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User-centered development of a worker guidance system for a flexible production line

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Abstract

Worker guidance systems are digital assistance systems in production, which provide work-related information and, thus, guide employees through production processes. This article describes the user-centered development of such a worker guidance system for a flexible production line in a metrology company. Usage context analysis and requirements analysis illustrate the need for a simple and independent system that can be used voluntarily by employees. After two iterations of the human-centered design process, an interactive software prototype was created and implemented on a tablet personal computer. In this prototype, all essential process and assembly information in the flexible production line is available to the employees in the form of text descriptions and pictures as step-by-step instructions, which can be selected via two-step navigation. The final evaluation was conducted as a user study with $N = 10$ assembly workers in the flexible production line under realistic conditions and was also intended to find out at which level of detail the information should be displayed in the system. The system scored well on the system usability scale (between 65.8 and 70.8) and concerning acceptance. Using the worker guidance system, no assembly faults occurred during the user study. Due to the significantly shorter assembly time, but no further significant differences, it was decided to set up the less detailed assembly information as a standard in the system. However, employees can call up more detailed information, if necessary. This system will be used by the company in the future.

KEYWORDS
assembly, user-centered design, worker guidance system

1 | INTRODUCTION

Production is increasingly oriented toward the demand for individual products in combination with high quality (Coletti & Aichner, 2011; Pine, 1993; Al Gaddawi & El Maraghy, 2012. This necessitates a flexible production, which often means for assembly employees an increasing workload, psychological strain, and potential for errors during assembly (Fast-Berglund et al., 2013). It is, therefore, important to support employees in this flexibilization process (Hold & Sihn, 2016). Digital assistance systems offer this potential and are, therefore, a relevant field of research for human factors and ergonomics (HFE).

One digital approach to support employees with assembly-based information is worker guidance systems. Following Wölfle (2014), Reinhart (2017), Lang (2007), Dombrowski et al. (2010), and Lušić et al. (2016), worker guidance systems can be described as cognitive assistance systems, which are integrated into the work environment and provide employees with relevant assembly-related information in a context-related manner.

Worker guidance systems can be considered as a kind of assistance system as they support employees during working tasks and operations without replacing them (Gery, 1993; Kasvi et al., 2000; Weidner et al., 2015). Reinhart (2017) further categorizes production-related assistance systems into the classes of perceptual assistance systems, decision assistance systems, and execution assistance systems according to the human information processing method developed by Sanders (1983). Following the bottleneck-oriented approach of information processing, worker guidance systems can be classified into decision assistance systems as the difficulty for workers in highly variable assemblies is to make appropriate, product-related decisions.

To support these decision-making processes, worker guidance systems show employees which product variant is the one to be manufactured, support them with appropriate assembly information or point out if, for example, there are differences in sequence or other irregularities. The design of these systems greatly influences how effectively such systems can support decision-making. Preferably, employees receive information without manual intervention and via the appropriate information channel (Franke & Risch, 2009). Information is provided using mobile electronic devices, for example, tablet computers, data glasses, or smartwatches, which offer information in a decentralized manner.

The main part of the empirical studies on worker guidance systems is devoted to the question, which hardware is best suited for implementation. For example, Funk, Kosch, and Schmidt (2016) and Blattgerste et al. (2017) compare different hardware implementations of the same worker guidance and analyze economic effects, especially in contrast to paper instructions. They show that digital assistance does not have a beneficial effect on assembly time, but primarily has a positive effect on quality. In contrast, Uva et al. (2018), Hou et al. (2013), and Aehnelt (2017) show that digital assistance has a positive effect on both assembly time and assembly quality compared to paper-based work instructions. Thorvald et al. (2010) showed a positive effect of their developed worker guidance system on quality while productivity was not affected. Jeske et al. (2014) and Watson et al. (2008) examined the effect of worker guidance systems in training processes. The authors did not compare different hardware options of the system but different media for the assembly instructions that were displayed on the screen. On the one hand, they conclude that less abstract and very detailed assembly information is well suited for training processes. On the other hand, the learning curves determined show that these effects converge with increasing practice. Experienced assembly employees do not benefit as much from digital assistance as less qualified employees and accordingly would not need that detailed information.

Overall, the results of the empirical studies show that the design of worker guidance systems (hardware and software) clearly influences assembly performance. Besides assembly times, this applies in particular to the quality of the products to be manufactured. Furthermore, some studies show that the design of worker guidance systems also influences individual user factors such as usability assessment or stress perception (Blattgerste et al., 2017; Hou et al., 2013). Especially from an HFE perspective, it is, therefore, relevant to deal with the design of worker guidance systems.

This is particularly the case for the design process because to implement these systems successfully, employee acceptance is crucial. This can be achieved by a participatory development, which is described in this article following the user-centered design process (ISO 9241-210, 2019). This approach is based on a profound understanding of the subsequent users and context and integrates users into the design activities. Especially for the context of assistance systems in manufacturing, the user-centered development approach is mentioned as particularly promising, although there is a certain uncertainty in its execution and application (Pokorni et al., 2020). The article describes this process completely, from start to finish, and thus, also presents the procedure, the methods used, and results.

The remainder of this article is structured as follows: Section 2 describes the user-centered design process, methods, and approach to developing the worker guidance system. Section 3 presents the results for each stage of Section 2. Then, the final developed prototype and, thus, the developed worker guidance system is presented in Section 4. The results of the user study are then presented in Section 5 and discussed in Section 6. Finally, a conclusion is drawn in Section 7.

2 | USER-CENTERED DESIGN PROCESS

In the literature, user-centered development and design processes are described in particular in medical (Babione et al., 2020; Gong & Chandra, 2011; Luna et al., 2017; Sonney et al., 2019) and in industrial contexts (Kluge & Termer, 2017; Pokorni et al., 2020; Schulze et al., 2005). The articles highlight, in particular, the development of a comprehensive user understanding in the early phase of development and the involvement of users in the evaluation of the concepts developed. Kluge and Termer (2017), for example, proceed by conducting in-depth interviews with users, developing them into scenarios, which are then used to visualize prototypes. Pokorni et al. (2020) set up the user-centered design as design sprints. In particular, they state that human-centered development approaches are particularly suitable for the context of assistance systems, but that there is nevertheless a great uncertainty in practice with regard to methods and procedures.

The worker guidance system described here was developed according to the user-centered design process (ISO 9241-210, 2019), which was also used in the abovementioned articles. The

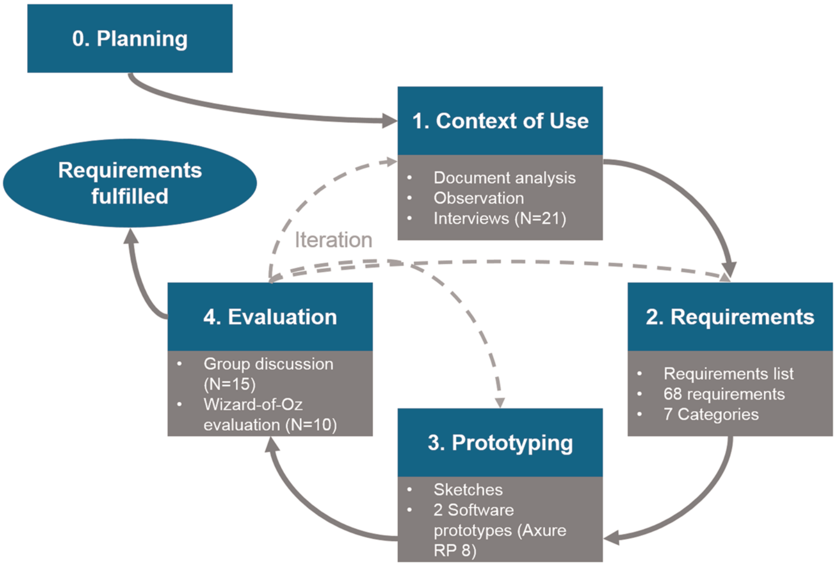


FIGURE 1 Human-centered design process (ISO 9241-210, 2019) and main development activities

methodological implementation of the four iterative steps of the process is shown in Figure 1.

