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A user study for the evaluation of adaptive interaction systems for inclusive industrial workplaces

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Abstract—In recent years production systems have become highly sophisticated and complex. As a result, while on the one hand the least-skilled labor has been partially displaced by machines, high-skilled labor is more required to supervise and control advanced automation systems. In many cases, the complexity of machines implies an increased complexity of human-machine interfaces (HMIs), which are the main point of contact between the operator and the machine. To enable effective use of HMIs and to enable their usage by workers with different knowledge and capabilities, novel design approaches have been proposed. In particular, in this paper we consider the approach developed in the framework of the European research project INCLUSIVE, which aimed at designing industrial HMIs that adapt to the skills and capabilities of human operators. As a case study, we consider an adaptive interaction system for the woodworking industry and present an extensive evaluation carried out in real production environment with shopfloor workers. The effectiveness of the INCLUSIVE approach has been assessed with subjective and objective measurements and compared to that of interaction systems customarily used in industry. Results have shown that users appreciated the INCLUSIVE system and largely preferred it over the customary system. Moreover, with regard to objective performance related measurements, they performed better when using the INCLUSIVE system, since they received tailored guidance during the considered working tasks.

Note to Practitioners—This paper was motivated by the fact that advanced automation systems are often highly complex for human operators. To address this problem, we focus on the importance of designing the automation system around users and discuss an approach for adaptive automation, called INCLUSIVE. Its main feature is that it adapts the human-machine interface (HMI) according to operator's skills, capabilities and current mental fatigue. In the paper we provide an extensive evaluation of the INCLUSIVE system, considering a company producing woodworking machines as a use case. Assessment was

carried out in the company shopfloor, considering real workers, and the INCLUSIVE system was compared with the customary HMI running on the company machines. The results of our study suggest that adapting the interaction to operator's needs allows better working performance, while letting workers more satisfied with the use of the system.

Index Terms—Human-machine interaction, User centered automation, Adaptive interaction systems, Human factors, Technology assessment.

I. INTRODUCTION

Modern manufacturing systems are getting increasingly complex in order to satisfy diversified market needs, flexible production and competitiveness. Notwithstanding, despite high automation levels in factories, humans remain central to manufacturing operations. Rather, advanced automation requires high-skilled labor for monitoring and managing new production systems [1]. Since control of automation systems mainly occurs through human-machine interfaces (HMIs), complexity of machines is often accompanied by increased complexity of user interfaces. Thus, HMIs cannot be considered anymore an accessory to the machine and their improvement has become an important part of the design of the whole systems, to enable a non-stressful interaction and make them easy to use even for workers with low technical competence and, in general, workers with different knowledge levels and capabilities. In this regard, progress has been made in two directions. On the one side, user oriented design of traditional HMIs has gained attention [2]; on the other side, novel interaction approaches have been proposed that overcome the bottleneck of monitors and keyboards and enable immersive interaction. This is the case, for example, of interaction systems based on augmented reality, such as in [3]–[5], and wearable devices, as [6]–[8], that extend the usability of the HMI and provide more direct interaction means.

Furthermore, while in the past people were expected to adapt to machine requirements, today's machines are becoming more adaptable to the capabilities of workers. Modern automation systems are being designed and developed so that they can recognise the users, remember their capabilities, skills and preferences, and adapt accordingly [9]. Humans and automation are therefore taking advantage of each other's strengths, having a symbiotic relationship for enhancing the capabilities, skills and quality of their work. The result is a

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more flexible, inclusive and safe workplace, as well as better work conditions and increased productivity and improved quality [10]. The design of automatic machines that dynamically adapt to their users falls in the domain of adaptive automation [11], [12]. Ways to achieve this include dynamically allocating functions, simplifying the task, or changing the level of autonomy of the machine in response to user's cognitive and physical demands, such as in [13]. In this regard, a general framework for adaptive automation has been proposed very recently to assist the operator during working tasks [14]. The system, called INCLUSIVE, consists in the measurement of the operator's constitutional and situational condition to adapt the HMI and provide additional offline and online training.

The aim of this paper is to report on the field validation of the INCLUSIVE interaction system, in order to compare adaptive automation to the interaction systems customarily used in industry. The adaptive system has been tested in real production environment with shopfloor workers and its effectiveness has been assessed with subjective and objective measurements. In particular, feedback from test participants was collected with questionnaires on their satisfaction and system usability. Moreover, objective measurements of user's mental strain were collected and these were correlated with subjective feedback information. Finally, objective performance metrics have been considered to compare the effectiveness of the INCLUSIVE adaptive HMI to that of customary user interfaces.

The rest of the paper is organized as follows. Background on adaptive automation and related work are presented in Sec. II. Then, the INCLUSIVE system is introduced in Sec. III, considering woodworking machines as use case. In Sec. IV we describe the procedure carried out for validating the INCLUSIVE system in a real industrial scenario. The results of tests are reported in Sec. V. Finally, Sec. VI follows with a general discussion and some final remarks.

II. RELATED WORK

Adaptive HMIs have been explored extensively over the last three decades [15]. However, quite few approaches have been proposed with specific reference to industrial settings. This is the case, for example, with monitoring systems [16], process industries [17], [18], maintenance [19], [20], and cognitive production environments [21]. As stated in [22], adaptive user interfaces are defined as systems that adapt their displays and available actions to the user's current goals and abilities by monitoring user's status, the system state and the current situation. To a large extent, adaptation can be provided by considering changing how information is presented, what information is presented, and how interaction is enabled: in [9] a set of general rules for these different levels of adaption are given. Specifically, adaptive menus have been considered, for example in [23], to guide users through menus, highlighting the menu items that they are likely to use next. In [24] user's perception capabilities are accommodated by resorting to adaptive layouts, which resize, rearrange or select widgets so that the resulting interface is suited for the user, device and context. Furthermore, adaptive assistance has been used to provide additional specific guidance to the users to help them

with complex tasks [25]. Finally, multi-modal interactions [26] ensure that the users can select the most appropriate interaction modalities, depending on user's characteristics and capabilities and the characteristics of tasks and environment.

It is worthwhile noting that, although they are meant as aid for users, the use of adaptive user interfaces might cause several obstacles in the interaction process, if they are not the result of a careful design process [22]. In particular, the following main risks have been identified: the end user's needs might be incorrectly captured or interpreted, the user might be disrupted by the adaptation, the end user might not know when and how the interface will be adapted by the system, the system might rarely provide the end user with some explanation on the adaptive process, the end user might be rarely given the opportunity to be involved in the adaptation process, or, finally, some privacy issues might take place with respect to information related to the user's needs being retained by the system [27].

To overcome these limitations, the European INCLUSIVE project aimed to design a smarter and more inclusive working environment to ensure high worker's acceptance and productivity with new automatic production systems. In particular, the project focused on the definition of a general approach to the design of industrial HMIs that adapt to the skills and capabilities of human operators [28], [29]. The goal was that of relieving the increasing complexity of modern production systems by providing operators with usable interfaces, enabling a smooth and easy interaction, also to every worker. The interfaces developed according to the INCLUSIVE approach adapt the information presented to the user and its visualization to the user's capabilities and strain level [9]. Thus, they allow for inclusive and flexible working environments accessible to any kind of operator, regardless of age, education level, cognitive and physical impairments and experience in the tasks to be performed [30]. Additionally, the approach includes a teaching module that adaptively provides training to unskilled users on the basis of their capabilities and current understanding of the working scenario [31], [32].

