Computers & Industrial Engineering 186 (2023) 109674

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Multi-assistance systems in manufacturing - a user study evaluating multi-criteria impact in a high-mix low-volume assembly setting

Tanja Zigart [a,*], Setareh Zafari [a], Felix Stürzl [a], Robert Kiesewetter [b], Hans-Peter Kasparick [b], Sebastian Schlund [a]

[a] TU Wien, Institute of Management Science, Theresianumgasse, 27, 1040 Wien, Austria
[b] Siemens AG, Werk für Kombinationstechnik Chemnitz (WKC), 09116, Chemnitz, Germany

ARTICLE INFO

Keywords:
User study
Multi-criteria evaluation
Assistance systems
Manufacturing
Human factors

ABSTRACT

Understanding how skilled workers interact with assistance systems in manufacturing and how they experience the factory environment is fundamental to modeling human interaction and optimizing the processes correctly. This paper investigates humans' behaviors and perceived experiences while interacting with cognitive and physical assistance systems. To enable decisions about the combined use of more than one assistance system within a manufacturing process, comprehensive and comparable knowledge about the impact of applications on productivity and human factors is needed. A multidimensional evaluation model with a mixed-methods approach was developed and applied in a user study. In 300 run-throughs in six different scenarios with skilled workers and students, a questionnaire on human factors was completed after finishing the task. Furthermore, productivity and quality were measured during the study. A comparison between skilled workers and students demonstrated that the usability score of all assistance systems was rated higher among the students. The students rated the ergonomics aspects better for five out of six scenarios. Results show higher compatibility with values and experiences in all investigated combinations for skilled workers than for students. Considering the collected data among the skilled workers, the overall compatibility with experience and values of multi-assistance system scenarios was more positive than in the single-assistance system scenarios. Our results show no significant differences in ergonomics, mental, physical, and temporal workload between single and multi-assistance system settings. With 150 run-throughs of industrial professionals and campus recruits each, the survey joins only two studies with more than 100 participants. To the authors' knowledge, it is the first systematic multi-criteria evaluation for the combined use of several (cognitive and physical) industrial assistance systems. The results help to ease practitioners' evaluation of technical support systems in manufacturing with an emphasis on multi-criteria evaluation and the consideration of interconnected (cognitive and physical) assistance systems. Furthermore, the results contribute to further research in human–machine interaction and its impact on productivity and human factors as they show potentials and prospective challenges of the implementation and application of multiple assistance systems.

1. Introduction

Assistance systems such as worker assistance systems, exoskeletons, collaborative robots, and augmented reality applications have been frequently introduced to support manufacturing workers in various activities. Especially high-mix low-volume assembly settings have been recently subject of implementation projects for various assistance systems (Wang et al., 2019). The rationale mostly draws from increased product and process complexity as well as increasing accessibility and providing support for (physically and cognitively) demanding tasks (Mayrhofer et al., 2019). Concurrently, increased sensor integration and ongoing skilled labor shortages further push industrial companies towards using and integrating existing assistance systems. Multi-assistance systems as combinations of single assistive technologies provide the potential to increase the workers' capabilities and performance towards operator 4.0 settings (Romero et al., 2017) while at the same time remaining human-centered. They represent a step towards adaptive automation (Schlund & Kostolani, 2022) and human-automation

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* Corresponding author.
E-mail address: tanja.zigart@tuwien.ac.at (T. Zigart).

https://doi.org/10.1016/j.cie.2023.109674
Received 2 May 2023; Received in revised form 17 September 2023; Accepted 7 October 2023

symbiosis (Mark et al., 2021) as a precondition for Industry 5.0 (European Commission, Directorate General for Research and Innovation, 2020). Following this idea, systematic and reliable evaluation and selection models are needed to compare different combination options. Within this paper, we aim at a more profound understanding of the effects of a combined use of different assistance systems in manufacturing, considering physical as well as cognitive support. For this reason, we analyze the use of various combinations of different assistance systems by means of a multi-criteria evaluation. As assistance systems experience vast technological progress and most evaluation studies focus on campus recruits or small sample sizes, more comprehensive empirical studies are needed. Therefore, a field study with a total of 300 run-throughs of assistance systems for the assembly of electro-control panels was carried out with 150 run-throughs by skilled workers in the industrial assembly site of Siemens WKC in Chemnitz and 150 by campus recruits with no prior experience at a laboratory setting at the TU Wien pilot factory. The research question was to receive insights into the effects of combining different assistance systems for mounting electro-control panels, and differences between people with no prior experience and skilled workers were aimed to be explored. The motivation from the company's perspective is to test different assistance systems in assembly to receive helpful feedback from their workers. The study shows ways of possible implementations and their effects. Additionally, a constantly changing factory environment, new customer projects, process changes, and organizational adjustments require an open culture of change. The study in the companies' production area created an opportunity to try out assistance systems directly on the shop floor.

To allow a holistic comparison of the use cases and the assistance systems, a multi-criteria evaluation framework from Zigart (2022) was used. Process-related (duration and quality) and human factors (user acceptance, usability, workload, ergonomics) criteria were evaluated. To the authors' knowledge, the results present the largest evaluation sample for multi-assistance systems within manufacturing. Compared to the current body of research, the results show a multi-criteria depiction of six scenarios and consider differences between campus recruits and skilled workers. The results contribute to the requirements and specifications for productive and accepted human-cyber-physical systems to untrap the potential of combined assistance systems or even seamlessly integrated human-automation symbiosis (Mark et al., 2021).

2. State of the art

Industrial assistance systems support operators in executing their tasks without substituting the operator. The sovereignty over the execution and operation of the system remains with the operator, and the system must not pose any danger to the person operating it or third parties (Weidner et al., 2015). Different approaches can be found in the literature for classifying assistance systems. In this paper, we classify systems based on the type of assistance and distinguish between cognitive and physical assistance. Physical assistance systems range from common production tools to highly technical systems, e.g., collaborative robots or exoskeletons. Cognitive assistance systems are used, for example, to display work instructions in assembly or maintenance (Reinhart, 2017).

When introducing assistance systems, the question of comparability of the systems in one process comes up. In this context, the comprehensive evaluation of the processes and the systems used is important in order to analyze the consequences. To consider several aspects, the company and human-centered perspective should be taken into account. For a multi-criteria evaluation of industrial assistance systems, different methods for solving a problem with several, sometimes conflicting, target attributes are considered (Triantaphyllou, 2000). Multi-criteria decision support methods (MCDA) can be used to find solutions in a structured manner and support the decision-makers in making a decision with at least two criteria. The evaluation method in this paper is based on the multi-criteria evaluation model from previous research of (Zigart, 2022) and (Zigart & Schlund, 2020). In a systematic literature review the most commonly used methods used for evaluating the criteria are shown. Based on the literature review the evaluation criteria and methods were chosen for the evaluation in this paper.

2.1. Evaluation of cognitive assistance systems

Several studies compare augmented reality with paper- or computer-based instructions. Rupprecht et al. (2020) compared a terminal computer with projection-based instruction with 16 students. They show an overall improvement in process time of 3–4 %. Usability was measured with the 'system usability scale' (SUS) and user acceptance with the 'technology acceptance model' (TAM). The average SUS-score for the projection system was 85,3, and for the terminal-based system, 71,1. The TAM shows better user acceptance for the projector than for the terminal (Rupprecht et al., 2020). In a further study with 25 students, shows workload reduction with 'NASA-task load index' while improving productivity (Rupprecht et al., 2022).

Mark et al. (2020) compare a paper-based and projection-based assistance system. Ten people with technical backgrounds between 23 and 31 years assemble pneumatic cylinders. Quantitative and qualitative data was collected. The learning curve showed that in the beginning, people working with the projection-based system were faster, but as soon as they knew all the steps, working with the paper-based instructions was superior (Mark et al., 2020). Lovasz-Bukvova et al. (2021) conducted a study with students and operators to measure the usability and task load of augmented and virtual reality applications. They found significant differences between students and operators. The operators considered the usability higher compared to the students, though age had no significant impact (Lovasz-Bukvova et al., 2021).