All activities were carried out at metrology company WIKA Alexander Wiegand SE & Co. KG at the production site in Klingenberg am Main, Germany.

To analyze the context of use for the worker guidance system at WIKA, the flexible production line and its environment were examined by means of document analysis and observation. To analyze the user specifications, interviews with $N = 21$ employees were conducted, which lasted about 20 min each. The questions and some example responses are presented in Table 1. Questions addressed work tasks of the employees and work-related goals, qualification, work satisfaction, and the need for assistance and job-related requests. The interviews were qualitatively evaluated and served as a basis for describing the context of use.

All collected aspects of the context of use were then summarized and categorized and converted into a list of requirements.

TABLE 1 Example questions and example responses during the interviews

Work tasks and goals	
"What is the most important aspect of your work?"	"The safe assembly of measuring devices" and "Not to make mistakes during assembly."
"What are your most important tasks?"	"The safe operation of the production equipment" and "To develop the process in consultation with colleagues to achieve ever better quality."
"Which mistakes should never happen in your work?"	"In general, errors in the assembly process, especially if they lead to unrecognized damage to the products that is only noticed by the customer, for example, if the wrong parts are used." and "Errors that lead to safety-relevant conditions or damage to equipment, such as the use of the wrong welding electrodes."
Qualification and work satisfaction	
"Would you like more information regarding your assembly tasks?"	"Yes, especially for new products, when sequences and procedures are not well trained."
"What information do you need to assemble new products safely?"	"Especially for new products, a detailed description of the individual work steps" and "In general, a presentation of the sequence of work steps and relevant workstations would be useful."
Needs and requests	
"Could you imagine a technical system to support your daily work?"	"Some kind of navigation system for everyday assembly would be nice."
"Which functions should an assistance system provide?"	"Above all, an overview of the tasks to be done and a nice overview of the relevant workstations, process sequences and handling" and "Background information on the products, their functions and their use by customers would help to better distinguish the products."

An ideation phase followed. On the basis of the requirements, several simple design prototypes realized as paper sketches and descriptions were developed and discussed by the design team to visualize and evaluate ideas at an early stage of the design process. After this phase, a software prototype was realized to illustrate concept, design, and functions as well as the interaction with the future system using Axure R8 prototyping software. A second, more detailed software prototype was then realized, which contains many functions of the worker guidance system.

The evaluation of the first software prototype was conducted to check whether the design concept and functions match the given requirements. For this purpose, the prototype was tested and discussed in a workshop format with the WIKA management, assembly workers, and the design team. $N = 15$ participants participated in the evaluation, which lasted half a day and took part at the flexible production line, which was built at that time. First, the production management presented the flexible production line, the products to be assembled there, and the corresponding production processes and equipment so that all participants could get an idea of the subsequent assembly processes. Then the prototype was presented and explained. The participants then tested the prototype in small groups and collected positive aspects, criticism, and suggestions for improvement. In plenary, these aspects were then collected and structured on metaplan boards to derive potential for improvement.

The second evaluation was conducted as a user study to test the second prototype in a "Wizard-of-Oz" environment (Green & Wei-Haas, 1985) under real conditions at the flexible production line. The user study had three objectives: First, the study was intended as a usability study under real conditions to test whether employees can use the system effectively and if they like to use it as well. Second, the economic effects of such a system, especially on productivity, were to be evaluated. As the literature on these systems does not give any recommendations on the appropriate amount of information, and on the contrary, the studies of Jeske et al. (2014) and Watson et al. (2008) show that the need for information can change over time, it should also be determined which level of detail of the information displayed in the system best suits the target group. $N = 10$ assembly operators participated in the user study.

3 | USER-CENTERED DEVELOPMENT OF THE WORKER GUIDANCE SYSTEM

WIKA is a manufacturer of high-quality measurement technology and has recently implemented a flexible production line to be able to manufacture consumer-specific products in different batch sizes very flexibly besides the production of serial products. This flexible production environment considerably shapes the context of use.

(a) Context of Use:

On the flexible production line, machines are complex and have to be operated manually and products are manufactured with a high degree of variability. The aim of the worker guidance system is to support operators in this complex and variable environment with product- and process-related information.

At the flexible production line, production facilities are scattered so that products are manufactured in a workshop production. Operators move between these workstations according to the sequence of the manufactured product, transporting the parts with them.

At the beginning of the assembly process, operators receive the production order with individual production details and boxes with commissioned parts. Operators take these boxes with them during the assembly process. Operators manufacture very different products and product variants, which may look similar but differ greatly in details and batch sizes. This requires a high level of attention and in-depth knowledge of products, operations, and production facilities.

Operators working at the flexible production line are identified as direct users of the guidance system. These operators are mainly qualified and experienced employees at WIKA. Furthermore, it is essential for the company that these operators are very reliable as these operations are very little formalized and are carried out with great freedom for the operators. Normally, employees are trained manually during ongoing operations without the use of digital technologies. This procedure is considered not to be suitable at the flexible production line. Paper-based work instructions exist for all operations and machines in WIKA production but are not regularly used by operators. For operators using the worker guidance system, the most important objectives reported are to get support for variably changing products and to be able to distinguish between these product variants, especially if there are only minor differences.

(b) Requirements:

Requirements were derived from the context of use. In total, the requirements list contains seven categories and 68 individual requirements. A summary of the requirement categories is given in Table 2. The usage context analysis, and in particular the interviews, revealed two aspects in particular, which are unusual for worker guidance systems and which had to be reflected in the requirements accordingly and which had to be given special consideration during development:

- The worker guidance system should be operated without connection to other equipment, production facilities, and external databases. The system should be reduced and designed as flexible as possible to provide easy and fast adaptation to new products.
- Operators should use the system voluntarily: It is not mandatory to use it during the production process, but it can be used when operators need assistance. As this may be the case during an entire production cycle or even at certain assembly steps, the system should provide a clear and simple structure to quickly get to the relevant operation.

(c) Prototyping:

On the basis of the results of the usage context analysis and

TABLE 2 Summary of the requirement categories

Category	Main requirements
Spatial conditions	• Mobile system • System must be able to be deposited at the workstations (size, shape). • System must be light enough for all employees to handle. • Sufficiently large screen so that the information can be read by all employees.
Users	• System must be easy to understand and provide easy navigation so that operators can use it effortlessly. • As much graphic information as possible should be included to complement the textual work instructions. • Appropriate level of information to illustrate unknown processes for quick reading.
Technical requirements	• No process data acquisition by machines and plants. • Worker guidance as a separate system. • Technical implementation as simple as possible.
Organizational requirements	• The system must be individually usable by several users simultaneously. • The system should enable user feedback on the work instructions.
Safety requirements	• Safety standards at WIKA must be met. • No distraction by the system.
Financial requirements	• It should be as easy and effortless as possible to generate content for new products in the worker guidance system.
Scheduling requirements	• The timeframe for developing the system is 6 months.

the requirements, it was decided that the system should provide the relevant assembly information in visual form. Tablet computers were specified for the hardware implementation as they provide all necessary functions required for the worker guidance system and the large screen and simple touch controls can be used intuitively by the operators. Furthermore, they are small and light enough to be carried by the operators.