To validate the INCLUSIVE methodology, three case studies have been selected as representative of a wide area of interest for the industry in Europe, in terms of both production requirements and involved operators. In particular, one of them refers to computer numerical control (CNC) machines used in the woodworking manufacturing sector. Given the extreme versatility, accuracy and ability to process many materials, CNC technologies have become the core equipment for manufacturing industry. Nevertheless, they pose specific additional challenges with respect to human-machine interaction [33]. Indeed, in addition to supervising the process during normal work production activity, operators have to carry out many activities to support the work cycle, including loading the program, positioning and preparing the raw pieces, the surfaces and the tools necessary for a specific program. Moreover, in addition to the different activities, a CNC machine has to control various types of material, from the hardest to the softest. To achieve an optimal result, it is necessary to correctly choose the cutting speeds and the type of tool to be used for the specific task at hand. In the recent paper [33], the

main criticalities in human-machine interaction for customary CNC machining, with specific focus on woodworking sector, have been identified. In particular, it has been found out that: i) current HMIs of CNC machines do not provide suitable support information, since standard user manuals, not problem oriented, are the only available resources and no effective troubleshooting solutions are given; ii) users have to move from the panel to the machine to perform physical interventions (e.g.: configure the machine on the HMI and mount the selected configuration); iii) presented information is not homogenous, since different machines over the production line have highly diversified HMIs, although relying on the same technology; iv) user's tasks do not focus on production functions, since they are in charge of supervising the progress of the process, but also of editing it [33].

To overcome these issues, a novel interaction system for CNC woodworking machines has been developed in the framework of the INCLUSIVE project. The system is able to support its target users, adapting to their capabilities and experience and to situational conditions. Specifically, it consists in an adaptive user interface that assists users in the selection of cutting tools from the tool warehouse and in a training module that provides guidance for troubleshooting alarms.

III. THE INCLUSIVE ADAPTIVE SYSTEM FOR WOODWORKING MACHINES

The aim of the INCLUSIVE system is to assist users with different levels of confidence in the process, when operating a woodworking machine, in nominal and fault conditions. As regards nominal conditions, we consider the task of setting the machine up with proper cutting tools required to run a given working task. In customary HMIs, there is no direct communication between the physical tools warehouse and the virtual one displayed on the HMI [33]. Thus, the operator has to physically mount the tools on the machine and, additionally, to configure the tool warehouse on the HMI by heart, entering for each position of the warehouse the tool that is mounted on the machine. Moreover, tools in the HMI are typically denoted by their ISO code [33], [34] that are familiar only to highly specialised workers.

In accordance with the adaptation rules presented [9], we propose to perform this activity by providing different amount of guidance in the HMI, depending on the level of expertise of the operator. For lower levels, the user is guided in the selection of the desired tool, whereas users with higher levels are allowed to perform the interaction task in a fast unguided way. To this end, three different user levels have been identified:

- expert,
- basic,
- with special needs,

where the lower user levels offer higher level of support and guidance. Users with special needs are those either affected by persistent impairments (e.g., visual impairments) or under situational mental strain. Each user of the HMI works using her/his own user profile, which is required for the operation of the machines. The user profile defines the default user level

and is determined in an a-priori assessment, based on the user's capabilities and skills. By capabilities we refer to characteristics such as gender, age, and any perceptive, cognitive or motoric characteristics relevant for the interaction with the system. Skills include those qualifications and competences that can be earned by the user, such as working experience, education, computer skills. Further details can be found in [35]. During operation, users may be requested to switch between the different levels depending on the experienced strain. Either the strain is continuously measured during machine operation by physiological parameters, measured with wearable devices, or performance values, such as mistakes or time spent completing a certain task. Threshold values for these parameters are also defined in the a-priori user assessment to determine when the user is experiencing increased mental strain. Should the measured strain exceed the defined threshold values, the HMI reacts, prompting users with the possibility of decreasing the level by one step. Once the strain levels have normalised, users may also return to the higher level.

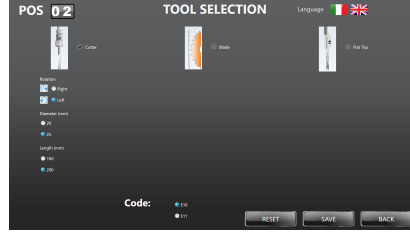
Following this approach, in the proposed HMI for woodworking, expert users are classified as users who are familiar with the machines and their setup to the degree that they have memorised the available tools and their codes. The focus of the HMI in this case lies in the quick selection and placement of the tools. The interface is filled with the least amount of information necessary, as shown in Fig. 1a. The basic user level is more geared towards users with less experience using the machine who have not yet memorised the tools and their codes. Thus, the users are guided through the selection process, starting with the selection of a specific tool, followed by the selection of the tool's specific attributes, as shown in Fig. 1b. The whole process is completed step-wise, with the following options only appearing once the first option has been selected. The level for users with special needs follows the same principle as the basic user level. The users are guided through the selection process step by step. However, in this case the shown information is simplified further in that only one selection option is shown on the screen at once, as in Fig. 1c. Furthermore, different attributes for the options are displayed larger in size and processes depicted in a graphic way. In this way, the level can accommodate the needs of users with either a visual impairment, or less experience with the functionality of the machine and its individual tools.

When it comes to equipping the machine with the tools positioned in the HMI, the user is prompted with a summary screen that provides support for tooling the physical warehouse based on the configuration saved in the HMI. Moreover, an offline training module is provided: it consists of a virtual environment that reproduces the environment in which the machine is located, the machine itself and the HMI. This module consists of two parts: a virtual environment that reproduces the machine and within which one moves as in a video game allowing to know the position of the various components and to interact with them (Fig. 2a), and a simulation of the user interface that allows to perform the same operations that would be performed on the machine in the virtual environment (Fig. 2b).

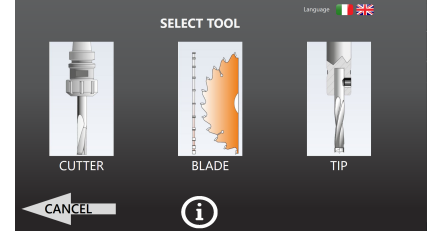
Finally, in the presence of alarms and machine faults, online



(a) Fast tool selection for expert operators.

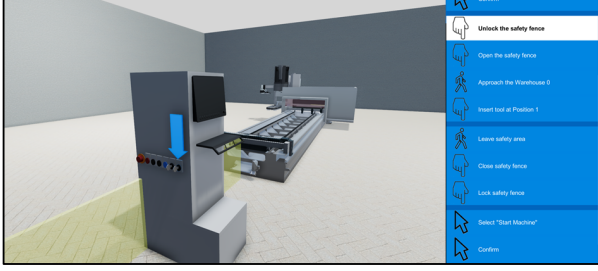


(b) Guided tool selection for basic operators.