Aschenbrenner et al. (2019) conducted a study comparing AR, paper- and projection-based assistance with students and technical apprentices. They report a lack of knowledge between students and employees regarding valid evaluation results of AR applications in the industry. Additionally, lab studies with a toy, like Lego©, are hard to compare with real-world applications like the assembly of an airplane wing (Pringle et al., 2019). Therefore, real-world applications should be chosen for studies (Aschenbrenner et al., 2019). Terhoeven et al. (2018) did a study with 59 employees to analyze mental strain, usability, and user acceptance of augmented reality. The analysis shows differences in results between operators and students or volunteers unrelated to the process (Terhoeven et al., 2018). Stockinger et al. (2022) conducted two user studies (one in a lab setting and one in a real production environment) with worker guidance systems showing different results depending on the design of the level of information given (Stockinger et al., 2023). Walczok and Bipp (2023) conducted a vignette case study investigating the effect of intelligent assistance systems on motivation in manufacturing. Two hundred three blue-collar workers tested three conditions, once working without an intelligent assistance system, once working with it, once working optionally. Their results show that intelligent assistance systems improve some motivational work characteristics while cognitive stress was not released (Walczok & Bipp, 2023).

2.2. Evaluation of physical assistance systems

Physical assistance systems provide physical support to the operators in manufacturing. Cobots assist humans in repetitive and higher-precision actions, and humans intervene when greater flexibility is required. This leads to increased productivity and safety in the manufacturing process. In order to fully reach the benefits of human-robot collaboration, it is essential to consider human-related aspects as well (Gervasi et al., 2023; Verna et al., 2022). To increase efficiency, product quality, and reduce defects, cobots are also used for in-process visual inspections in quality control, but still play a marginal role. There are still barriers for the widespread use of cobots in quality control, e. g. costs, technical limitations, integration in the manufacturing process (Verna et al., 2022).

Gervasi et al. (2023) conducted a study with 36 participants in a 4-hours shift using a cobot in a repetitive assembly process. They did questionnaires on user experience (perceived workload, affective state, perceived physical exertion), physiological response (electrodermal activity, heart rate variability), and defects (process and product defects). The study shows that the cobot enhances physical ergonomics and cognitive support for operators in repetitive processes. The utilization of collaborative robotics in the human-robot collaboration setting leads to reduced mental effort, stress, and process defects, ultimately improving process quality by also cognitive support (Gervasi et al., 2023). Schmidbauer et al. (2023) conducted a cobot study with 25 experienced workers from the shop floor in an industry setting, evaluating the workload with NASA-RTLX and the usability with SUS. They found that workers prefer to give manual tasks to the robot and keep cognitive tasks for themselves. Holm et al. (2021) did a field study with 41 operators using a cobot in different scenarios. The participants expressed a positive attitude towards working with the cobot. In all tested scenarios, the participants complained about the slow movements of the cobot, even though these were for safety reasons.

Constantinescu et al. (2019) show an approach to evaluate exoskeletons in simulated workstations. It allows an analysis of ergonomics, usability, cycle time, donning and doffing time of the exoskeleton, ergonomic parameters, load analysis, product quality, scrap rate, and other criteria. In the simulations, exoskeletons shorten some workstations' cycle time and lengthen it at others. The stress analysis shows that the employees are less tired and exhausted after their shift due to the use of exoskeletons (Constantinescu et al., 2019).

2.3. *Multi-assistance systems*

By combining advantages from humans and assistance systems, significant capability enhancements can be acquired, e.g., increased work efficiency, quality, and stability of systems. Additionally, knowledge management can be improved by transferring human knowledge to the cyber system (Zhou et al., 2018). With different challenges in one process, multiple assistance systems can aid in problem-solving. Papanastasiou et al. (2019) present a case study using a robotic coworker with a safety skin, augmented reality glasses, a smartwatch, and an adaptive vision system. They point out that such a setting raises the operator's safety assurance and high acceptance of the technical systems. Therefore, they worked on a seamless collaboration scheme between all systems. They improved the cycle time and the operator's satisfaction by reducing waiting times in the case study. Additionally, flexibility and quality were increased without highly relevant investments. The return on investment was calculated at 2.5 years, which was acceptable for the industry (Papanastasiou et al., 2019). In a similar case study, Andronas et al. (2021) used an augmented reality headset, a smartwatch, a tablet, and a cobot. They used the System Usability Scale (SUS) to evaluate usability. The SUS-score reached an average of 78.33 %, which shows an acceptance in the industrial environment. They also found that customizing each interface to operators' needs raises user acceptance. Verna et al. (2023) proposes also to include product complexity into the evaluation process, as the increased performance, e.g. productivity, quality, and costs, often directly depends on it.

2.4. *Assistance systems for the assembly of an electro-control panel*

In electro-control panel construction, companies face problems such as equipping control cabinets with mounting rails, components, and wires (Nägele & Dörbaum, 2021). Numerous manual steps characterize these processes and are often time-consuming, expensive, and error-prone. Around 500 connections are laid for the control technology in an average electro-control panel, with different cross-sections, colors, and assemblies. In a test application, Nägele & Dörbaum (2021) show a solution for automated control cabinet assembly using lightweight robots. The order-based manufacturing leads to small batch sizes and complicates the automation of processes. Abraham & Annunziata (2017) compare the placement and wiring of a wind turbine control box to a company's current process using paper instructions and a technician performing the same task using augmented reality glasses. The application improved the worker's Performance by 34 % the first time it was used, showing a significant improvement with the assistance system (Abraham & Annunziata, 2017). At Siemens WKC, circuit diagrams and specific information about the control panel are provided to the respective areas, such as electrical production, mechanical processing, cable assembly, or picking according to standard specifications, mainly in paper form. Another way to provide information in electro-control panel assembly is laser projection to display the position and related information onto the control cabinet (LAP Laser Applikationen, 2019).

2.5. *Novelty/research gap/discussion of the state of the art*

Our research introduces a novel approach for systematically evaluating multi-assistance systems, considering several cognitive and physical assistance within a single industrial process. While previous studies (e. g. Aschenbrenner et al., 2019; Gervasi et al., 2023; Holm et al, 2021) have separately examined the different types of assistance systems separately, our work integrates multiple systems within one process and provides a comprehensive framework for a multi-criteria evaluation. This approach unveils potential synergies between multiple assistance systems within the same industrial process, thus filling a research gap in the existing literature and offering a comparable method for evaluating changes when applying assistance systems in real-world industrial settings.

3. Use case setting, study procedure, and methods

During the study, skilled workers and students tested a set of assistance systems to evaluate the systems in an industrial production environment. Multiple cognitive and physical assistance systems were applied in the case study.

3.1. *Use case setting*

With over 24.000 control panels produced annually at an average batch size of less than 2, Siemens WKĆs production program can be described is predominantly customer specific. The circuit diagrams and specific information about the control panels are provided to the respective areas, such as electrical production, mechanical processing, cable assembly, or picking according to standard specifications, mainly in paper form. A production process was used to conduct the study in which a control panel is assembled and wired. A mounting plate with five attached mounting rails represented a workstation in the production line of the control panel. According to DIN 33402-2 (2020), the maximum vertical reach at the 50th percentile is 195 cm for women and 208 cm for men. Based on this information, the mounting plate was fixed at a height between 150 cm and 190 cm to allow for a placement that is within reach of most people. Furthermore, the setup consisted of two different-sized screwdrivers, terminal blocks of various colors and sizes, boxes functioning as a material supply system, and multiple assistance systems. Fig. 1 (a) shows the setup of the workstation, including the assistance systems (blue) and general equipment (white), and (b) the use case at the assembly site.