The main function of the software is to present the work instruction for the corresponding work step and, thus, guide operators through the specific production processes. Following Lang (2007), Agrawala et al. (2003), and Söderberg et al. (2014), the worker guidance system to be implemented should offer step-by-step instructions to provide easy navigation on the one hand and to facilitate information processing on the other hand. However, as mentioned before, there are no recommendations in the literature for the appropriate level of information for this step-by-step assembly information. This had to be found out in the course of the design process and especially with the involvement of the users for the system to be developed.

The transition phase, from the creation of requirements to the development of initial implementation ideas and concepts, was supported by visualizing approaches and ideas with simple

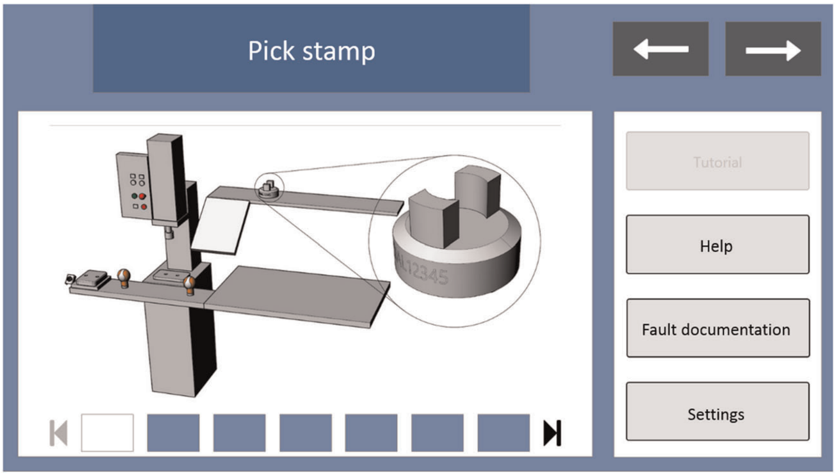


FIGURE 2 First software prototype with pictographs showing the principle layout of the worker guidance system

sketches and discussing them within the development team. Once a consensus had been reached and the team had a clear idea of the implementation, these ideas and concepts were summarized and detailed in the form of a first software prototype, as shown in Figure 2.

The main function, the provision of step-by-step assembly information, is represented in the prototype by the large area in the middle, as shown in Figure 2. This assembly information is essentially presented in graphic form and illustrated by pictograms. The instructions contain only very brief text information, which is arranged above the pictograms. The arrow-shaped buttons in the upper right corner can be used to navigate step-by-step to the next or previous assembly step. These assembly steps are also illustrated by the boxes shown below. These show a process overview and can also be selected directly. The arrow-shaped buttons next to this overview can be used to display the next or previous process steps. The menu on the right side contains additional functions, e.g. the request of support, fault documentation, and settings. The button tutorial reflects considerations by presenting the level of information in two different ways to find out the right amount.

(d) Evaluation:

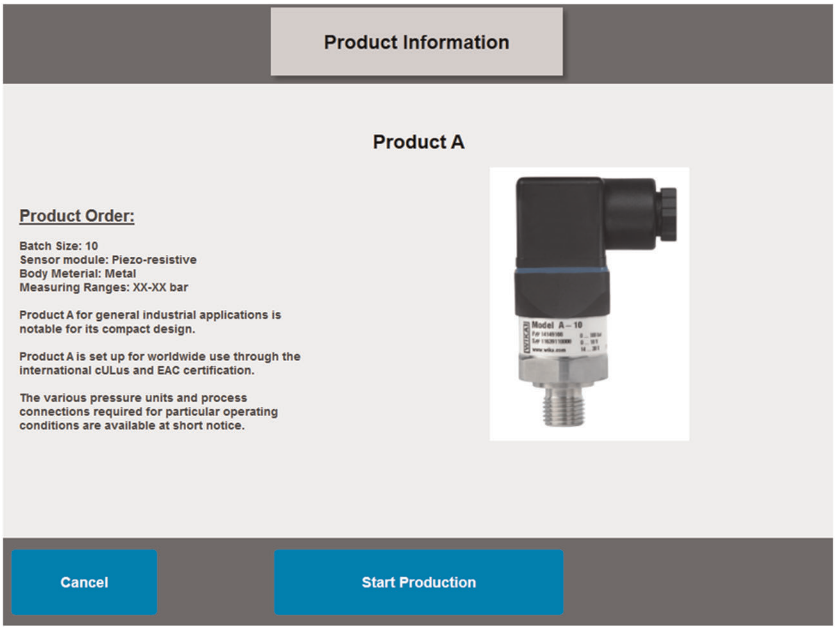
The first evaluation showed that the prototype and some user requirements had to be adapted. The prototype shows the assembly information using pictograms and very little text, as pictograms were considered a way to present information intuitively in a compromised form. The discussion with operators revealed that this form of presentation would not be suitable for the worker guidance system. Pictures were considered to show more detailed and less abstracted information compared to pictograms and to be easier to understand for operators. Furthermore, the system should contain more detailed textual information than the prototype provided. The textual information should focus especially on possible differences of product variants. Furthermore, it should be easier to navigate precisely to the work step needed so that two-step navigation for workstation and work steps would be reasonable as well as an overview of relevant steps and their sequence. Additionally, transporting the system by hand was considered to be uncomfortable for operators.

4 | FINAL PROTOTYPE

With regard to the hardware implementation with tablet computers, the evaluation revealed no need for changes. The prototype was implemented using a 10.6-in. tablet computer with a resolution of 1,366 × 768 pixels. It is designed as an independent, separate system that is not connected to other data systems of the production, for example, manufacturing execution or enterprise resource planning. As the evaluation showed that it could be inconvenient for employees to carry the tablet computer permanently with them, it is placed on an assembly trolley that is also used to move the preselected parts in the flexible production line. The worker guidance function is realized as a software prototype using the Axure RP 8 prototyping software.

The evaluation showed that the operators particularly expect the system to inform them about variant-specific features and processes and to draw their attention to them. This was addressed on the one hand by providing more detailed textual assembly information. On the contrary, the beginning of the assembly of a product was identified as a suitable opportunity to emphasize precisely these variant-specific features.

To start the assembly process, operators enter the production order number and the corresponding information and sequences are preselected by the system. To emphasize variant specifics, in the first



Product Information

Product A

Product Order:

Batch Size: 10
Sensor module: Piezo-resistive
Body Meterial: Metal
Measuring Ranges: XX-XX bar

Product A for general industrial applications is notable for its compact design.

Product A is set up for worldwide use through the international cULus and EAC certification.

The various pressure units and process connections required for particular operating conditions are available at short notice.