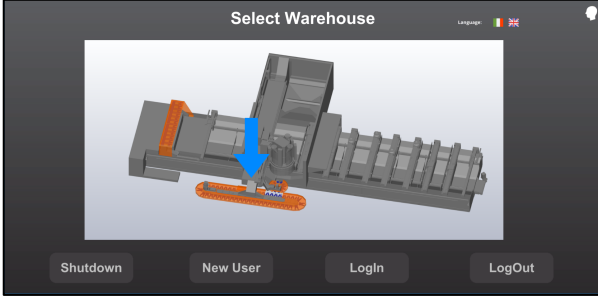


(c) Guided tool selection for operators with special needs.

Fig. 1: Adaptive HMI for selection of tools from tool warehouse [9].



(a) Virtual environment.



(b) HMI with instructions on the operations to be performed.

Fig. 2: Offline training system for tooling physical warehouse.



Fig. 3: Online support system for troubleshooting of alarms.

help, tailored to troubleshooting, is provided. It consists of HTML pages containing images, videos and detailed descriptions that allow the operator to take the correct actions in case of error. An example in this regard is shown in Fig. 3.

A. System architecture and implementation tools

The architecture of the INCLUSIVE system is depicted in Fig. 4. In particular, two remarks are noteworthy. First, the

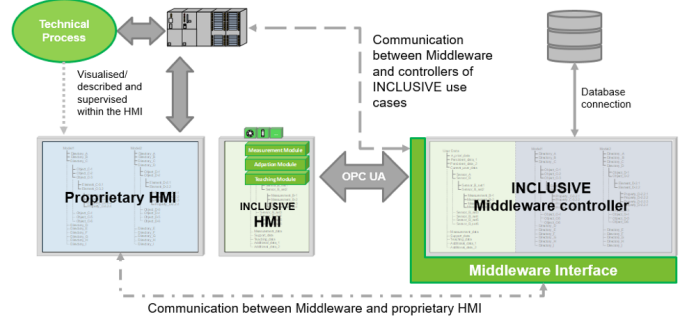


Fig. 4: Architecture of the INCLUSIVE system.

system has been implemented in a modular way, with the three modules for user's measurement, HMI adaptation and offline and online training operating separately and exchanging information. Second, to allow for hardware independence, the INCLUSIVE system, as a whole, has been designed as an independent system that is connected to the customary proprietary automation. Communication among the modules of the INCLUSIVE system and with the proprietary system is managed by an adaptive automation middleware¹, that is connected to the INCLUSIVE system via the OPC UA protocol and to the proprietary HMIs via (Fast Ethernet) TCP/IP connection.

Details about the implementation of the three modules of the INCLUSIVE system can be found in [14]. Specifically, measurement of user's status has been carried out by recording heart rate and Galvanic skin response with the wearable wristband Empatica E4². This information is then processed by means of the commercial software ThingWorx Analytics³ for estimating mental strain. The adaptive HMI has been implemented with the industrial software platform Movicon.NEXT⁴. Finally, as regards offline and online training tools, they have been implemented using Microsoft Unity⁵ for the virtual environment and HTML for step-by-step guidance.

¹<https://www.kepware.com/en-us/products/kepserverex/>

²<https://www.empatica.com/research/e4/>

³<https://www.ptc.com/en/resources/iiot/product-brief/thingworx-analytics>

⁴<https://www.progea.com/movicon-next/>

⁵<https://dotnet.microsoft.com/apps/games/unity>

IV. DESCRIPTION OF TESTS

A. Case study

The proposed system was validated considering, as a case study, SCM (Rimini, Italy), one of the world leading producers of woodworking machines. In particular, we considered the 5 axes CNC working center shown in Fig. 5. It is a flexible work cell for the production of window and door frames, fitted with automatic loading and unloading. It can perform batch or unit production; the work cycle is never interrupted and always at highest feed speed. It ensures maximum flexibility to process special window and door frames or other types of elements as the worktable can be accessed also for manual loading and unloading.

As mentioned above, two working scenarios were addressed by the INCLUSIVE system and they refer to the following operational modes:

- *use case 1* concerns a standard operation, to be performed daily or several times during the working day by the operator, which is the tooling of the machine tool warehouse;
- *use case 2* concerns an extraordinary operation, i.e. a maintenance operation following the error message "Spindle not locked".

B. Test protocol

At the beginning of the test, participants were asked to self-assess with respect to their computer skills and knowledge of the machine, in order to identify the initial user level for the INCLUSIVE HMI [36]. Then, tests consisted in asking participants to perform the tasks of the just mentioned use cases considering the customary user interface and the INCLUSIVE system. Specifically, workers were first given the characteristics and position in the warehouse of three tools and they were asked to add these tools in the HMI and on the machine. Then, the alarm referred to the spindle was forced, test participants were prompted with the error message "Spindle not locked" and were asked to solve it. In this regard, while the customary interface does not provide any further information or instructions, the INCLUSIVE system provides the online support system of Fig. 3.

These tasks were repeated twice for each participant. In order to avoid learning effects in results, half users tested the INCLUSIVE HMI before the customary one, while the other half performed the test in reverse order. After performing the tasks, users were asked to fill out questionnaires measuring system usability and worker satisfaction.

C. Test participants

All test participants were, at the time of tests, employees of SCM Group. They were enrolled on a volunteer basis by the company human resources department, and no requests for enrolment were made by department heads. A total of 18 participants (17 male, 1 female), between the ages of 19 and 54 ($AM = 35$; $SD = 13.1$), were enrolled in tests. Participants earned all education degrees from elementary degree to Master's degree. The duration of the employment also varied greatly, ranging from under six months to, in many

cases, over ten years. As a result of the initial self-assessment of computer skills and knowledge of the machine, half of the participants reported average computer skills, whereas the other half reported low computer skills. Moreover, half reported they had no knowledge of the machine, whereas the other half reported to be familiar with it. Finally, a test participant had mild cognitive impairments, whereas two had visual impairments. As a result, test participants resulted in a heterogeneous sample, representative of end users of SCM working centres.

Each participant was explained the overall goals of the tests and the protocol. Moreover, in compliance with the General Data Protection Regulation (EU) 2016/679 (GDPR), each participant and the SCM main researcher signed the informed consent form.

The whole study was approved by the Ethics Committee of the Province of Modena and the Ethics Committee responsible for SCM Group, in Rimini.

D. Performance metrics

To provide a thorough assessment of the INCLUSIVE adaptive system, objective and subjective performance metrics were considered [37]. As regards objective metrics, these consisted in performance related indexes measured during tests

- by recording the amount of time needed by users to perform the requested tasks, with the proposed INCLUSIVE system and with the customary HMI,
- by counting the number of mistakes occurred while carrying out the procedure with the two systems.

As regards subjective metrics, after test sessions, participants were administered two questionnaires:

- the *system usability scale* (SUS) questionnaire,
- the *worker satisfaction* questionnaire.

The SUS questionnaire [38] is an established tool to assess the usability of a wide variety of products and services. It is suited for industrial settings, since it offers a quick and simple assessment [39]. Examples of questions are "I think that I would like to use this system frequently", "I found the system unnecessarily complex" and "I felt very confident using the system". The worker satisfaction questionnaire was developed in the context of the INCLUSIVE project based on a model of worker satisfaction. Such a model relies on the assumption that the assessment of an interaction system can be influenced by some other external factors present at the workplace. These are physical factors, such as noise, temperature, dust or posture, as well as psychosocial working conditions, such as autonomy, participation, justice or social support. Equally, as the system will process sensitive personal data, which discloses barriers of human capabilities, different ethical and legal requirements to protect the user against harm and disadvantages have also to be taken into account. Thus, the worker satisfaction questionnaire includes three main sections: i) physical working conditions, ii) psychosocial working conditions and ethical aspects, and iii) user's satisfaction with HMI, including health and safety issues. In this study, we are presenting results of the worker satisfaction with HMI.