For providing information, two systems were elaborated: (1) a digital instruction shown on a tablet and (2) projected instructions on the mounting plate, both with information via text, pictures, and optional detailed assembly videos. Depending on the scenario (Table 2), one of the instruction systems was used to give the user step-by-step instructions on how to assemble the control panel. To assemble the panel, the user had to install 12 terminal blocks in the correct order and position on the mounting rails. In addition, 5 wires had to be installed

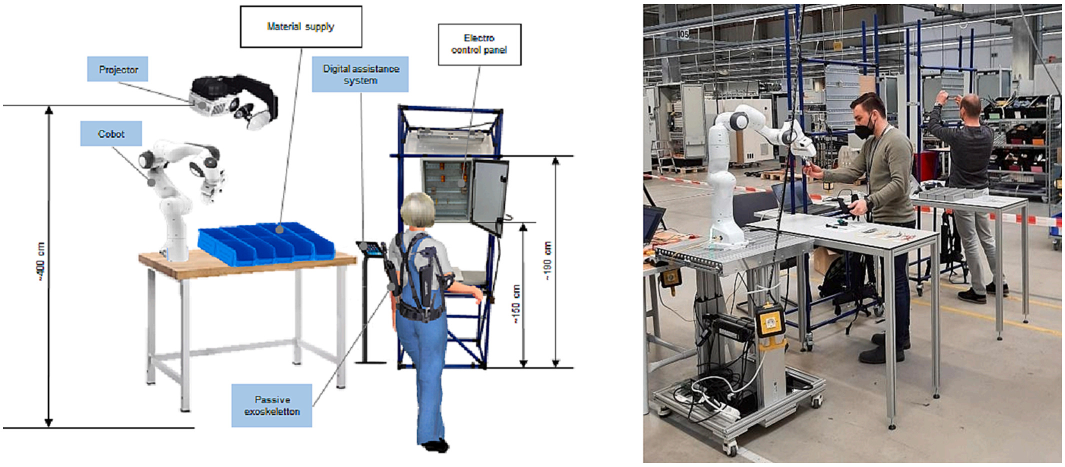

Fig. 1. (a) Use case setting, (b) at the assembly site (© Siemens WKC).

Table 1
Assistance systems.

Assistance System	Producer	Model
Tablet	Microsoft	Microsoft Surface Pro
Projection setup	Panasonic projector	Panasonic PT-RZ660BE
	Dynamic component	Dynamic Projection Mirror Head
	Desktop PC	Dynamic Projection MDC-X Media Server
	Media Software	Dynamic Projection MDC Software
	Participant Interaction	WIFI/MQTT-Button next to the mounting plate
Cobot	Franka Emika	Panda
Passive exoskeleton	Ottobock	Paexo Shoulders

according to the wiring instructions provided by the system. Some of the terminal blocks and wiring required the use of one of two screwdrivers. Information on which screwdriver to use was also provided by the instruction system. Fig. 2 shows the detailed assembly process in an extended event-driven process chain (eEPC) diagram.

A collaborative robot (cobot) and a passive exoskeleton were implemented into the process for physical support. The cobot provided the assembly parts to the skilled worker in the correct order via a magnetic mount. The cobot was signaled to hand over the next part by pressing the cobot's head. This offers a higher operator control to support higher flexibility and efficiency throughout the process (Wang et al., 2019). Exoskeletons are mainly used preventively in production to enhance the actual ergonomic work situation of the operators (Dahmen & Constantinescu, 2020). Since the operators had to perform much of the experiment overhead, a passive exoskeleton was used, which facilitates efforts when working above shoulder height. Detailed information about the assistance systems used is shown in Table 1.

3.2. Tested scenarios and study procedure

The assistance systems were used in six scenarios to test different single- and multi-assistance systems (see Table 2). Each scenario consisted of at least one cognitive assistance system (to provide the required instruction information) and none to two physical assistance systems. This was done to evaluate using an assistance system alone and compare it to the user in a multimodal setup.

Fig. 3 shows the study procedure. At first, the participants got a code number to identify the related questionnaires later. Afterward, the participants read and signed a form about research ethics and privacy policy and continued by filling out a demographic questionnaire. Information about the task and instructions on operating the assistance systems were given. In the second step, the process was executed by the participants. During the execution, the task completion time and eventual errors were recorded. Participants of the skilled worker group completed at least two cases, while participants of the student group completed at least one case. After finishing the case, the attendees completed a questionnaire to evaluate the assistance systems.

3.3. Evaluation criteria and methods

A multi-criteria evaluation was conducted to allow a holistic comparison of the use cases. Process-related (duration and quality) and human factors (user acceptance, usability, workload, ergonomics) criteria were evaluated. The evaluation is based on the evaluation model from Zigart (2022).

3.3.1. Duration and quality

The researchers measured the time needed to complete the task during the study. To ensure comparability, time spent due to distractions, breaks, or technical issues was excluded from the time taking process. The quality check was at the end of the process on an ordinal scale from 1 to 3. 3 defines good quality without any errors; 2 is for errors with the sequence and alignment of the claims; 1 for not tightly screwed, no completeness, or if more than one of the previously described errors occurred. The human factors were collected using a questionnaire after finishing each scenario. The questionnaire includes user acceptance, usability, workload, and ergonomics questions. All questionnaires must fit all cognitive and physical assistance systems to compare combinations of scenarios.

Table 2
Test scenarios.

Assistance System		Scenario 1 (T)	Scenario 2 (P)	Scenario 3 (TE)	Scenario 4 (TC)	Scenario 5 (TEC)	Scenario 6 (PEC)
Cognitive Assistance System	Tablet (T)	X		X	X	X	
	Projection (P)		X				X
Physical Assistance System	Exoskeleton (E)			X		X	X
	Cobot (C)				X	X	X

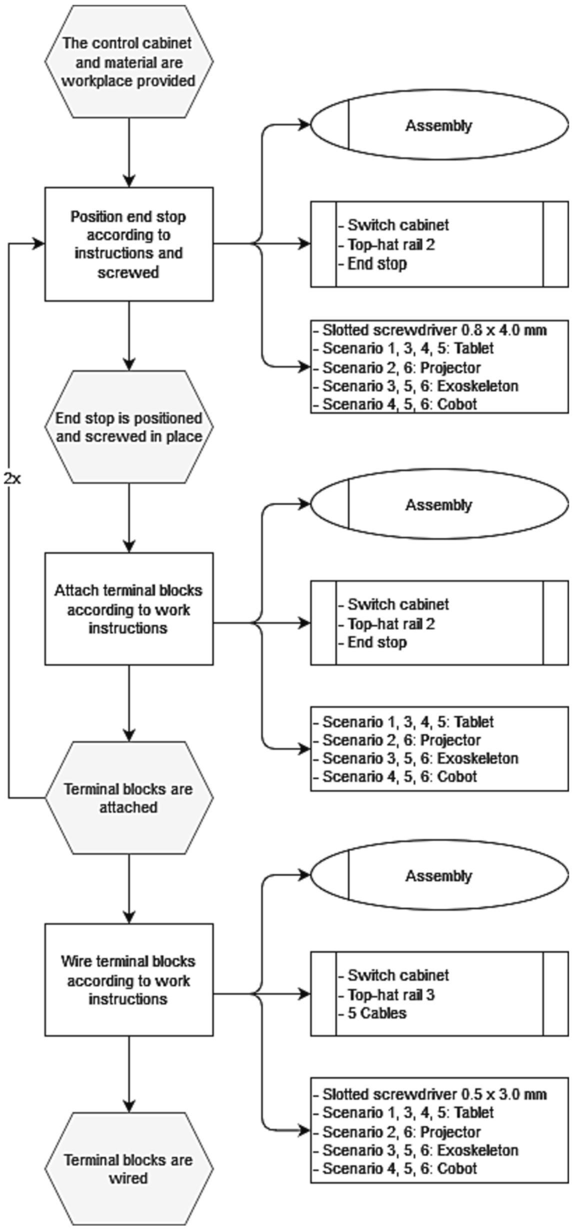

Fig. 2. eEPC process diagram of the assembly process.

