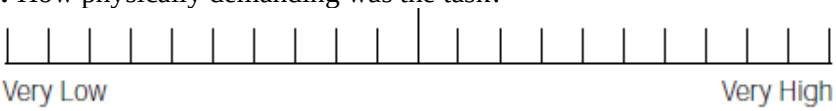
APPENDIX

NASA Task Load Index

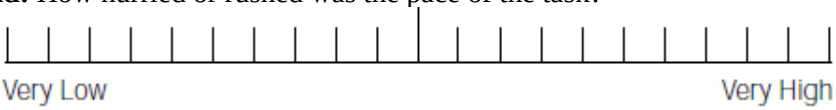
Mental Demand: How mentally demanding was the task?



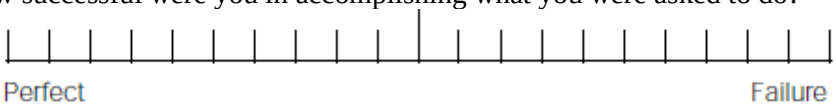
Physical Demand: How physically demanding was the task?



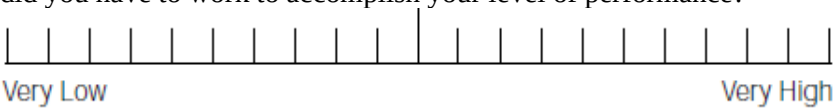
Temporal Demand: How hurried or rushed was the pace of the task?



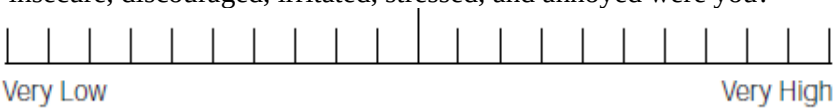
Performance: How successful were you in accomplishing what you were asked to do?



Effort: How hard did you have to work to accomplish your level of performance?



Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?



Example:



The System Usability Scale (SUS)

Items	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree
1. I think that I would like to use this system frequently.					
2. I found the system unnecessarily complex.					
3. I thought the system was easy to use.					
4. I think that I would need the support of a technical person to be able to use this system.					
5. I found the various functions in this system were well integrated.					
6. I thought there was too much inconsistency in this system					
7. I would imagine that most people would learn to use this system very quickly.					
8. I found this system very awkward to use.					
9. I felt very confident using the system.					
10. I needed to learn a lot of things before I could get going with this system					

Perceived Safety and Comfort

Items	**1 Never**	**2 Sometimes**	**3 Often**	**4 Constantly**
1. I trusted the robot to do the right thing at the right time.				
2. The robot did not understand how I wanted to do the task.				
3. The robot kept getting in my way.				
4. The robot and I worked well together.				
5. I felt safe when working with the robot.				
6. The robot moved too fast for my comfort.				
7. The robot came too close to me for my comfort.				
8. I trusted the robot would not harm me.				

Situation Awareness Rating Technique (SART)

For each of the 10 contributing factors, please mark one of the seven boxes that best represents your experience.

Instability of situation: How changeable is the situation? Is the situation high unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

Low ☐☐☐☐☐☐☐☐ High

Complexity of Situation: How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

Low ☐☐☐☐☐☐☐☐ High

Variability of Situation: How variable was the situation, or how frequently did it change? Are there a large number of factors varying (high) or are there very few variables changing (Low)?

Low ☐☐☐☐☐☐☐☐ High

Arousal: How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

Low ☐☐☐☐☐☐☐☐ High

Concentration of Attention: How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

Low ☐☐☐☐☐☐☐☐ High

Division of Attention: How much is your attention divided into the situation? Are you paying attention to many aspects of the situation (High) or focused on only one (Low)?

Low ☐☐☐☐☐☐☐☐ High

Spare Mental Capacity: How much mental capacity do you have to spare in the situation? Do you have sufficient capacity to attend to many variables (High) or nothing to spare at all (Low)?

Low ☐☐☐☐☐☐☐☐ High

Information Quantity: How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

Low ☐☐☐☐☐☐☐☐ High

Information Quality: How good is the information you have gained about the situation? Is the knowledge communicated very useful (High) or is it usable at all (Low)?