Fig. 5: Woodworking machine considered as a case study.

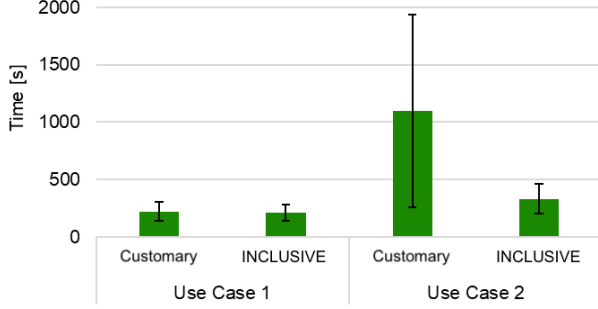


Fig. 6: Execution time per use case in seconds with the user interface customarily used at the case study and the proposed INCLUSIVE system.

V. RESULTS

A. Objective performance measurement

As quantitative metrics for performance measurement, time needed and mistakes occurred to perform the requested tasks were considered.

The tasks for each use case were completed twice, once using the customary HMI (i.e., the one currently used at the case study) and once again using the INCLUSIVE HMI. For each condition, the time required to complete the use case task was measured. The results are reported in Fig. 6. For the first use case, only a marginal difference between the execution time can be observed. The use of the INCLUSIVE HMI did however lead to a 4.2% reduction in the average time required. Nevertheless, this difference did not show statistical significance according to the the paired t -test ($p = 0.623$). For the second use case, the use of the INCLUSIVE HMI led to a much larger decrease in execution time of 69.7% when compared to the customary HMI system. This is due to the fact that no guidance at all is provided by the customary user interface when the error message is prompted. Moreover, when users declared that they were not able to perform the task, the maximum allowed time for completion (30 minutes) was automatically registered. The exact values for the mean execution time and standard deviation are reported in Table I.

TABLE I: Mean (AM) and standard deviation (SD) of execution time per use case.

| | HMI | Time AM [s] | Time SD [s] |
|------------|-----------|----------------|----------------|
| Use case 1 | Customary | 223.06 | 19.288 |
| | INCLUSIVE | 213.72 | 16.371 |
| Use case 2 | Customary | 1098.36 | 224.859 |
| | INCLUSIVE | 332.93 | 35.112 |

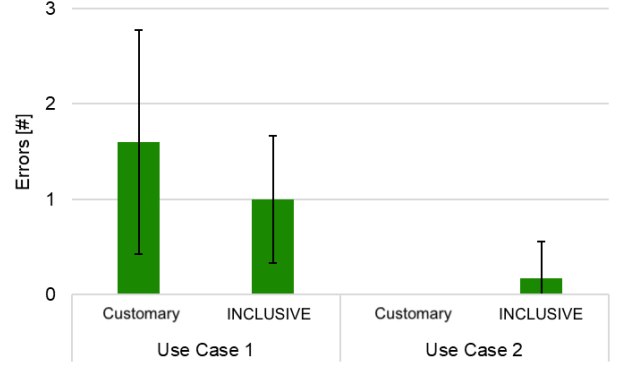


Fig. 7: Number of errors per use case with the user interface customarily used at the case study and the proposed INCLUSIVE system.

TABLE II: Mean (AM) and standard deviation (SD) of errors per use case.

| | HMI | Errors AM | Errors SD |
|------------|-----------|--------------|--------------|
| Use case 1 | Customary | 1.6 | 1.174 |
| | INCLUSIVE | 1 | 0.667 |
| Use case 2 | Customary | 0 | 0 |
| | INCLUSIVE | 0.2 | 0.389 |

Next to the execution time, the number of errors made during the completion of the use case task were also recorded. The results can be seen in Fig. 7. Generally, more errors occurred during the use case 1. Compared to the customary HMI, the use of the INCLUSIVE HMI led to a reduction in errors made of 37.5%. The paired t -test for the two systems returned $t(9) = 2.25, p = 0.051$. For the use case 2, when using the INCLUSIVE HMI, on average 0.2 errors were made. No errors happened with the customary use case only because no support is given and, hence, there is no procedure that could be misunderstood or mistaken. The exact values for the mean errors and standard deviation can be found in Table II.

B. Subjective assessment

1) *Usability assessment*: The assessment of usability consisted in four parts. Achieved results are summarized in Figures from 8 to 10. At first, demographic data, such as personal information (age, gender, education, current profession) was collected; further the participant's experience with different electronic devices was checked. In the second part, participants were asked to fill out the SUS questionnaire [38] once for the customary HMI, currently used by the company, and then again for the INCLUSIVE HMI. This questionnaire consists of 10 questions with a 5-point Likert Scale ("I do not agree" to "I completely agree"). The questions can be taken from Fig. 9. The third part consisted of another set of nine questions and three text fields, in which the two HMI systems were directly compared to each other. Again, each question had five possible answers ("I do not agree" to "I completely agree"). The questions can be taken from Fig. 10. Finally, some open questions to collect subjective feedback about the INCLUSIVE

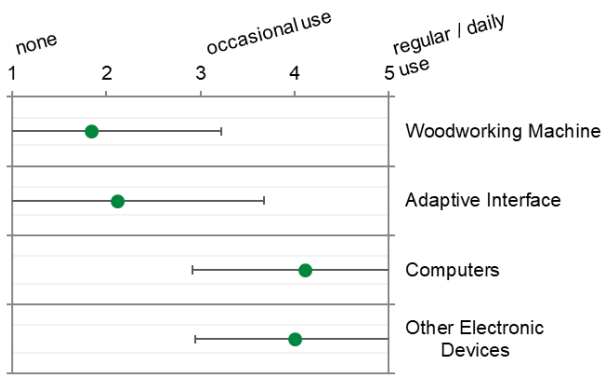


Fig. 8: Prior experience of the participants.

system were presented ("What do you think was in particular positive about the INCLUSIVE HMI?" and "Where do you think the INCLUSIVE HMI needs to be improved?").

As shown in Fig. 8, only a few of the participants had prior experience with woodworking machines ($AM = 1.83$; $SD = 1.38$). The prior experience with adaptive interfaces was also limited ($AM = 2.11$; $SD = 1.56$). As regards computers and other electronic devices, participants reported regular to daily use for work purposes ($AM = 4.11$; $SD = 1.20$ and $AM = 4.0$; $SD = 1.05$, respectively).

The results of the SUS questionnaire following the use of both the customary and the INCLUSIVE HMI show that the INCLUSIVE HMI scores are higher ($AM = 78.3$; $SD = 16.0$) than the customary HMI ($AM = 57.4$; $SD = 27.1$). The SUS score should not be interpreted as a percentage score, with 100 indicating full usability, rather a higher SUS score indicates a higher usability. According to [40] and [41], a score of 68 is seen as average. This shows that the usability of the customary HMI system is good, but has some potential of improvement. The INCLUSIVE HMI, on the other hand, received an above average rating. The average score for each question of the SUS questionnaire is reported in Fig. 9. It becomes clear that items formulated positively were rated above average and negative items were rated below average, resulting in an overall positive evaluation concerning the INCLUSIVE HMI.