3.3.2. *System usability scale (SUS)*

The System Usability Scale (SUS) offers a simple and quick way to measure how people perceive the usability of systems (Brooke, 2013). Due to the frequent use of SUS, some *meta*-studies provide comparative values for interpreting usability scores (Lewis & Sauro, 2017). The ten statements of SUS are rated on a 1 to 5 Likert scale (strongly disagree - agree) (Cronbach's α = 0.8). The statements are phrased positively and negatively to avoid response bias and require respondents to consider whether they agree or disagree with each question. For each assistance system, usability is measured.

3.3.3. *Workload (NASA-RTLX)*

The NASA-TLX is a widely used, subjective, multidimensional assessment tool that evaluates perceived workload to assess the effectiveness of a task, system or team, or other aspects of performance, also for assistance systems (Hart & Field, 2006; Hill et al., 1992). It uses six dimensions: Mental stress, physical demand, temporal demand, performance, effort, and frustration. The procedure for administering and analyzing the test is labor-intensive and time-consuming (Hill et al., 1992). Several studies have used an unweighted (raw) version of the TLX score, the NASA-Raw Task Load Index (NASA-RTLX). This omits weighting and calculates a score by averaging the six dimensions (Georgsson, 2020). Almost equivalent to the original TLX scale, the analysis takes much less time (Hart & Field, 2006). Due to its faster execution with almost equivalent results, the NASA-RTLX was chosen for the user study.

3.3.4. *Technology acceptance model (TAM)*

The technology acceptance model (TAM) from Davis et al. (1989) was used to assess user acceptance. TAM focuses on perceived usefulness (PU) and perceived ease of use (PEOU), the two main variables to measure user acceptance (Davis et al., 1989). The first six questions ask about Perceived Usefulness (PU_1-6) (Cronbach's α = 0.9), questions seven to twelve about Perceived Ease of Use (PEoU_1-6) (Cronbach's α = 0.9), and 13 to 15 about Behavioral Intention to Use (BI_1-3) (Cronbach's α = 0.7), and 16 and 17 about Actual System Use (U_1 & 2) (pearson correlation = 0.7). All questions are answered on a five-point Likert scale. TAM assumes that people know the operational application and the actual state. As this was not the case for the students, the multidimensional concept of technology compatibility from Karahanna et al. (2006) was used additionally. The technology compatibility is based on TAM and maps the following constructs: (1) Compatibility with experience (CEXP_1-4) (Cronbach's α = 0.9), (2) compatibility with values (CVAL_1-5) (Cronbach's α = 0.8), and (3) compatibility with preferred practice (CPREF_1-4) (Cronbach's α = 0.9). Karahanna et al. (2006) found that technology compatibility positively influences expected usefulness and usability from TAM and, in turn, on intention to use. Therefore, regardless of the actual state, it can be assumed that higher technology compatibility represents potential acceptance of the

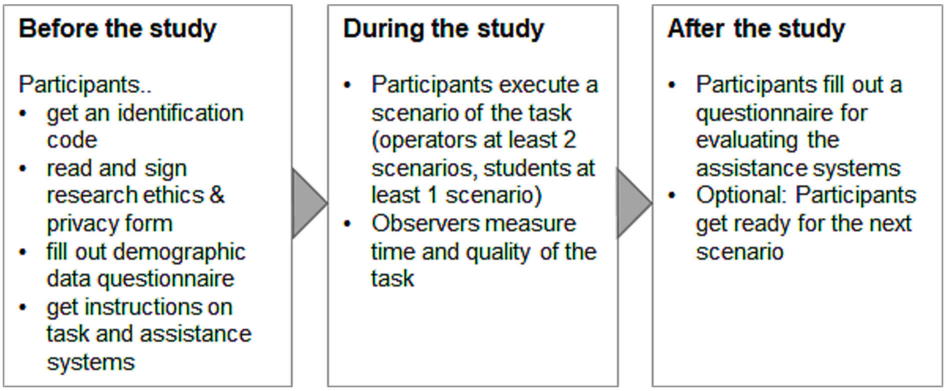

Fig. 3. Study procedure.

technology (Karahanna et al., 2006). The perceived ergonomics were rated with the single question, “How would you rate the overall ergonomics of the process?” on a 1 to 5 Likert scale (very poor - very good).

4. Results

4.1. Participants

The study’s first part occurred between June 14th and December 1st, 2021, in the TU Wien Pilot Factory. Voluntary students were recruited during pilot factory visits and tried one or more test scenarios. 24 % of the scenarios were conducted by female participants, 75.33 % by males, and a further 0.67 % by participants with unreported gender. Nobody was below 20, 66.67 % were between 20 and 29 years old, 26,67 % between 30 and 39, 5.33 % between 40 and 49, and 1.33 % over 50. No students had previous knowledge of assembling electro-control panels, and 13,50 % worked in the manufacturing industry besides their studies. The student participants rated technology affinity to technology interaction high (M = 4.23, SD = 0.89). For the second part of the study, skilled workers at Siemens WKC, who participated in the study between March 29th and 31st, 2022, in Chemnitz. 8.21 % of the participants identified themselves as female and 91.79 % as male. 1 % was below 20, 14.33 % were between 20 and 29 years old, 39.71 % between 30 and 39, 32.75 % between 40 and 49, and 12.22 % over 50. The affinity to technology interaction was, on average, high among the participants (M = 4.13). Almost 60 % of participants were active shop floor workers, 30 % used to work in the manufacturing process and are executives or in related areas (e.g., production planning, lean management), and 10 % of participants have never been involved in the manufacturing process. Participants rated the affinity for technology interaction relatively high (M = 4.06, SD = 0.68). The number of participants per scenario are shown in Table 3.

The software SPSS (Statistical Package for the Social Sciences) version 26 was used to conduct a series of one-way ANOVA, *t*-test, subsequent pairwise comparisons (Bonferroni corrections applied), and the Wilcoxon signed rank test (for non-parametric distribution) to explore the differences between or within subjects.

4.2. Comparisons of skilled workers with students

According to Table 4, students required significantly longer time to complete the task than skilled workers in all scenarios (it is noteworthy to mention that only for scenario 1 (T) the difference was not significant). Students reported significantly better perceived ergonomics scores for scenario 3 (TE) (t(47) = -2.30p <.05) and scenario 6 (PEC) (t(50) = -2.55p <.05) than skilled workers. Scenario 1 (T) was rated worse by students compared to skilled workers (t(47) = 3.38, p <.001). We found no significant difference in terms of quality between the skilled worker and student groups.

An independent-samples *t*-test was conducted to compare usability scores for each assistance system between skilled workers and students groups. According to Table 5, all assistant systems were rated higher in terms of usability by students than skilled workers.

The mental demand for scenario 2 (P) (t(47) = -2.03, p <.05) and scenario 3 (TE) (t(57) = -3.27, p <.001) were rated higher by students than skilled workers. Physical demand and effort for scenario 1 (T) (t(47) = -3.88, p <.001), scenario 2 (P) (t(47) = -3.11, p <.001), scenario 3 (TE) (t(57) = -2.70, p <.01), and scenario 6 (PEC) (t(50) = -2.82, p <.01) was higher among students than workers. Students rated temporal demand higher than workers only in scenario 3 (TE) (t(57) = -2.60, p <.01) as well as in scenario 6 (PEC) (t(50) = -2.72, p <.01). Workers rated performance higher for all scenarios (see Table 6) than students.

According to Table 7, students reported lower compatibility with values than skilled workers for all scenarios. Compatibility with experience was rated higher by students than skilled workers for all scenarios except scenario 1 (T), which was rated lower. Students reported lower compatibility with preferred practice than skilled workers for all scenarios (it is noteworthy to mention that only for scenario 6 (PEC) the difference was not significant).

4.3. Comparison within skilled workers - multi-assistance systems hypotheses

To explore the differences among the multi-assistance systems, we conducted several within-subject tests in which each participant experienced a single assistant system and a combination of at least two assistant systems. Since our data was not normally distributed, we used the non-parametric Wilcoxon signed rank test to compare the repeated measure between dependent random samples.