FIGURE 3 Product information is shown when operators enter the production order into the worker guidance system

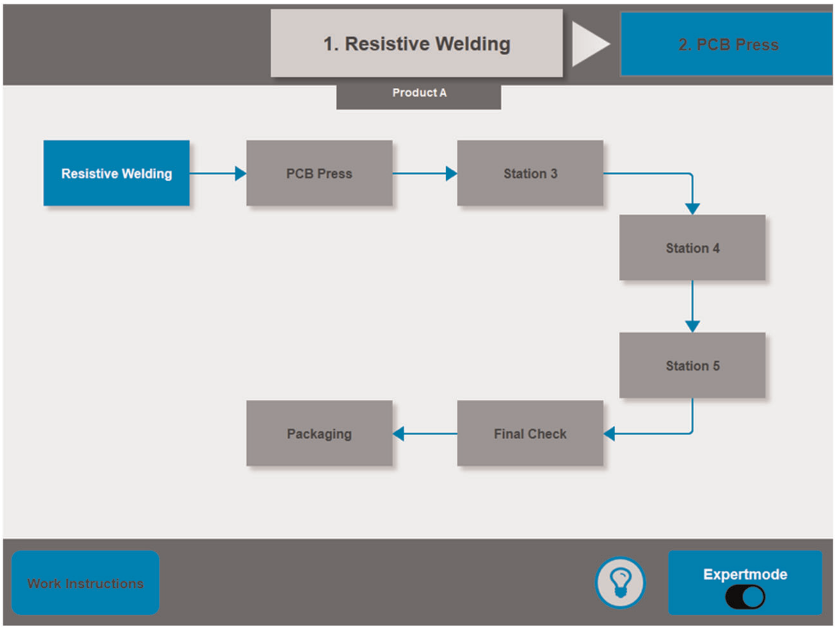
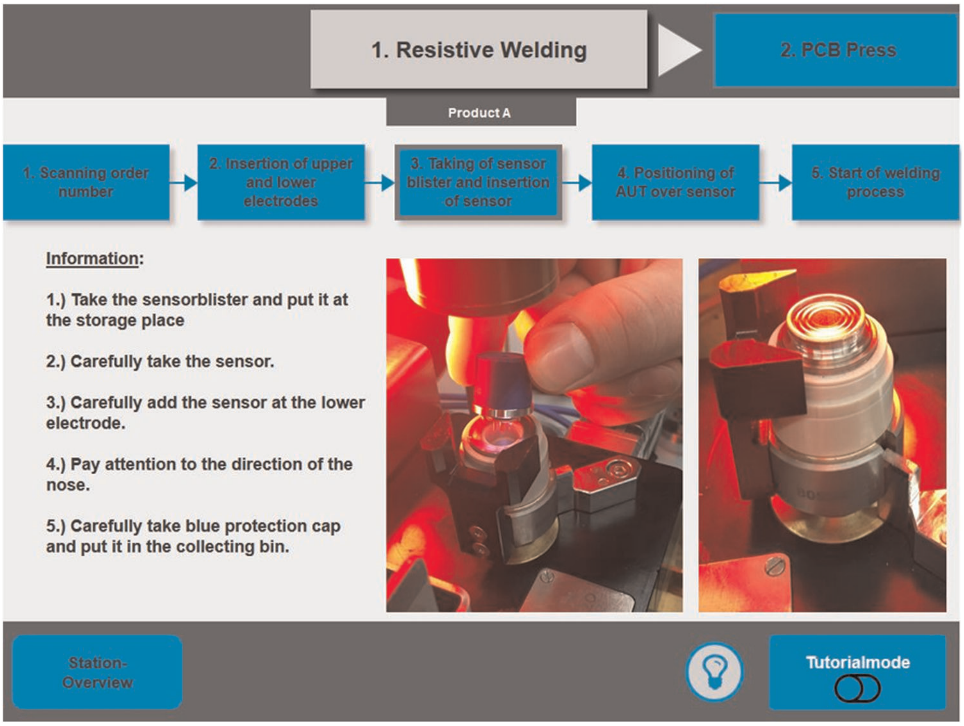


FIGURE 4 Before starting to manufacture the actual product, it is important to know the relevant workstations and their sequence. The station overview screen shows this information



Information:

1.) Take the sensorblister and put it at the storage place

2.) Carefully take the sensor.

3.) Carefully add the sensor at the lower electrode.

4.) Pay attention to the direction of the nose.

5.) Carefully take blue protection cap and put it in the collecting bin.

FIGURE 5 Showing textual and graphical work instructions is the main function of the worker guidance system. Tutorial mode means that detailed instructions for all work steps are shown. Workstations (upper line) and included work steps (line below) are selectable

instance, the system shows the corresponding product information so that the operators are able to compare production order and worker guidance and to clarify which product is to be produced (Figure 3). Then the actual assembly begins providing a station overview showing the production sequence for the product (Figure 4). Hereafter, navigation is possible by either selecting the appropriate workstation directly in this overview or using the system continuously and click further. As the station overview can always be selected, this provides an easy way for navigating directly to the relevant information.

Figure 5 shows the work instruction screen in the worker guidance system, which is the main function of the system. The structure of the display is the same for all workstations. The upper area shows the navigation, which now takes place on two levels: The top line shows the current workstation (in the middle and highlighted in gray), as well as the previous workstation (on the left) and the next one (on the right). The buttons are designed in blue to highlight that they can be selected. The product currently being manufactured is shown in the middle, below the current workstation. The line below shows the work steps for the corresponding workstation. The one in use is highlighted with a gray border.

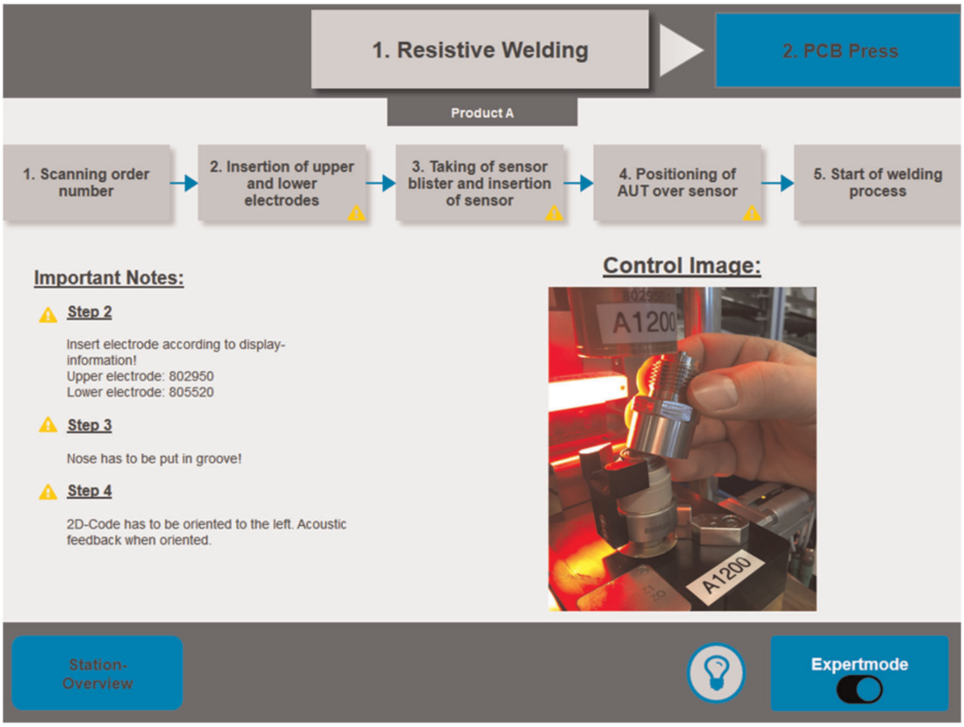
The work instructions are arranged below containing text information on the left and one or multiple pictures on the right side. The text information is presented in much more detail than in the first prototype and in particular presents the special features of the product to be manufactured. Pictures are presented in the first-person perspective and are sometimes provided with additional graphic highlights. Compared to the pictograms in the first prototype, the graphic information is, thus, more detailed, more intuitive, and less abstract. The creation of the content is also much easier.

Additional functions are placed at the bottom line containing the station-overview, a feedback function if instructions are misleading or hard to understand (light bulb symbol). The symbol on the right side takes into account the mentioned question about the appropriate amount of information shown by the system. To find this out, two modes for the worker guidance system have been created on the basis of a hierarchical task analysis, which differs in their level of information.