Moreover, the answers for the questionnaire directly comparing both HMIs can be found in Fig. 10. This confirms the results of the determined SUS scores, for example showing that the users felt that the INCLUSIVE HMI offered better support ($AM = 4.11$; $SD = 1.15$), was more intuitive ($AM = 4.17$; $SD = 0.83$) than the customary HMI, and has the potential to improve customary production systems ($AM = 4.28$; $SD = 0.65$).

Finally, as regards open questions about the usability of the INCLUSIVE system, 7 test participants expressly reported appreciation for being supported to solve problems without asking for help from a second user and regardless of their knowledge of the machine. Moreover, the presence of videos and images was explicitly appreciated by 3 subjects. As regards possible areas for improvement, 2 subjects reported that voice interaction would be appreciated. Moreover, other subjects reported minor comments to the technical implementation of the system, such as it should be more responsive or

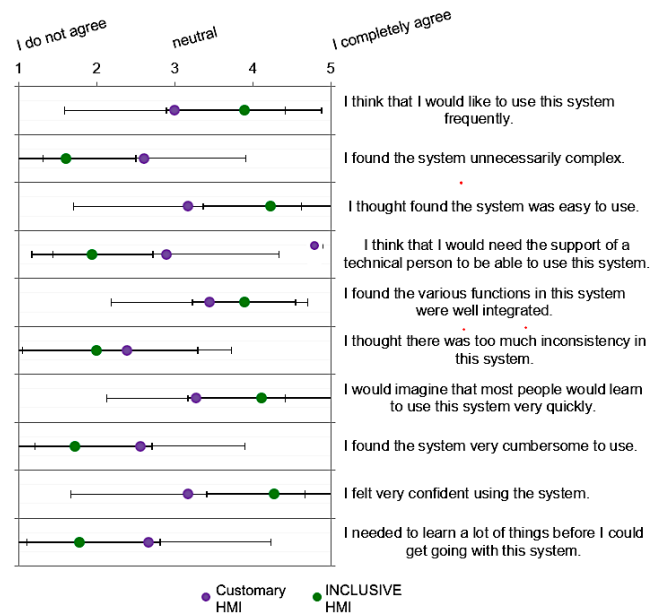


Fig. 9: Answers to the questions of the SUS questionnaire: comparison between the customary and the INCLUSIVE HMI.

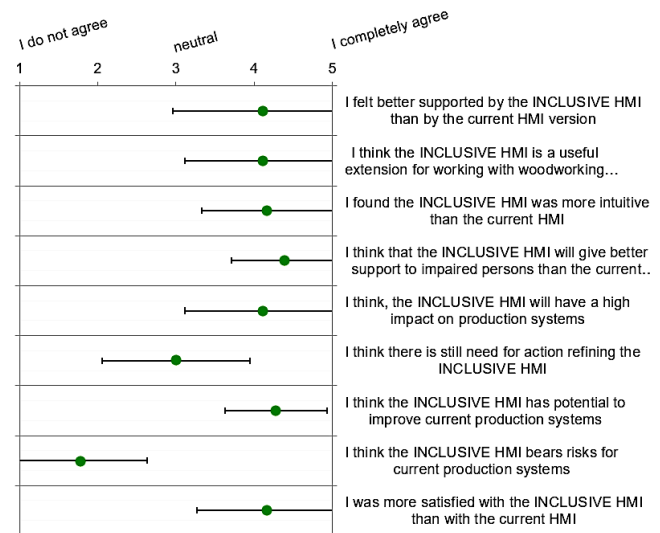


Fig. 10: Answers to the SUS questionnaire comparing both HMIs.

icons should be bigger, to accommodate big fingers or the use of gloves.

2) *Worker satisfaction questionnaire results:* At the end of the interaction tasks, test participants were asked to fill in also the worker satisfaction questionnaire.

Overall, most users (85%) felt satisfied and very satisfied with the INCLUSIVE HMI. There were no dissatisfied users. 15% of the group felt neither satisfied, nor dissatisfied (Fig. 11a, left). In case of the general satisfaction with the safety functions of the new HMI, more variability of satisfaction level was observed (Fig. 11a, right).

A total of 73.34% of the group thought that the INCLUSIVE HMI fulfilled all the safety functions to a large and to a very large extent and 20% of the users believed that HMI fulfilled

all the safety functions to a small and very small extent. Most users (78.95%) thought the layout of the INCLUSIVE HMI was appropriate to a large extent and to a very large extent. 21.05% of the group felt less satisfied with the layout (Fig. 11b, left). Most users believed that the new HMI was easy to learn: 68.43% answered "to a large extent" or "to a very large extent". 26.32% of the group agreed with this to a very small extent and to a small extent, suggesting that there was still room for improvement in this aspect (Fig. 11b, right).

Again, the majority of the study group was satisfied with the efficiency related to work with the new HMI. 78.95% of the group agreed that the INCLUSIVE HMI helped them to be more productive at work to a large and very large extent. 21.05% did agree with this statement only to a small and very small extent (Fig. 11c, left). The majority of the group (68.42%) felt that the adaptive HMI adjusted to the user's actual capabilities/mental states, while 15.79% of the group agreed with this only to a small or very small extent (Fig. 11c, right).

It was also observed that 68.43% of the group felt less stressed out using the adaptive HMI to a large or very large extent, confirming that the system could be useful in decreasing the pressure felt by the worker. However, 26.32% of the users felt less stressed out to a small or very small extent when using the adaptive HMI (Fig. 11d, left). 68.2% of the group felt they were making fewer mistakes/errors when using the INCLUSIVE HMI, suggesting its positive role in supporting workers in maintaining their performance (Fig. 11d, right).

It was observed that most users found the monitoring of their strain beneficial to them: 72.22% of the group agreed with this statement to a large and very large extent (Fig. 11e, left). They also found the measurement system rather comfortable: 76.7% of the study group thought that the measurement system could challenge their physical comfort only to a very small and to a small degree (Fig. 11e, right).

Most of the study group (57.90%) felt that the online training system was helpful in mastering the new HMI; 21.05% of the group found the online training system somewhat helpful (Fig. 11f, left). More users were satisfied with the offline training system: 63.16% of the group believed the offline training system to be helpful for them to master the INCLUSIVE HMI to a large and to a very large extent (Fig. 11f, right). However, the percentage of users who responded "to a very large extent" was higher in the assessment of the online training system compared to the offline training system.

VI. DISCUSSION AND CONCLUSIONS

The INCLUSIVE HMI was developed as an adaptive system, reacting towards the target user's needs. The design solution implemented three different user profiles (expert, intermediate, basic) with successively increasing operation support. For this study, the HMI was used for a woodworking machine. A questionnaire was considered to directly compare the usage of the INCLUSIVE HMI to the usage of the customary HMI currently run in industry. The study was conducted with participants of which the majority (66.7%) have

no prior experience with woodworking machines. Therefore the influence of experience using the customary system on the results are reduced. Results show that most participants (88.9%) are familiar with the use of computers or electronic devices, resulting in experience with menus and navigation structures. For this reason, participants opinion about the two systems has to be seen in relation to their experience.