Wilcoxon signed-rank test indicated that in terms of compatibility with experience, scenario 1 (T) was rated less favorably than scenario 3 (TE) (Z = -3.87, p <.001), scenario 4 (TC) (Z = -2.85, p <.01), scenario 5 (TEC) (Z = -2.94, p <.01), and scenario 6 (PEC) (Z = -2.85, p <.01). Moreover, a significant change in terms of effort was revealed between scenario 1 (T) and scenario 6 (PEC) (Z = -2.00, p <.05).

The duration of task completion in scenario 1 (T) was only longer compared to scenario 3 (TE) (Z = -2.76, p <.01). Furthermore, in terms of compatibility with value, scenario 2 (P) was rated less favorably than scenario 3 (TE) (Z = -2.83, p <.01) and scenario 4 (TC) (Z = -2.04, p <.05). The differences between duration, workload dimensions, and ergonomics were not significant (see Table 8).

5. Discussion

Understanding how skilled and unskilled workers interact with assistance systems in manufacturing and how they experience the factory environment is fundamental to correctly modeling human interaction and optimizing the processes. The question even gains importance as multiple assistance systems emerge within manufacturing settings. This paper investigates humans’ behaviors and perceived experiences while interacting with state-of-the-art assistance systems. We measured several subjective measurements, such as compatibility beliefs, behavioral intentions, ergonomics, workload, and usability, as well as objective measurements, such as duration and quality of task performance.

5.1. Comparison of skilled workers and students

A comparison between skilled workers and students demonstrated that the usability score of all assistance systems (T, P, E, C) was rated higher among the students than skilled workers. Furthermore, students needed more time to complete the task across all scenarios. This result

Table 3
Number of participants per scenario.

Number of participants	Scenario 1 (T)	Scenario 2 (P)	Scenario 3 (TE)	Scenario 4 (TC)	Scenario 5 (TEC)	Scenario 6 (PEC)
Skilled workers	24	24	24	25	27	24
Students	25	25	35	15	25	28
Total	**49**	**49**	**59**	**40**	**52**	**52**

Table 4

Comparison of duration, ergonomic scores and quality between students and skilled workers per scenario.

		Duration			Ergonomics			Quality		
Assistance System		M	SD	p	M	SD	p	Mean rank	sum of ranks	p
Scenario 1 (T)	W	6.76	2.47	n.s.	3.46	0.779	<0.001	25.6	768	n.s.
	S	7.88	2.71		2.64	0.907		21.18	360	
Scenario 2 (P)	W	5.48	1.16	<0.001	3.52	0.846	n.s.	23.98	1527.5	n.s.
	S	8.19	2.11		3.36	1.287		24.02	600.5	
Scenario 3 (TE)	W	5.03	1.04	<0.001	3.5	1.063	<0.05	20.12	523	n.s.
	S	10.59	2.35		4.09	0.887		23.75	380	
Scenario 4 (TC)	W	6.59	2.26	<0.001	3.36	0.757	n.s.	20.44	490.5	n.s.
	S	10.48	3		3.47	1.06		21.79	370.5	
Scenario 5 (TEC)	W	6.13	2.15	<0.001	3.63	0.884	n.s.	26.43	713.5	n.s.
	S	9.1	2.61		4.08	0.759		28.57	771.5	
Scenario 6 (PEC)	W	5.85	1.31	<0.001	3.42	0.881	<0.05	22	418	n.s.
	S	9.06	2.23		4	0.77		22	528	

Note: W = skilled workers, S = students.

Table 5

SUS scores of students and skilled workers per assistance system.

Assistance System		M	SD	*t*-test	p
Tablet	Skilled workers	78,65	12,29	−2,62	<0.05
	Students	86,9	9,69		
Projector	Skilled workers	70,63	18,73	−2,60	<0.05
	Students	83,1	14,69		
Exoskeleton	Skilled workers	73,85	19,36	−2,36	<0.05
	Students	83,43	11,74		
Cobot	Skilled workers	74,2	10,17	−2,27	<0.05
	Students	82,83	13,83		

was expected as students had to experience working with the tools, and the working setup and procedures were entirely new. Similarly in terms of perceived ergonomics, we only found differences among students rating and skilled workers concerning scenario 1 (T), scenario 3 (TE) and scenario 6 (PEC). While studentś perceptions of the ergonomic aspects of scenario 3 (TE), and scenario 6 (PEC) were greater than those of skilled workers, their ergonomic evaluations of scenario 1 (T) were lower than those of skilled workers. This poor evaluation of scenario 1 (T) in terms of ergonomics is somewhat surprising given the fact that they rate the usability higher than skilled workers. This inconsistency may imply that while students find working with Tablet easy and efficient, it may not be designed with their long term comfort.

In all scenarios, the compatibility with experiences for skilled workers was lower than the students' group except in scenario 1 (T). On the other hand, the compatibility with values and existing work practices were higher for skilled workers rather than the students' group across all scenarios. While compatibility to prior experience describes operational compatibility, which is the extent of congruence between new technology and the situation in which it is being utilized, compatibility with values is cognitive perceptions (Karahanna et al., 2006). Therefore, we suggest that while all combinations fit better into the lifestyle of the students, they fit better with the needs of skilled workers.

Regarding workload, the amount of effort (TLX5) for students was significantly higher for all scenarios except scenario 4 (TC) and scenario 5 (TEC). A possible explanation could be that students had no prior experience with the work processes and, therefore, they needed to work harder than skilled workers to perform the required task. Moreover, the degree of goal accomplishment (TLX4) was higher among the skilled workers than in the students' group for all scenarios. This implies that skilled workers were more satisfied with their performance in accomplishing these goals.

To complete the task students required significantly longer than skilled workers in all scenarios. In terms of quality, there is no significant difference between the skilled worker and student groups.

5.2. Multi-assistance systems

Considering the collected data among the skilled workers, the overall user experience of multi-assistance system use cases was more favorable across different workload and user acceptance dimensions than in the single assistance system use case. While task completion in scenario 1 (T) was longer compared to scenario 3 (TE), our results show that the compatibility with experience for the tablet alone was lower than any other combination with it (e.g., TE, TC, TEC). Similarly, the compatibility with value favored multi-assistance settings (e.g., TC and TE) rather than the projector alone. Previous studies (e.g., [35–38]) suggested that the compatibility of one's experience and values with a technology directly influences technology use and cognitive burden. In other words, higher consistency with their previous experience facilitates the learning process (Karahanna et al., 2006). Therefore, taking our findings into consideration, a higher possibility of achieving successful acceptance for multi-assistance systems in combination with a tablet can be expected than single assistance systems (e.g., P or T). Regarding the negative evaluation of the projector, a possible explanation could be that the current projector implementation was not ideal for the workplace environment, and with some improvement (such as light and accuracy), adoption can be preferred.

From the workload perspective, the amount of (physical and mental) effort was significantly different only between scenario 1 (T) and scenario 6 (PEC) and no other multi-assistance system scenario (e.g., TE, TC, TEC). A lower amount of physical and mental effort for scenario 1 (T) implies that participants had to work harder to accomplish the desired level of performance while working with the multi-assistance system scenario 6 (PEC). Moreover, negative comments about the speed and functionality of the cobot and projector were mentioned during the interviews. This issue has been reflected by Participant 33, who stated that "the separate operation of the assistance systems is a

Table 6
Comparisons of workload between students and skilled workers per scenario.