The prototype showing detailed information is called “tutorial mode” and is already shown in Figure 5. The prototype showing only brief information is called “expert mode” and is shown in Figure 6. Both prototypes were tested in the final evaluation to find out which level of detail is best suited for effective and efficient use of the system.

FIGURE 7 The two products A-1200 and MPR-1 were assembled in the user study. The simpler product is the A-1200. The assembly of the MPR-1 is more complex

The tutorial mode contains detailed textual information and images that explain precisely how to proceed for every single operation. Furthermore, confirmations are implemented for some specific work steps, especially if retooling is necessary or at safety-critical steps to raise awareness of the operators. In contrast, only brief information is displayed in expert mode (Figure 7). Here, single work steps are not explained in detail and, therefore, are not selectable. The navigation bar of the work steps also serves as an essential source of information about the operations to be performed. In the main view, only very important information is



1. Scanning order number → 2. Insertion of upper and lower electrodes ⚠ → 3. Taking of sensor blister and insertion of sensor ⚠ → 4. Positioning of AUT over sensor ⚠ → 5. Start of welding process

Important Notes:

⚠ **Step 2**

Insert electrode according to display-information!
Upper electrode: 802950
Lower electrode: 805520

⚠ **Step 3**

Nose has to be put in groove!

⚠ **Step 4**

2D-Code has to be oriented to the left. Acoustic feedback when oriented.

FIGURE 6 Expert mode is the second variant of the prototype showing only brief work instructions for workstations displayed. The toggle symbol in the bottom line shows the current mode (right side).

5 | USER STUDY

As already mentioned, the final evaluation was carried out as a user study under realistic conditions in a Wizard-of-Oz setting at the flexible production line.

5.1 | Methods

5.1.1 | Experimental design

The aim of the user study was to find out whether the users rated the system well, what the economic impact would be, and what level of information is more suitable for the users. To answer the question of the appropriate level of information, the test persons use both the tutorial and expert mode. The level of information is, thus, the first independent variable and is initialized in the study by the two variants of the worker guidance system, the tutorial, and expert mode. The second independent variable represents the task complexity. Their starting point is the complexity of the products to be manufactured, whereby two products of different complexity were specifically selected (Figure 7).

5.1.2 | Equipment

The study took place at the flexible production line, which was equipped with all the items and tools needed for manufacturing. The material needed for the assembly was provided in prepicked boxes at the line, which the test subjects carried with them. Additional material was also provided at a few workstations. All necessary assembly information was provided via the worker guidance system, which the test persons also carried with them.

5.1.3 | Procedure

A within-design was chosen so that all participants performed three assembly runs: Twice the assembly of the A-1200, each with the tutorial and expert mode of the worker guidance system, and once the assembly of the MPR-1 using the tutorial mode. Before the test persons carried out these three assembly runs, the participants evaluated their assembly experience at WIKA, their assembly-related competencies using the German Kompetenz-Reflexions-Inventar (Competence Reflection Inventory; Kauffeld et al., 2007), as well as their technological affinity with the TA-EG questionnaire (Karrer et al., 2009). They were then introduced to the system, describing, in particular, its operation and use for assembly. During the assembly runs, the sequence of the products and worker guidance variants were permutated. Although the test persons were experienced assembly workers, they were not familiar with the products, processes, and equipment in the flexible assembly line so that the study simulated a learning situation. As the worker guidance system was developed for such situations, especially when new products are manufactured, the test persons were not informed of the processes in advance, hence used the system during the assembly runs. As it was expected that significant learning effects would occur (cf. Jeske et al., 2014; Watson et al., 2008), especially during the assembly of the A-1200, the sequence was randomized and, thus, individualized for each test person. During each product assembly, assembly faults and assembly time were captured. After each pass, participants had to fill out a German variant of the Davis (1989) questionnaire, which was adapted to the context of worker guidance systems to assess acceptance. Furthermore, System Usability Scale (SUS) (Brooke, 2013) was used to assess usability. The evaluation took place in February 2019 for 3 days. The evaluation lasted on average about 4 h per subject and was set up in such a way that two participants could conduct the experiment at the same time (one subject at the assembly, one subject filling out the questionnaires).

5.1.4 | Participants

N = 10 participants tested the system. Five participants were male, five were female. The average age is 46 years. Participants were very experienced assembly operators. Eight out of 10 participants worked in production at WIKA for more than five years. Participants rated their professional competence with an average of 7.4 (scale from 0 [low] to 10 [high]). Especially items expressing a high process knowledge and the ability to analyze and improve processes were rated with an average of more than eight. Methodological competence was also rated quite high, averaging 7.6 (from 0 [low] to 10 [high]). The affinity for technology averages 3.5 (from 0 [low] to 5 [high]), which shows that participants, even though used to working with technology, are open-minded but not euphoric about electronic technologies.

5.2 | Results

5.2.1 | Production time and quality

MANOVA (multivariate analysis of variance) (sphericity not assumed: Mauchly-$W(2) = .252$, $p = .004$) shows that there are significant differences in the mean production times using the variants of the worker guidance system ($F(1,144) = 63.689$, $p = .000$, partial $\eta^2 = 0.876$, $N = 10$; corrections according to Greenhouse-Geisser), Figure 8. The effect strength according to Cohen (1992) is $r = 1.816$ and, thus, corresponds to a strong effect. Bonferroni corrected paired comparisons show that production times for the simple product are significantly higher when using the tutorial mode ($M = 1{,}056.5$, $SD = 404.7$; $p = .019$) compared to using the expert mode ($M = 660.4$, $SD = 173.7$). This results in a

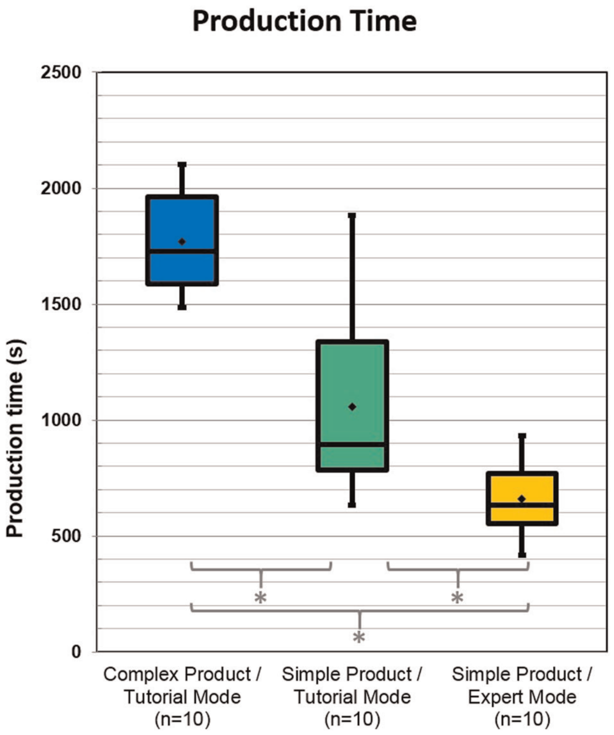


FIGURE 8 Production times (s) for the test runs. Bonferroni corrected paired comparisons show significant differences

difference of more than 37% in production time, which is exclusively due to the design of the worker management system as the production processes were identical for both runs. The time difference emerges because the more detailed information of the tutorial mode needs more time for reading and processing and because the tutorial mode necessitates a more intensive interaction with the system. The complex product, assembled using the tutorial mode, needs even more production time (*M* = 1,772.5, *SD* = 235.1; *p* = .001), which is a significant difference to the simple product.