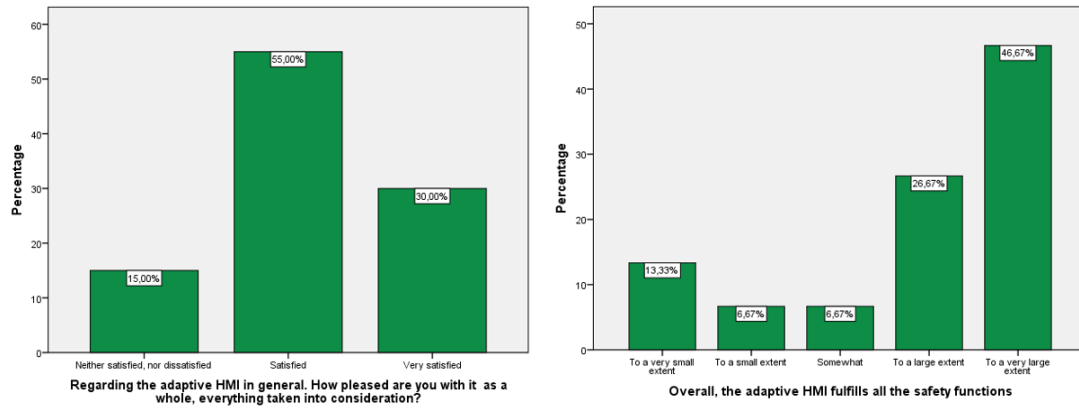
Results of the SUS score imply that usability of the customary HMI can be improved by means of the implemented adaptation, since the average rating is higher for the INCLUSIVE system than for the customary HMI. However, the SUS score for the INCLUSIVE HMI is rated only slightly higher than the average defined by [40] and [41], implying still some potential for improvement, as reflected also by the answers to the open questions. Fig. 9 shows the background of the SUS score in detail. The customary HMI was rated exactly on average (3 points of a 5-point Likert scale), whereas the INCLUSIVE HMI constantly received 4 to 5 points rating. This points out that the INCLUSIVE HMI was perceived by test participants as an improvement with regards to the customary HMI for all dimensions, for instance frequent use, complexity, ease of use, functions, consistency, and learning effort.

Also, when directly comparing the systems, results in Fig. 10 show the advantages of the developed system compared to operating the state-of-the-art HMI. The developed HMI was perceived as useful with regards to the specific use case of woodworking. In addition, the handling was evaluated quite positive. Following these thoughts, the HMI should undergo another iteration before implementation in industry. Another explanation could be that participants mental models contain more conservative approaches for machine HMIs, and that they refrain from the implementation of an adaptive HMI, yet. Satisfaction of the users was above average. Risks for customary production systems were rated very low, showing an uncertainty amongst participants, but obviously no danger. Further research would be required to get a better insight into this topic.

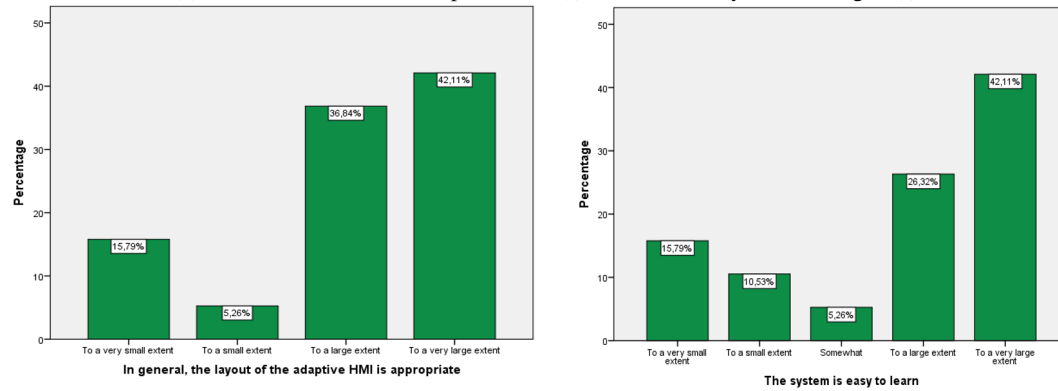
Through the worker satisfaction questionnaire, it was found that users felt rather satisfied with the new adaptive HMI in general as well as with various aspects analysed. Users felt that the new system was easy to learn and safe, with appropriate design, supporting employees efficiency and decreasing subjective strain, adapting to user's capabilities. The measurement system was assessed to be comfortable and beneficial for the worker and the teaching module was helpful for the user to master the new HMI.

In summary, the test participants agreed that the INCLUSIVE system could support them whilst working, in the considered use case. These preliminary results need to be consolidated in a more extensive assessment, including more test subjects and, possibly, customary HMIs from other vendors of woodworking machines. Then, based on the results of further testing, it would be possible to propose the concrete application of adaptive interaction systems in industrial working environments. In order for this to happen, acceptance by workers and trust in the use of the system need further appropriate investigation.

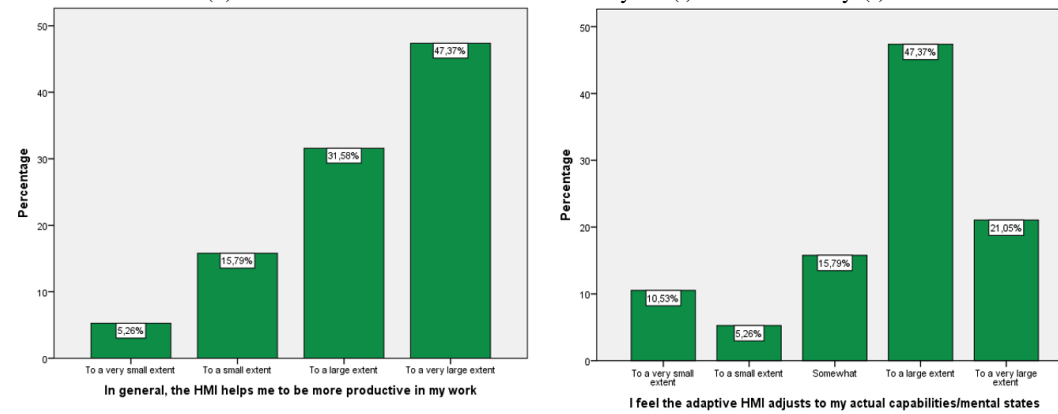
As a final remark, we would like to point out that the con-



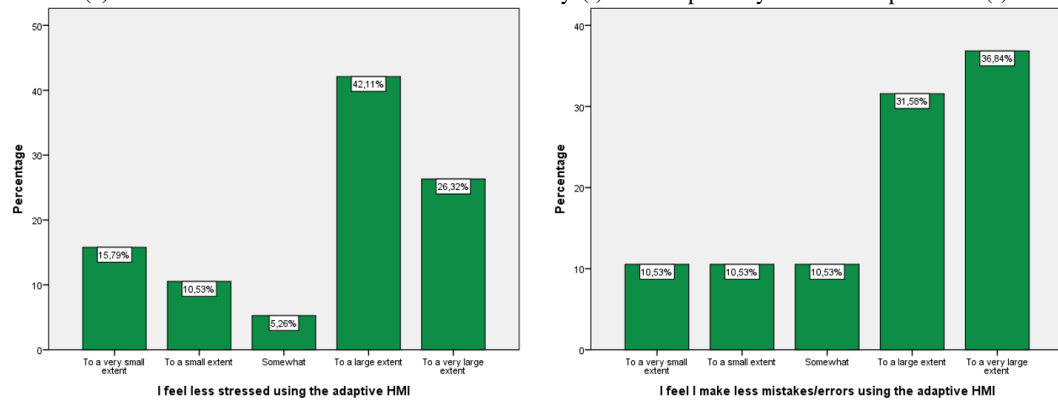
(a) Satisfaction with the adaptive HMI (l) and with safety while using it (r).