		Scenario 1 (T)			**Scenario 2 (P)**			**Scenario 3 (TE)**		
		M	SD	p	M	SD	p	M	SD	p
TLX1	W	1.63	0.88	n.s.	1.67	0.87	<0.05	1.5	0.659	<0.001
	S	2.08	0.86		2.24	1.09		2.23	0.942	
TLX2	W	1.63	0.92	<0.001	1.42	0.58	<0.001	1.54	0.721	<0.01
	S	2.64	0.91		2.24	1.16		2.14	0.912	
TLX3	W	1.42	0.65	n.s.	1.21	0.41	n.s.	1.25	0.532	<0.05
	S	1.72	0.79		1.44	0.77		1.77	0.877	
TLX4	W	3.29	1.16	<0.001	3.29	1.27	<0.01	3.67	1.341	<0.001
	S	2.2	0.82		2.32	1.07		2.37	0.877	
TLX5	W	1.67	0.96	<0.05	1.58	0.72	<0.05	1.5	0.59	<0.01
	S	2.24	0.78		2.2	1.12		2.11	0.932	
TLX6	W	1.5	0.88	n.s.	1.5	0.83	n.s.	1.38	0.77	n.s.
	S	1.4	0.58		1.6	1		1.46	0.78	
		Scenario 4 (TC)			**Scenario 5 (TEC)**			**Scenario 6 (PEC)**		
		M	SD	p	M	SD	p	M	SD	p
TLX1	W	1.76	0.831	n.s.	1.78	0.801	n.s.	1.67	−1.48	n.s.
	S	2.07	1.033		2.24	1.012		2.04		
TLX2	W	1.56	0.712	n.s.	1.44	0.751	n.s.	1.46	−2.82	<0.01
	S	2	1.254		1.76	0.97		2.18		
TLX3	W	1.64	0.86	n.s.	1.52	0.643	n.s.	1.17	−2.72	<0.01
	S	1.67	0.976		1.6	0.913		1.64		
TLX4	W	3.36	0.952	<0.001	3.59	1.152	<0.001	3.63	5.08	<0.001
	S	2.13	1.187		2.36	1.114		2.14		
TLX5	W	1.96	0.841	n.s.	1.67	0.734	n.s.	1.42	−2.96	<0.001
	S	1.8	0.775		1.92	1.077		2.07		
TLX6	W	1.56	1.044	n.s.	1.37	0.629	n.s.	1.42	−1.81	n.s.
	S	1.47	0.743		1.6	0.816		1.89		

Note: TLX1 = mental workload, TLX2 = physical workload, TLX3 = temporal workload, TLX4 = performance, TLX5 = effort, TLX6 = frustration, W = skilled workers, S = students.

Table 7
Comparison of compatibility scores between students and skilled workers per scenario.

		Scenario 1 (T)			**Scenario 2 (P)**			**Scenario 3 (TE)**		
		M	SD	p	M	SD	p	M	SD	p
CEXP	W	3.39	1.17	<0.01	1.76	0.93	<0.001	1.66	0.93	<0.001
	S	2.5	1.13		3.37	1.23		3.89	0.8	
CVAL	W	4.32	0.7	<0.001	4.31	0.98	<0.001	4.24	0.97	<0.001
	S	1.45	0.67		1.33	0.61		1.37	0.54	
CPREF	W	3.02	0.89	<0.05	2.7	0.99	<0.001	2.81	1.24	<0.05
	S	3.63	0.82		3.81	0.78		3.49	0.94	
		Scenario 4 (TC)			**Scenario 5 (TEC)**			**Scenario 6 (PEC)**		
		M	SD	p	M	SD	p	M	SD	p
CEXP	W	2.09	0.75	<0.001	1.68	0.65	<0.001	1.73	0.85	<0.001
	S	3.1	1.27		3.35	1.28		3.48	1.22	
CVAL	W	4.06	1.01	<0.001	4.16	0.83	<0.001	4.27	1.09	<0.001
	S	1.39	0.81		1.44	0.72		1.63	0.87	
CPREF	W	2.85	1.12	<0.01	2.7	1.02	<0.001	3.13	1.08	n.s.
	S	3.87	0.93		3.9	0.89		3.57	1.14	

Note: CEXP = compatibility with experience, CVAL = compatibility with value, CPREF = compatibility with preferred practice, W = skilled workers, S = students.

hindrance”. It implies that individually coordinating each assistance system causes more effort for workers, leading to higher overload. Participant 31 also confirms this by proposing that “it would be better if the cobot itself recognizes when it should hand over the next part”. This highlights that the incompatibility of an assistance system may lead to an increased workload for the workers. Table 9 shows the summarized qualitative feedback from skilled workers regarding each assistance system.

It is noteworthy that our results showed no significant differences in perceived ergonomics and a majority of workload dimensions between the single assistance system scenarios 1 (T) or 2 (P) and multi-assistance systems scenarios. While the analysis of the human workload helps understand whether assigning some tasks to assistance systems allows for avoiding human overload, we found only evidence that in terms of effort, there is a difference between working only with a tablet and a combination of projector, exoskeleton, and cobot. An alternative explanation for this result might be related to potential conflicts of using these assistance systems together as they may not be fully compatible.

5.3. *Implications for further use of multi-criteria evaluation*

In our research, we showed the applicability of the multi-criteria evaluation model for cognitive and physical assistance systems in one industrial process. We evaluated human behaviors and perceived experiences while using industrial assistance systems. The multi-criteria evaluation method allows a comprehensive assessment for multi-use of industrial assistance systems, instead of the consideration of only one system at the time. For future research, the application is planned to be extended to further domains and other industrial assistance systems than applied in this paper. Additionally, the positive industry feedback highlights its practical feasibility. This encourages a broader adoption for the evaluation of multi-assistance solutions in industry.

Table 8
Comparison of variables between single and multi-assistance systems.

	Median Scenario 1 (T)	Scenario 3 (TE)	Z N = 21	p	Median Scenario 1 (T)	Scenario 4 (TC)	Z N = 11	p
CEXP	2.50	4.75	−3.87	< 0.001	2.50	3.87	−2.85	< 0.01
TLX5	1.00	1.00	−1.62	n.s.	1.00	1.50	−1.68	n.s.
Duration	6.70	5.00	−2.76	< 0.01	6.50	6.60	−1.60	n.s.
	Scenario 1 (T)	Scenario 5 (TEC)	N = 11		Scenario 1 (T)	Scenario 6 (PEC)	N = 12	
CEXP	2.50	4.50	−2.94	< 0.01	2.50	4.60	−2.85	< 0.01
TLX5	1.00	1.50	−0.33	n.s.	1.00	2.00	−2.00	< 0.05
Duration	6.10	6.00	−1.77	n.s.	6.00	5.90	−1.75	n.s.
	Scenario 2 (P)	Scenario 3 (TE)	N = 13		Scenario 2 (P)	Scenario 4 (TC)	N = 11	
CVAL	1.00	1.40	−2.83	< 0.01	1.00	1.80	−2.32	< 0.05
	Scenario 2 (P)	Scenario 5 (TEC)	N = 16		Scenario 2 (P)	Scenario 6 (PEC)	N = 17	
CVAL	1.00	1.50	−0.71	n.s.	1.00	1.00	0.00	n.s.

Note: CEXP = compatibility with experience, CVAL = compatibility with value, TLX5 = effort.

Table 9
Qualitative feedback from skilled workers.

Assistance system	**Qualitative feedback**						
Exoskeleton	Unspecific positive feedback	Unspecific negative feedback	Time to put on too long	Back pain	Difficulty in moving arms downwards/ upwards pressure/ unnatural positioning of the arms	Drains blood in arms/ Rubbing or numbness in arms	
Number of mentions	1	6	1	2	11	4	
Cobot	Unspecific positive feedback	Unspecific negative feedback	Cobot too slow	Cobot functionality (too cumbersome, too many buttons to push in a multi-assistance systems scenario, hands over only one part at once)		Cobot interaction is not sensitive enough	
Number of mentions	1	4	4	8		5	
Projection	Unspecific positive feedback	Unspecific negative feedback	Projection too slow	Bad positional accuracy	Positioning the button for interaction is not optimal	Bad visibility	Bad clarity
Number of mentions	1	4	1	8	4	5	4
Tablet	Unspecific positive feedback	Unspecific negative feedback	Poor Clarity	Positioning of the tablet in relation to the workspace			
Number of mentions	/	/	7	6			

5.4. Limitations

The generalisability of our results is subject to certain limitations. First is the small sample size. Although 300 run-throughs were made, the number per scenario (6 in total) was limited to 25 for students and skilled workers each. Due to time restrictions, not every participant was able to test all six scenarios, which limits comparability. The data validity would be higher with more diverse study participants and larger groups. The technical implementation of the assistance systems needs to be improved to avoid unnecessary slowdowns by the systems and higher acceptance by the skilled workers for multi-assistance system use. This is necessary to untrap the potential of human-system-symbioses, where machines assist humans in work systems to use their skills and abilities in an ideal way (Romero et al., 2017).