Besides production time, quality is often cited as the main motivation using worker guidance systems. This aspect can be confirmed here: During the entire evaluation, no assembly error could be detected. All assembled products were faultless at a high-quality standard.

5.2.2 | Acceptance

Acceptance rating is an important aspect of understanding whether operators would use the system if it were introduced out in the flexible production line. MANOVA shows no significant differences in the mean acceptance values of the variants ($F(2) = 1.366$, $p = .28$, partial $\eta^2 = 0.132$, $N = 10$; sphericity assumed: Mauchly-$W(2) = 0.799$, $p = .408$). All variants of the system achieve good results in terms of acceptance (scale from 1 [low] to 7 [high]), see Figure 9. The assembly of the complex product reaches the best acceptance results (*M* = 5.094, *SD* = 1.3), followed by the expert mode with the simple product (*M* = 4.9, *SD* = 1.6). The tutorial mode for the simple product is rated worse (*M* = 4.8, *SD* = 1.3), although differences are not statistically significant.

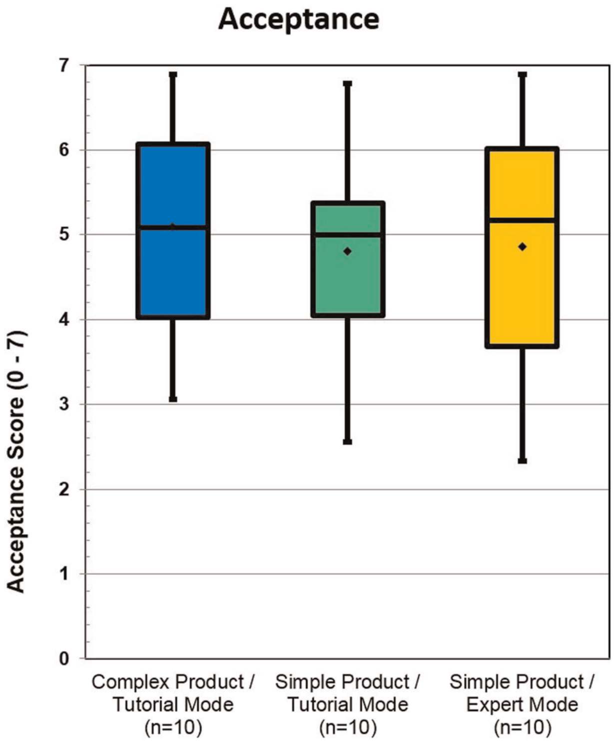


FIGURE 9 Acceptance values for the runs showed no significant differences

5.2.3 | Usability

SUS was used to analyze the usability of the system (scale from 0 [low] to 100 [high]). MANOVA (sphericity assumed: Mauchly-$W(2) = 0.768$, $i = 0.348$) shows that there is no significant difference between the system variants with respect to the SUS score ($F(2) = 1.003$, $p = .386$, partial $\eta^2 = 0.1$, $N = 10$), Figure 10. Using the expert mode for the simple product leads to the best result (*M* = 70.8, *SD* = 25.5), followed by the tutorial mode of the simple product (*M* = 69.8, *SD* = 19.1). The tutorial mode with the complex product is rated worse than the two runs with the simple product (*M* = 65.8, *SD* = 23.5), although differences are not statistically significant. SUS provides a reference value of 68 or more for good usability. Both variants for the simple product achieve even better results. The tutorial mode for the complex product reaches a result below this reference value, which is still acceptable.

6 | DISCUSSION

6.1 | Design process

This article describes the human-centered design process from start to finish for the development of a digital assistance system for a flexible production line. It also shows that the human-centered, participative approach is particularly well suited to the field of assistance systems, supporting Pokorni et al. (2020). As a case study, the article also describes the concrete procedure and methods that

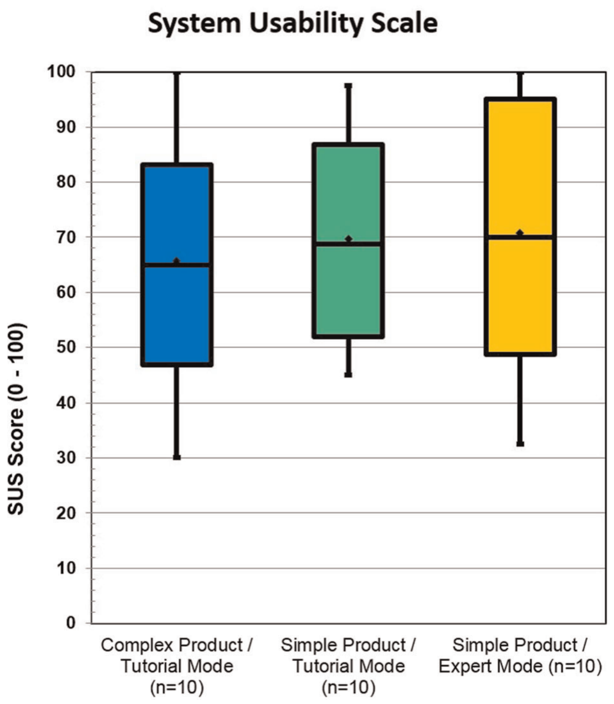


FIGURE 10 System Usability Scale (SUS) score showed acceptable and good usability with no statistically significant differences

were used during the development. The procedure follows the typical approach and has already been used for applications in the context of production (Kluge & Termer, 2017; Schulze et al., 2005) or medicine (Babione et al., 2020; Gong & Chandra, 2011; Luna et al., 2017; Sonney et al., 2019). During the approach, it became clear that especially specific and detailed questions were raised, such as the choice of media and the level of detail of the assembly information presented.

Human-centered design often means a rather long and more effortful process, as was the case in this project (Emspak, 1995). Also, especially in the early phases of the process, contradictions or dependencies can occur that require a lot of effort to resolve (e.g., in the case of conflicting requirements). In this respect, the project benefited greatly from the fact that the context of use could be clearly limited to the flexible assembly line and its users. This made the analysis phase concrete and contributed a lot to developing a clear picture of the context of use.

The procedure and the interim results of the process further illustrate the importance of visualizing solutions as quickly as possible (Kluge & Termer, 2017). Especially in the design of software, simple drawings or software prototypes are useful for this purpose. Discussions with users during the ideation phase, for example, showed that this enables them to assess the usage much better and develop a differentiated understanding of the application. This can lead to a shift in requirements, as for example was evident in the process after the first evaluation. Adapting the design at this stage was not very complex. Adapting the design of the assembly information after the roll-out would be much more time-consuming and expensive. This supports the procedure of Pokorni et al. (2020), who organized the entire process through agile methods.

However, the intensive integration of employees generates acceptance, which is especially necessary for a worker guidance system as employees will work with the system quite intensively. Moreover, it shapes work processes, which may interfere with personal habits or preferences and, therefore, can restrict individual freedom. The evaluation shows significant differences in production time for the system variants and no significant differences in subjective ratings. All tested variants of the worker guidance performed well, especially concerning the quality as no production faults were made.

6.2 | Results

Empirical studies on worker guidance systems have so far mainly been based on highly experimental settings (e.g., Blattgerste et al., 2017; Funk, Kosch, Kettner, et al., 2016). The user study conducted represents a field study in a real context and with trained and experienced assembly workers. On the one hand, it shows satisfactory results for the developed prototype, both in terms of the assembly performance and in terms of the users' assessment of acceptance. On the other hand, the user study itself made it possible to realistically assess the potential of the worker guidance system.