(b) Satisfaction with INCLUSIVE HMI layout (l) and learnability (r).

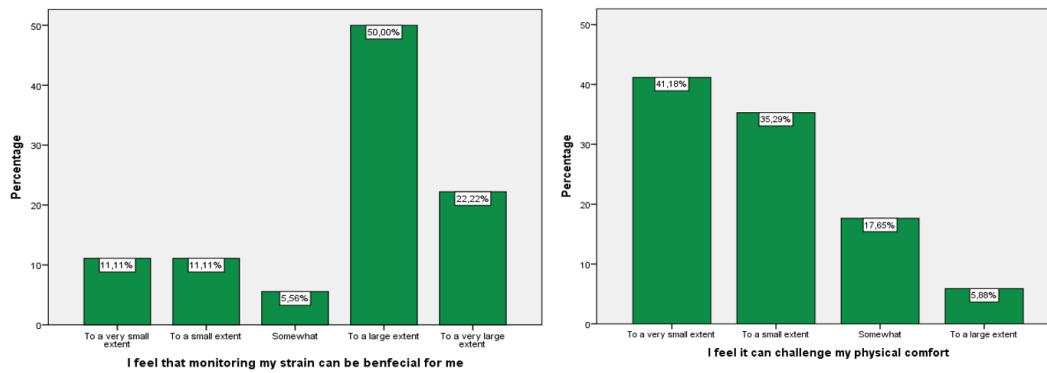


(c) Satisfaction with INCLUSIVE HMI efficiency (l) and adaptability to user's capabilities (r).

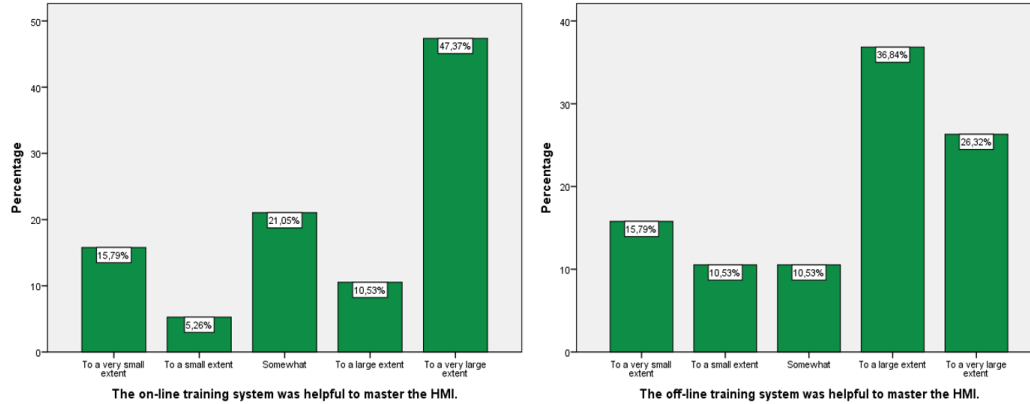


(d) Stress level experienced (l) and subjective assessment of number of errors when working with the INCLUSIVE HMI (r).

Fig. 11: Results for the worker satisfaction questionnaire.



(e) Assessment of the strain monitoring in INCLUSIVE HMI to be beneficial (r) and of the comfort of the INCLUSIVE measurement system.



(f) Satisfaction with the online (l) and offline (r) training system.

Fig. 11: Results for the worker satisfaction questionnaire.

crete application of adaptive interaction systems in industrial working environments cannot disregard linked ethical, legal and social implications, mainly related to worker's monitoring and measurement [30]. In particular, robust countermeasures for data protection must be implemented in order to prevent any risk of stigmatization of workers: if a data protection system is already in use in companies, proper improvement must be done in order to account for possible criticalities introduced by adaptive automation on this issue.

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REFERENCES

- [1] M. Russmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch, "Industry 4.0: The future of productivity and growth in manufacturing industries," Boston Consulting Group, Tech. Rep., 2015.
- [2] P. A. Hancock, R. J. Jagacinski, R. Parasuraman, C. D. Wickens, G. F. Wilson, and D. B. Kaber, "Human-automation interaction research: Past, present, and future," *Ergonomics in Design*, vol. 21, no. 2, pp. 9–14, 2013.
- [3] G. Michalos, P. Karagiannis, S. Makris, Ö. Tokçalar, and G. Chrysosouris, "Augmented reality (AR) applications for supporting human-robot interactive cooperation," *Procedia CIRP*, vol. 41, pp. 370–375, 2016.
- [4] D. Mourtzis, J. Angelopoulos, and V. Zogopoulos, "Integrated and adaptive ar maintenance and shop-floor rescheduling," *Computers in Industry*, vol. 125, p. 103383, 2021.
- [5] S. Webel, U. Bockholt, T. Engelke, N. Gavish, M. Olbrich, and C. Preusche, "An augmented reality training platform for assembly and maintenance skills," *Robotics and autonomous systems*, vol. 61, no. 4, pp. 398–403, 2013.
- [6] C. Gkourmelos, P. Karagiannis, N. Kousi, G. Michalos, S. Koukas, and S. Makris, "Application of wearable devices for supporting operators in human-robot cooperative assembly tasks," *Procedia CIRP*, vol. 76, pp. 177–182, 2018.
- [7] H. Liu and L. Wang, "Gesture recognition for human-robot collaboration: A review," *International Journal of Industrial Ergonomics*, vol. 68, pp. 355–367, 2018.
- [8] V. Villani, L. Sabattini, N. Battilani, and C. Fantuzzi, "Smartwatch-enhanced interaction with an advanced troubleshooting system for industrial machines," *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 277–282, 2016.
- [9] V. Villani, L. Sabattini, F. Loch, B. Vogel-Heuser, and C. Fantuzzi, "A general methodology for adapting industrial hmis to human operators," *IEEE Trans. Automation Science and Engineering*, 2019.
- [10] ACE Factories Cluster, "Human-centred factories from theory to industrial practice. lessons learned and recommendations," Tech. Rep., 2019. [Online]. Available: <http://ace-factories.eu/wp-content/uploads/ACE-Factories-White-Paper.pdf>
- [11] R. Parasuraman, M. Barnes, K. Cosenzo, and S. Mulgund, "Adaptive automation for human-robot teaming in future command and control systems," Army research lab aberdeen proving ground md human research and engineering ..., Tech. Rep., 2007.
- [12] M. W. Scerbo, *Theoretical Perspectives on Adaptive Automation*. Routledge, 2018.
- [13] D. Mourtzis, V. Siatras, J. Angelopoulos, and N. Panopoulos, "An intelligent model for workforce allocation taking into consideration the operator skills," *Procedia CIRP*, vol. 97, pp. 196–201, 2021.
- [14] V. Villani, L. Sabattini, P. Bara'nska, E. Callegati, J. N. Czerniak, A. Debbache, M. Fahimipirehgalin, A. Gallasch, F. Loch, R. Maida,