Participants doing more than one scenario had a learning curve for the assembly task, even though different assistance systems were used. Due to the different information content in the tablet instruction and the projection, all persons started with the tablet instruction (or a variant of it, e.g., TE, TC, TEC). This leads to longer durations for the first assembly operation. Doing more than one scenario can also lead to a lack of objectivity and biases due to habituation effects and fatiguing aspects (Schmidtler et al., 2017).

For further research, the scenarios will be varied more to have slightly different assembly tasks for each scenario to counteract the learning curve, as Participant 4 mentioned that “the use case could have been more complex”. The provided information will be adapted based on the participants’ previous knowledge. As our study was descriptive, the causing factors for the multi-assistance systems evaluation results should be elaborated. Also, some combinations of assistance systems were left out, for example, PE. This will be added for a second study.

Additionally, the exoskeletons used were medium size and would need more individual adjustments for each participant (e.g., changing the shells for the correct upper arm and adjustment of the support strength), which was not done due to time and availability issues. This led to “an unpleasant rubbing against the arms” of Participant 6 and “numbness in the arms after continuous use” of Participant 34.

6. Conclusion

Systems to assist human workers in manufacturing have experienced considerable growth over the last decade. The use of digital devices, cobots, and exoskeletons has made significant progress from lab scale into manufacturing facilities. Today, most large enterprises and a growing number of SMEs operate at least one of the systems mentioned above (Mayrhofer et al., 2020; Vieth et al., 2022). While automation of manufacturing processes rapidly advances, high-mix, low-volume assembly processes still rely on a significant share of human labor in both the cognitive and the manual dimensions of work. Therefore, several different assistance systems are specifically developed and implemented into processes like the assembly of electro-control panels.

Reliable evaluations of assistance systems in manufacturing are rare, typically due to the low number of participants and the focus on campus recruits for experiments. The fact especially accounts for the combined use of multiple assistance systems within assembly processes. As the trend to integrate separate assistance systems can be considered a straightforward development, understanding the combined use's specific impact is still rare and lacks empirical evidence.

This paper explores multi-assistance systems and their implications regarding technology and work-related metrics. A study with 300 run-throughs comparing skilled workers and students in an industrial use case in a high-mix low-volume assembly process was conducted. The used multi-criteria evaluation model gives a comprehensive picture of various perspectives and allows a broad comparison. The results show significant differences between the two peer groups (students and skilled workers), especially regarding productivity and usability. Regarding the comparisons between different multi-assistance settings, only the compatibility with value, experience, and task completion time show favorable results towards multi settings of "known" technologies like tablets or cobots. While high compatibility may lead to increased adoption of multi-assistance systems, this study could not detect significant differences between single and multi-assistance systems regarding workload, usability, and ergonomics. Some results seem specific to the technology used, as pointed out in the limitation section. Nevertheless, qualitative evidence supports the hypothesis that a multi-assistance system's overall complexity hinders usability and its potential adoption. Against this background and in parallel with technological advances, further evaluation research for the combined use of assistance systems is needed to derive guidelines and recommendations for designing, implementing, and using multi-assistance systems.

From a company perspective, the results contribute to the understanding of the implementation of assistance systems, showing significant differences between user groups that are familiar with the assembly process and campus recruits. Results suggest a well-planned implementation process, especially considering the integration of multiple assistance systems. Furthermore, the results show the significance of high TRL for technology acceptance and give insights into needed further development potential of spatial augmented reality systems and passive exoskeletons for use in high-mix low-volume settings. The next step is the application of assistance systems at actual work processes. The workflows are more complex and take longer than the study setting. Questions regarding the timely and future use of assistance systems at high-mix, low-volume workplaces and the accompanying change process will be investigated in further studies.

CRediT authorship contribution statement

Tanja Zigart: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Setareh Zafari:** Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Felix Stürzl:** Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Robert Kiesewetter:** Validation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Hans-Peter Kasparick:** Validation, Writing – original draft, Writing – review & editing. **Sebastian Schlund:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

Special thanks are directed to all the participants at Siemens WKC and in the TU Wien pilot factory for being part of the study and for their constructive cooperation. This work was supported by the Austrian Research Promotion Agency (FFG), the Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK), and the TU Wien through the endowed professorship "HCCPPAS" [FFG-852789].

References

Abraham, M., & Annunziata, M. (2017). *Augmented Reality Is Already Improving Worker Performance* (Operations and Supply Chain Management). *Harvard Business Review.* https://hbr.org/2017/03/augmented-reality-is-already-improving-worker-performance.

Andronas, D., Apostolopoulos, G., Fourtakas, N., & Makris, S. (2021). Multi-modal interfaces for natural Human-Robot Interaction. *Procedia Manufacturing, 54*, 197–202. https://doi.org/10.1016/j.promfg.2021.07.030

Aschenbrenner, D., Leutert, F., Çençen, A., Verlinden, J., Schilling, K., Latoschik, M., & Lukosch, S. (2019). Comparing Human Factors for Augmented Reality Supported Single-User and Collaborative Repair Operations of Industrial Robots. *Frontiers in Robotics and A, I*, 6. https://doi.org/10.3389/frobt.2019.00037

Brooke, J. (2013). SUS - a Retrospective. *Journal of Usability Studies, 8*(2), 29–40.

Constantinescu, C., Todorovic, O., & Ippolito, D. (2019). Comprehensive modelling and simulation towards the identification of critical parameters for evaluation of exoskeleton-centred workplaces. *Procedia CIRP, 79*, 176–179. https://doi.org/10.1016/j.procir.2019.02.040

Dahmen, C., & Constantinescu, C. (2020). Methodology of Employing Exoskeleton Technology in Manufacturing by Considering Time-Related and Ergonomics Influences. *Applied Sciences, 10*(5), 1591. https://doi.org/10.3390/app10051591

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User Acceptance of Computer Technology A Comparison of Two Theoretical Models. *Management Science, 35*(8), 982–1003.

DIN 33402-2. (2020). *Ergonomie – Körpermaße des Menschen – Teil 2: Werte*.

European Commission. Directorate General for Research and Innovation. (2020). *Industry 5.0: Human centric, sustainable and resilient.* Publications Office. https://data.europa.eu/doi/10.2777/073781.

Georgsson, M. (2020). NASA RTLX as a Novel Assessment Tool for Determining Cognitive Load and User Acceptance of Expert and User-based Usability Evaluation Methods. *European Journal of Biomedical Informatics.* https://www.ejbi.org/abstract/nasa-rtlx-as-a-novel-assessment-tool-for-determining-cognitive-load-and-user-acceptance-of-expert-and-userbased-usabilit-5988.html.

Gervasi, R., Capponi, M., Mastrogiacomo, L., & Franceschini, F. (2023). Manual assembly and Human-Robot Collaboration in repetitive assembly processes: A structured comparison based on human-centered performances. *The International Journal of Advanced Manufacturing Technology, 126*(3–4), 1213–1231. https://doi.org/10.1007/s00170-023-11197-4

Hart, S. G., & Field, M. (2006). *NASA-Task Load Index (NASA-TLX); 20 Years Later, 5*.