One aim of the user study was to find out which level of information operators would prefer, tutorial or expert mode. The results do not show a significant difference in terms of acceptance and usability, but a tendency in favor of the expert mode. Production time results show that operators were significantly faster using the expert mode (without making more mistakes). In summary, it can be assumed that the expert mode is more suitable for operators on the flexible production line. Of course, it must be taken into account that the user study mainly involved very experienced operators, even though they are not familiar with the processes on the flexible production line. However, as the worker guidance system was also intended to be used explicitly for training new employees on the flexible production line, it was decided to implement both modes, with the possibility of changing them at any time. However, the expert mode was set as the default mode.

A further aim of the study was to find out whether the worker guidance system is also suitable for the more complex product assembly. In addition to the significantly longer assembly time of the complex product, which is independent of the worker guidance system, the evaluation shows that the test persons also succeeded in assembling faultless products. Even the subjective evaluation does not differ significantly from the simple product assembly.

During the evaluation, participants also commented on the work instructions. When there were any ambiguities or comments, the test manager noted these aspects. On this basis, the work instructions were improved after the evaluation, for example, by describing some work steps in more detail.

Some participants were already familiar with some work steps or machines in the flexible production area. Even though machines and settings of the flexible production line are unique, similar products and equipment exist. Therefore, a transfer of knowledge was possible for some experienced operators. This leads to a specific danger at the flexible production line: As mentioned before, product variants and machines are unique. However, differences might exist in detail and have a great effect. For instance, the electrodes of welding machines are different compared to other production areas but look similar. They have to be adapted to the right product. It has been observed that some participants tend to ignore the worker guidance system and conduct the work steps they are used to, even though they might be wrong. As the worker guidance system is used voluntarily, this shows the importance of two aspects: On the contrary, it is important to design the worker guidance as simple and as intuitive as possible. Employees should receive the information needed in a simple form as possible and with the least effort, to minimize the reason for not using the system. On the contrary, it is important to raise employees' awareness of the fact that processes in the flexible production areas are different and more variable.

6.3 | Limitations

A clear limitation of the study, however, is the small sample size of $N = 10$, which leads to an insufficient statistical significance of the user study. For this reason, the user study cannot be generalized, especially with regard to the results on performance and acceptance of the system. The user study with its small sample size allowed for a realistic evaluation of the developed solution in a concrete application context and did show promising results here.

It should be noted that also the context of use described here is very specific. In this respect, the process and the results achieved are also specific in this respect, and the procedure cannot be adopted identically for other projects or transferred directly to other contexts. The human-centered design process should, therefore, always be adapted to the respective context. However, as a case study, the process described can give indications on how to proceed. The design of the worker guidance system is, thus, similarly individual and cannot be directly transferred to other contexts. The results of the user study are, however, promising in which the developed concept with the essential functions is particularly well suited to multivariant production or workshop production and can support employees. Individual adaptations should then, however, particularly concern the presentation of the work instructions, for example, with regard to the choice of media and a suitable level of detail.

Looking chronologically at the test runs shows a clear learning effect, which is in accordance with Watson et al. (2008) and Jeske et al. (2014): The average time needed for the first test run was almost twice as long as the time needed for the next runs, regardless of which mode of the system was used. Two aspects are connected to this: It shows how important it is to permute the sequence of test runs to compensate for sequential effects. However, it must be considered that the learning effects increase the variance of the data, making it difficult to prove significant differences. The alternative between-design might be more suitable in this respect but was not pursued in this study due to its susceptibility to disturbance effects.

Furthermore, it is shown that the evaluation did not depict a realistic operating scenario. Whereas the potential of worker guidance systems lies in the flexible production of many, often changing variants and of complex products, the evaluation was carried out with only two products, which have been assembled only one time each by every subject. The study simulates a training scenario that does not correspond to a real operation in which the users are already more familiar with the products and processes. However, this normal operation also contains many more products and variants, which is expected to lead to situations that are familiar to training.

The determination of the appropriate level of information through the late evaluation caused additional effort and greater uncertainty in the design. It is quite conceivable to address and evaluate this question separately and, thus, earlier. In this case, however, a realistic test was preferred, which the final evaluation offered.

6.4 | Future work

In the course of the development, it became clear that there are some empirical findings on suitable hardware for worker guidance systems. However, there are only a few findings on the content design of worker guidance systems (Jeske et al., 2014; Watson et al., 2008), or more generally on assembly instructions (Agrawala et al., 2003). Studies on the impact of different design approaches would, therefore, not only help to quantify the extensive design options of digital assistance but would also have very concrete practical relevance. This concerns, for example, the question addressed in the evaluation regarding the appropriate level of information.

As the user study focuses on short-training processes, long-term evaluations of worker guidance systems are of special interest for future work. These are relevant to consider whether the system can also generate acceptance in regular and long-term use and how it is used, in particular, whether it also has a positive effect on assembly performance in regular operation.

The results of the project support Pokorni et al. (2020) in which a human-centered design seems to be particularly suitable for the area of assistance systems. Findings on the human-centered design of other types of assistance, such as physical assistance would, therefore, also be relevant here.

With the approach used here, it was possible to develop a clear understanding of the context of use and to communicate and evaluate the concept early on through an initial evaluation, which helped, in particular, to implement the nontrivial design of the assembly information in the system well. These two aspects in particular helped enormously in designing a capable and accepted system. For development and implementation projects, also in other contexts, a thorough usage-context analysis and an early evaluation should be taken into account accordingly.

7 | CONCLUSIONS

With the human-centered approach described above, it was possible to design a capable prototype, as the user study shows. Although it is more time-consuming and complicated, the results show the benefits of the user-centered design process. Particularly acceptance and usability of the system are quite notable, showing that a participatory design approach is especially rewarding for systems that have to be used quite intensively by employees. Three aspects, in particular, became clear, which should also be considered for the development of further worker guidance systems: The usage context analysis made it clear that the system to be developed should be used voluntarily by the employees. In contrast to the often prescribed or firmly integrated application of worker guidance systems in production processes, this emphasizes the supporting aspect of worker guidance systems. This especially requires quick and easy navigation to call up the relevant assembly information as simply and intuitively as possible. The third aspect concerns adaptability and individualization. WIKA will apply to the system with both levels of information, whereby the users can adapt it individually and for each work step, whereas it starts in expert mode. This simple implementation of adaptability could also be integrated into newly developed worker guidance systems.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Aehnelt, M. (2017). *Informationsassistenz zur kognitiven Automatisierung manueller Montagearbeitsplätze* (Doctoral dissertation), Universität Rostock, Rostock, Germany.

Agrawala, M., Phan, D., Heiser, J., Haymaker, J., Klingner, J., Hanrahan, P., & Tversky, B. (2003). Designing effective step-by-step assembly instructions. *ACM Transactions on Graphics*, *22*(3), 828–837.

Al Geddawy, T., & El Maraghy, H. (2012). Product variety management in design and manufacturing: Challenges and strategies. In H. El Maraghy (Ed.), *Enabling manufacturing competitiveness and economic sustainability* (pp. 518–523). Springer. https://doi.org/10.1007/978-3-642-23860-4_85

Babione, J., Ocampo, W., Murphy, S., Yang, C., Zuk, T., Kaufman, J., Carpendale, S., Ghali, W., & Altabbaa, G. (2020). Human-centred design processes for clinical decision support: A pulmonary embolism case study. *International Journal of Medical Informatics*, *142*. https://doi.org/10.1016/j.ijmedinf.2020.104196

Blattgerste, J., Strenge, B., Renner, P., Pfeiffer, T., & Essig, K. (2017). Comparing conventional and augmented reality instructions for manual assembly tasks, *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments* (pp. 75–82). ACM.