- A. Mertens, Z. Mockało, F. Monica, V. Nitsch, E. Talas, E. Toschi, B. Vogel-Heuser, J. Willems, D. Żołnierczyk Zreda, and C. Fantuzzi, "The inclusive system: A general framework for adaptive industrial automation," *IEEE Transactions on Automation Science and Engineering*, pp. 1–14, 2020.
- [15] A. F. Norcio and J. Stanley, "Adaptive human-computer interfaces: A literature survey and perspective," *IEEE Transactions on Systems, Man, and cybernetics*, vol. 19, no. 2, pp. 399–408, 1989.
- [16] A. Lee and J. Martinez Lastra, "Enhancement of industrial monitoring systems by utilizing context awareness," in *IEEE Int. Multi-Disciplinary Conf. Cognitive Methods in Situation Awareness and Decision Support (CogSIMA 2013)*, 2013.
- [17] F. Jammes and H. Smit, "Service-oriented paradigms in industrial automation," *IEEE Trans. Industrial Informatics*, vol. 1, no. 1, pp. 62–70, 2005.
- [18] L. Urbas, S. Hennig, H. Hager, F. Doherr, and A. Braune, "Towards context adaptive hmis in process industries," in *9th IEEE Int. Conf. Industrial Informatics*. IEEE, 2011, pp. 244–249.
- [19] C. Woods, M. Hodkiewicz, and T. French, "Requirements for adaptive user interfaces for industrial maintenance procedures: A discussion of context, requirements and research opportunities," in *Proc. 31st Australian Conf. Human-Computer-Interaction*, 2019, pp. 322–326.
- [20] F. Loch, J. Czerniak, V. Villani, L. Sabattini, C. Fantuzzi, A. Mertens, and B. Vogel-Heuser, "An adaptive speech interface for assistance in maintenance and changeover procedures," in *Int. Conf. Human-Computer Interaction (HCI)*. Springer, 2018, pp. 152–163.
- [21] F. Wallhoff, M. AblaBmeier, A. Bannat, S. Buchta, A. Rauschert, G. Rigoll, and M. Wiesbeck, "Adaptive human-machine interfaces in cognitive production environments," in *IEEE Int. Conf. Multimedia and Expo*. IEEE, 2007, pp. 2246–2249.
- [22] T. Lavie and J. Meyer, "Benefits and costs of adaptive user interfaces," *Int. J. Human-Computer Studies*, vol. 68, no. 8, pp. 508–524, 2010.
- [23] J. Vanderdonckt, S. Bouzit, G. Calvary, and D. Chêne, "Exploring a design space of graphical adaptive menus: Normal vs. small screens," *ACM Transactions on Interactive Intelligent Systems (TiiS)*, vol. 10, no. 1, pp. 1–40, 2019.
- [24] K. Gajos and D. S. Weld, "SUPPLE: automatically generating user interfaces," in *Proc. 9th Int. Conf. Intelligent user interfaces*. ACM, 2004, pp. 93–100.
- [25] M. ElKomy, Y. Abdelrahman, M. Funk, T. Dingler, A. Schmidt, and S. Abdennadher, "ABBAS: an adaptive bio-sensors based assistive system," in *Proc. 2017 Conf. Human Factors in Computing Systems (CHI)*. ACM, 2017, pp. 2543–2550.
- [26] M. Turk, "Multimodal interaction: A review," *Pattern Recognition Letters*, vol. 36, pp. 189–195, 2014.
- [27] S. Bouzit, G. Calvary, J. Coutaz, D. Chêne, E. Petit, and J. Vanderdonckt, "Design space exploration of adaptive user interfaces," in *Int. Conf. Research Challenges in Information Science (RCIS)*, IEEE, Ed., 2017.
- [28] "Smart and adaptive interfaces for INCLUSIVE work environment." [Online]. Available: <http://www.inclusive-project.eu>
- [29] V. Villani, L. Sabattini, J. N. Czerniak, A. Mertens, B. Vogel-Heuser, and C. Fantuzzi, "Towards modern inclusive factories: A methodology for the development of smart adaptive human-machine interfaces," in *22nd IEEE Int. Conf. Emerging Technologies And Factory Automation (ETFA)*. IEEE, 2017.
- [30] V. Villani, L. Sabattini, J. N. Czerniak, A. Mertens, and C. Fantuzzi, "MATE robots simplifying my work: benefits and socio-ethical implications," *IEEE Robot. Automat. Mag.*, vol. 25, no. 1, pp. 37–45, 2018.
- [31] F. Loch, M. Fahimipirehgalin, J. N. Czerniak, A. Mertens, V. Villani, L. Sabattini, C. Fantuzzi, and B. Vogel-Heuser, "An adaptive virtual training system based on universal design," *IFAC-PapersOnLine*, vol. 51, no. 34, pp. 335–340, 2019.
- [32] F. Loch, G. Koltun, V. Karaseva, D. Pantförder, and B. Vogel-Heuser, "Model-based training of manual procedures in automated production systems," *Mechatronics*, vol. 55, pp. 212–223, 2018.
- [33] G. Lotti, V. Villani, N. Battilani, and C. Fantuzzi, "New trends in the design of human-machine interaction for cnc machines," *IFAC-PapersOnLine*, vol. 52, no. 19, pp. 31–36, 2019.
- [34] X. Xu and Q. He, "Striving for a total integration of cad, capp, cam and cnc," *Robotics and Computer-Integrated Manufacturing*, vol. 20, no. 2, pp. 101–109, 2004.
- [35] V. Villani, J. N. Czerniak, L. Sabattini, A. Mertens, and C. Fantuzzi, "Measurement and classification of human characteristics and capabilities during interaction tasks," *Paladyn, J. Behav. Robot.*, vol. 10, no. 1, pp. 182–192, 2019.
- [36] J. Czerniak, V. Villani, L. Sabattini, C. Fantuzzi, C. Brandl, and A. Mertens, "Systematic approach to develop a flexible adaptive human-machine system," in *Proc. 20th Congress Int. Ergonomics Association*, Springer, Ed., 2018, pp. 276–288.
- [37] V. Villani, G. Lotti, N. Battilani, and C. Fantuzzi, "Survey on usability assessment for industrial user interfaces," *IFAC-PapersOnLine*, vol. 52, no. 19, pp. 25–30, 2019.
- [38] J. Brooke *et al.*, "SUS: A quick and dirty usability scale," *Usability evaluation in industry*, vol. 189, no. 194, pp. 4–7, 1996.
- [39] A. Bangor, P. T. Kortum, and J. T. Miller, "An empirical evaluation of the system usability scale," *Intl. J. Human-Computer Interaction*, vol. 24, no. 6, pp. 574–594, 2008.
- [40] A. Bangor, P. Kortum, and J. Miller, "Determining what individual SUS scores mean: Adding an adjective rating scale," *Journal of usability studies*, vol. 4, no. 3, pp. 114–123, 2009.
- [41] J. Sauro, "Measuring usability with the system usability scale (SUS)," Tech. Rep., 2011. [Online]. Available: <https://measuringu.com/sus/>