Hill, S. G., Lavecchia, H. P., Byers, J. C., Bittner, A. C., Zaklade, A. L., & Christ, R. E. (1992). Comparison of Four Subjective Workload Rating Scales. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 34*(4), 429–439. https://doi.org/10.1177/001872089203400405

Holm, M., Senington, R., Wang, W., & Lindblom, J. (2021). Real-World Industrial Demonstrators on Human-Robot Collaborative Assembly. In L. Wang, X. V. Wang, J. Váncza, & Z. Kemény (Eds.), *Advanced Human-Robot Collaboration in Manufacturing* (pp. 413–438). Springer International Publishing. https://doi.org/10.1007/978-3-030-69178-3_17.

Karahanna, E., Agarwal, R., & Angst, C. M. (2006). Reconceptualizing Compatibility Beliefs in Technology Acceptance Research. *MIS Quarterly, 30*(4), 781–804.

LAP Laser Applikationen. (2019). *Assembly 4.0 with laser projection.* https://www.pressebox.com/pressrelease/lap-gmbh-laser-applikationen/Assembly-4-0-with-laser-projection/boxid/975367.

Lewis, J. R., & Sauro, J. (2017). Revisiting the Factor Structure of the System Usability Scale. *Journal of Usability Studies, 12*(4), 183–192.

Lovasz-Bukvova, H., Hölzl, M., Kormann-Hainzl, G., Moser, T., Zigart, T., & Schlund, S. (2021). Usability and Task Load of Applications in Augmented and Virtual Reality: How Applicable are the Technologies in Corporate Settings? In M. Yilmaz, P. Clarke, R. Messnarz, & M. Reiner (Hrsg.), *Systems, Software and Services Process Improvement* (Bd. 1442, S. 708–718). Springer International Publishing. 10.1007/978-3-030-85521-5_48.

Mark, B. G., Rauch, E., & Matt, D. T. (2020). Study of the impact of projection-based assistance systems for improving the learning curve in assembly processes. *Procedia CIRP, 88*, 98–103. https://doi.org/10.1016/j.procir.2020.05.018

Mark, B. G., Rauch, E., & Matt, D. T. (2021). Worker assistance systems in manufacturing: A review of the state of the art and future directions. *Journal of Manufacturing Systems, 59*, 228–250. https://doi.org/10.1016/j.jmsy.2021.02.017

Mayrhofer, W., Kames, D., & Schlund, S. (2020). Made in Austria 2019—Survey Results of the first Industry Panel on Production Work in Austria. *Management and Production Engineering Review, 11*(3).

Mayrhofer, W., Rupprecht, P., & Schlund, S. (2019). One-fits-all vs. tailor-made: User-centered workstations for field assembly with an application in aircraft parts manufacturing. *Procedia Manufacturing, 39*, 149–157.

Nägele, F., & Dörbaum, M. (2021). *Automatisierte Tragschienenmontage mit Robotern* (WAGO, S. https://www.wago.com/de/roboter-automatisierte-tragschienenmontage?utm_source=social&utm_medium=li_organic&utm_term=Bild&utm_content=MM36508 & utm_campaign=MA806000). Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA.

Papanastasiou, S., Kousi, N., Karagiannis, P., Gkournelos, C., Papavasileiou, A., Dimoulas, K., … Makris, S. (2019). Towards seamless human robot collaboration: Integrating multimodal interaction. *The International Journal of Advanced Manufacturing Technology, 105*(9), 3881–3897. https://doi.org/10.1007/s00170-019-03790-3

Pringle, A., Hutka, S., Mom, J., van Esch, R., Heffernan, N., & Chen, P. (2019). Ethnographic study of a commercially available augmented reality HMD app for industry work instruction. In *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments* (pp. 389–397). https://doi.org/10.1145/3316782.3322752

Reinhart, G. (Hrsg.). (2017). *Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik*. Carl Hanser Verlag GmbH & Co. KG. 10.3139/9783446449893.

Romero, D., Bernus, P., Noran, O., Stahre, J., & Fast-Berglund, A. (2017). *The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems*. https://link.springer.com/chapter/10.1007/978-3-319-51133-7_80.

Rupprecht, P., Kueffner-Mccauley, H., & Schlund, S. (2020). Information provision utilizing a dynamic projection system in industrial site assembly. *Procedia CIRP, 93*, 1182–1187. https://doi.org/10.1016/j.procir.2020.04.053

Rupprecht, P., Kueffner-Mccauley, H., Trimmel, M., Hornacek, M., & Schlund, S. (2022). Advanced Adaptive Spatial Augmented Reality utilizing Dynamic in-situ Projection in Industrial Site Assembly. *Procedia CIRP, 107*, 937–942. https://doi.org/10.1016/j.procir.2022.05.088

Schlund, S., & Kostolani, D. (2022). Towards Designing Adaptive and Personalized Work Systems in Manufacturing. In P. Plapper (Hrsg.), *Digitization of the work environment for sustainable production* (S. 81–96). GITO Verlag. 10.30844/WGAB_2022_5.

Schmidbauer, C., Zafari, S., Hader, B., & Schlund, S. (2023). An Empirical Study on Workers' Preferences in Human-Robot Task Assignment in Industrial Assembly Systems. *IEEE Transactions on Human-Machine Systems, 1–10*. https://doi.org/10.1109/THMS.2022.3230667

Schmidtler, J., Bengler, K., Dimeas, F., & Campeau-Lecours, A. (2017). In *A questionnaire for the evaluation of physical assistive devices (QUEAD): Testing usability and acceptance in physical human-robot interaction* (pp. 876–881). Man: and Cybernetics (SMC). https://doi.org/10.1109/SMC.2017.8122720.

Stockinger, C., Polanski-Schräder, L., & Subtil, I. (2023). The effect of information level of digital worker guidance systems on assembly performance, user experience and strain. *Applied Ergonomics, 106*, Article 103896. https://doi.org/10.1016/j.apergo.2022.103896

Terhoeven, J., Schiefelbein, F.-P., & Wischniewski, S. (2018). User expectations on smart glasses as work assistance in electronics manufacturing. *Procedia CIRP, 72*, 1028–1032. https://doi.org/10.1016/j.procir.2018.03.060

Triantaphyllou, E. (2000). *Multi-criteria Decision Making Methods: A Comparative Study (Bd* (p. 44).). US: Springer.

Verna, E., Genta, G., & Galetto, M. (2023). A new approach for evaluating experienced assembly complexity based on Multi Expert-Multi Criteria Decision Making method. *Research in Engineering Design, 34*(3), 301–325. https://doi.org/10.1007/s00163-023-00409-3

Verna, E., Puttero, S., Genta, G., & Galetto, M. (2022). Challenges and opportunities of collaborative robots for quality control in manufacturing: Evidences from research and industry. *International Conference on Quality Engineering and Management*, 235–262.

Vieth, D., Mayrhofer, W., & Schlund, S. (2022). *Made in Austria: Produktionsarbeit in Örsterreich 2022, Studie*.

Walczok, M., & Bipp, T. (2023). Investigating the effect of intelligent assistance systems on motivational work characteristics in assembly. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-023-02086-4

Wang, L., Gao, R., & Avanza, J. (2019). *Symbiotic human-robot collaborative assembly. CIRP annals, 68*(2), 701–726.

Weidner, R., Redlich, T., & Wulfsberg, J. P. (Hrsg.). (2015). *Technische Unterstützungssysteme*. Springer Berlin Heidelberg. 10.1007/978-3-662-48383-1.

Zhou, J., Li, P., Zhou, Y., Wang, B., Zang, J., & Meng, L. (2018). Toward New-Generation Intelligent Manufacturing. *Engineering, 4*(1), 11–20. https://doi.org/10.1016/j.eng.2018.01.002

Zigart, T., & Schlund, S. (2020). Evaluation of Augmented Reality Technologies in Manufacturing – A Literature Review. In I. L. Nunes (Ed.), *Advances in Human Factors and Systems Interaction* (pp. 75–82). Springer International Publishing. https://doi.org/10.1007/978-3-030-51369-6_11.

Zigart, T. (2022). *Entwicklung eines multikriteriellen Evaluierungsmodells für industrielle Assistenzsysteme* [TU Wien]. 10.34726/HSS.2022.98440.