Low ☐☐☐☐☐☐☐☐ High

Familiarity with Situation: How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

Low ☐☐☐☐☐☐☐☐ High

State trait Anxiety Inventory

Read each statement and select the appropriate response to indicate how you feel right now, that is, at this very moment. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

Items	**1 Not at all**	**2 A little**	**3 Somewhat**	**4 Very Much So**
1. I felt calm while working alongside the robot.				
2. I felt safe during the robot-assisted task.				
3. I felt tense while interacting with the robot.				
4. I felt physically or mentally strained during this task with the robot.				
5. I felt at ease while performing the task with the robot.				
6. I felt upset while collaborating with the robot.				
7. I was worried that something might go wrong during the task.				
8. I felt satisfied with how the task progressed with the robot.				
9. I felt frightened during the robot-assisted session.				
10. I felt comfortable working near the robot.				
11. I felt confident in completing the task alongside the robot.				
12. I felt nervous during this robot interaction.				
13. I felt jittery while working with the robot.				
14. I found it hard to make quick decisions while the robot was operating.				
15. I felt relaxed during the robot session.				
16. I felt content with the flow of the task involving the robot.				
17. I felt worried about how the robot might move or behave.				
18. I felt confused about what to do during the robot task.				
19. I felt steady and in control during the collaboration.				
20. I felt positive about working with the robot in this session.				

Trust scale questionnaire (Charalambous, 2016)

Items	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree
1. The way the robot moved made me uncomfortable.					
2. I felt I could rely on the robot to do what it was supposed to do.					
3. The speed at which the gripper picked up and released the component made me uneasy.					
4. I felt safe interacting with the robot.					

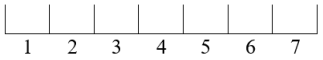
5. I knew the gripper would not drop the components.					
6. The size of the robot did not intimidate me.					
7. The robot gripper did not look reliable.					
8. I was comfortable that the robot would not hurt me.					
9. I trusted that the robot was safe to cooperate with.					
10. The gripper seemed like it could be trusted.					

Trust Perception Scale-HRI

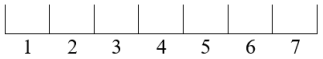
Items	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
What % of the time will this robot be …											
1. How often was the robot dependable during the task?											
2. How often did the robot act in a reliable manner?											
3. How often did the robot seem unresponsive to task needs?											
4. How predictable were the robot's actions?											
5. How often did the robot behave like a good teammate?											
6. Did the robot act consistently throughout the task?											
7. How often did the robot provide feedback (e.g., visual, auditory)?											
8. Did the robot's behavior meet the needs of the task or mission?											
9. To what extent did the robot perform the task better than a novice human?											
10. How often did the robot provide appropriate information to support the task?											
11. How often did the robot communicate clearly with you (or the team)?											
12. How often did the robot perform exactly as instructed?											
13. To what extent did you consider the robot as part of the team?											
14. How well did the robot follow directions?											

Trust in automation by (Jian, 2000)

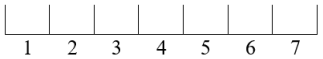
1. The system is deceptive.



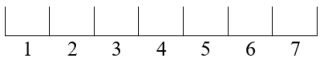
2. The system behaves in an underhanded manner.



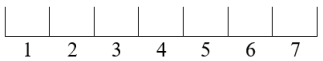
3. I am suspicious of the system's intent, action, or outputs.



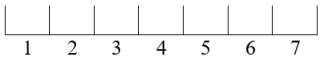
4. I am wary of the system.



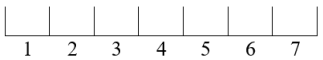
5. The system's actions will have a harmful or injuries outcome.



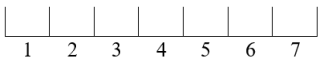
6. I am confident in the system.



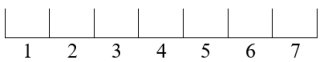
7. The system ensures safety.



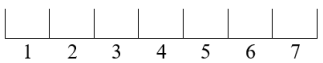
8. The system has integrity (acts in a fair and trustworthy way).



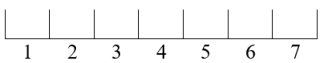
9. The system is dependable.



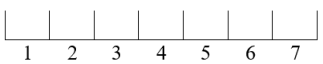
10. The system is reliable.



11. I can trust the system.



12. I am familiar with the system.



Self- Assessment Manikin (SAM)

Please choose one picture from each row that best represents your feelings during the experiment.