Brooke, J. (2013). SUS: A retrospective. *Journal of Usability Studies*, *8*(2), 29–40.

Coletti, P., & Aichner, T. (2011). *Mass customization*. Springer.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, *13*(3), 319–340. https://doi.org/10.2307/249008

Dombrowski, U., Wesemann, S., & Korn, G. H. (2010). Werker informations system. *Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb*, *105*(4), 282–287. https://doi.org/10.3139/104.110279

Emspak, F. (1995). Integrating design engineering and the work-force. *IFAC Proceedings Volumes*, *28*(21), 193–198.

Fast-Berglund, Å., Fässberg, T., Hellman, F., Davidsson, A., & Stahre, J. (2013). Relations between complexity, quality and cognitive automation in mixed-model assembly. *Journal of Manufacturing Systems*, *32*(3), 449–455. https://doi.org/10.1016/j.jmsy.2013.04.011

Franke, J., & Risch, F. (2009). Effiziente Erstellung, Distribution und Rückmeldung von Werkerinformationen in der Montage. *ZWF*, *104*(10), 822–826. https://doi.org/10.3139/104.110167

Funk, M., Kosch, T., Kettner, R., Korn, O., & Schmidt, A. (2016). MotionEAP: An overview of 4 years of combining industrial assembly with augmented reality for Industry 4.0. *Proceedings of the 16th International Conference on Knowledge Technologies and Data-driven Business*, *Graz* (Vol. 16, p. 5), *Graz*.

Funk, M., Kosch, T., & Schmidt, A. (2016). Interactive worker assistance. In Lukowicz, P., Krüger, A., Bulling, A., Lim, Y. K. & Patel, S. N. (Eds.), *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 934–939). ACM.

Gery, G. J. (1993). *Electronic performance support systems. How and why to remake the workplace through the strategic application of technology*. Ziff Institute.

Gong, Y., & Chandra, A. (2011). Developing an integrated display of health data for aging in place. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *26*(4), 473–482.

Green, P., & Wei-Haas, L. (1985). The Rapid development of user interfaces: Experience with the Wizard of OZ method. *Proceedings of the Human Factors Society Annual Meeting*, *29*(5), 470–474. https://doi.org/10.1177/154193128502900515

Hold, P., & Sihn, W. (2016). Towards a model to identify the need and the economic efficiency of digital assistance systems in cyber-physical assembly systems. *2016 1st International Workshop on Cyber-Physical Production Systems (CPPS)* (Vol. 1, pp. 1–4). *Vienna, Austria*.

Hou, L., Wang, X., Bernold, L., & Love, P. E. D. (2013). Using animated augmented reality to cognitively guide assembly. *Journal of Computing in Civil Engineering*, *27*(5), 439–451.

International Organization for Standardization. (2019). Ergonomics of human-system interaction—Part 210: Human-centred design for interactive systems (ISO Standard No. 9241-210:2019). https://www.iso.org/standard/52075.html

Jeske, T., Meyer, F., & Schlick, C. M. (2014). Einfluss der Gestaltung von Arbeitsplänen auf die Anlernzeit sensumotorischer Tätigkeiten. *Zeitschrift für Arbeitswissenschaft*, *68*(1), 1–6.

Karrer, K., Glaser, C., Clemens, C., & Bruder, C. (2009). Technikaffinität erfassen—der Fragebogen TA-EG. In A. Lichtenstein, C. Stößel, & C. Clemens (Eds.), *Der Mensch im Mittelpunkt technischer Systeme. 8. Berliner Werkstatt Mensch-Maschine-Systeme* (pp. 196–201). VDI Verlag.

Kasvi, J. J. J., Vartiainen, M., Pulkkis, A., & Nieminen, M. (2000). The role of information support systems in the joint optimization of work systems. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *10*, 193–221. https://doi.org/10.1002/(SICI)1520-6564(200021)10:2<193::AID-HFM5>3.0.CO;2-H

Kauffeld, S., Grote, S., & Henschel, A. (2007). Das Kompetenz-Reflexions-Inventar (KRI). In J. Erpenbeck, & L. Rosenstiel (Eds.), *Handbuch Kompetenzmessung* (pp. 337–347). Schäffer-Poeschel.

Kluge, A., & Termer, A. (2017). Human-centered design (HCD) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. *Applied Ergonomics*, *59*, 170–181.

Lang, S. (2007). *Durchgängige Mitarbeiterinformation zur Steigerung von Effizienz und Prozesssicherheit in der Produktion*. Meisenbach.

Luna, D., Rizzato Lede, D., Rubin, L., Otero, C., Ortiz, J., García, G., Rapisarda, R., Risk, M., & Quirós, F. (2017). User-centered design improves the usability of drug-drug interaction alerts: A validation study in the real scenario. *Studies in Health Technology and Informatics*, *245*, 1085–1089.

Lušić, M., Fischer, C., Bönig, J., Hornfeck, R., & Franke, J. (2016). Worker information systems. State of the art and guideline for selection under consideration of company specific boundary conditions. *Procedia CIRP*, *41*, 1113–1118. https://doi.org/10.1016/j.procir.2015.12.003

Pine, J. B. (1993). *Mass customization: The new frontier in business competition*. Harvard Business.

Pokorni, B., Zwerina, J., & Hämmerle, M. (2020). Human-centered design approach for manufacturing assistance systems based on design sprints. *Procedia CIRP*, *91*, 312–318.

Reinhart, G. (2017). *Handbuch Industrie 4.0*. Hanser.

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica*, *53*(1), 61–97. https://doi.org/10.1016/0001-6918(83)90016-1

Schulze, H., Brau, H., Haasis, S., Weyrich, M., & Rhatje, T. (2005). Human-centered design of engineering applications: Success factors from a case study in the automotive industry. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *15*, 421–443.

Söderberg, C., Johansson, A., & Mattsson, S. (2014, September 16–18). Design of simple guidelines to improve assembly instructions and operator performance. In J. Stahre (Ed.), The Sixth Swedish Production Symposium, 2014, Gothenburg, Sweden.

Sonney, J., Duffy, M., Hoogerheyde, L. X., Langhauser, E., & Teska, D. (2019). Applying human-centered design to the development of an asthma essentials kit for school-aged children and their parents. *Journal of Pediatric Health Care. Official Publication of National Association of Pediatric Nurse Associates & Practitioners*, *33*(2), 169–177.

Thorvald, P., Brolin, A., Högberg, D., & Case, K. (2010, August). *Using mobile information sources to increase productivity and quality*. 3rd Applied Human Factors and Ergonomics (AHFE) International Conference, Miami, FL. https://doi.org/10.1201/EBK1439834916-c46

Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., & Fiorentino, M. (2018). Evaluating the effectiveness of spatial augmented reality in smart manufacturing: A solution for manual working stations. *The International Journal of Advanced Manufacturing Technology*, *94*(1–4), 509–521.

Watson, G., Curran, R., Butterfield, J., & Craig, C. (2008). The effect of using animated work instructions over text and static graphics when performing a small scale engineering assembly. In R. Curran, S.-Y. Chou, & A. Trappey (Hrsg.) (Eds.), *Collaborative product and service life cycle management for a sustainable world* (pp. 541–550). Springer.

Weidner, R., Redlich, T., & Wulfsberg, J. P. (2015). *Technische Unterstützungssysteme*. Springer.

Wölfle, M. (2014). *Kontextsensitive Arbeitsassistenzsysteme zur Informationsbereitstellung in der Intralogistik* (Doctoral dissertation), Technische Universität München, München, Germany.

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