

This is the peer reviewed version of the following article:

A General Methodology for Adapting Industrial HMIs to Human Operators / Villani, Valeria; Sabattini, Lorenzo; Loch, Frieder; Vogel-Heuser, Birgit; Fantuzzi, Cesare. - In: IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING. - ISSN 1545-5955. - 18:1(2019), pp. 164-175. [10.1109/TASE.2019.2941541]

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

19/12/2025 04:20

A general methodology for adapting industrial HMIs to human operators

Valeria Villani¹, Lorenzo Sabattini¹, Frieder Loch², Birgit Vogel-Heuser² and Cesare Fantuzzi¹

Abstract—Modern production systems are becoming more and more complex to comply with diversified market needs, flexible production and competitiveness. Despite technological progress, the presence of human operators is still fundamental in production plants, since they have the important role of supervising and monitoring processes, by interacting with such complex machines. 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. 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 machines, to enable a non stressful interaction and make them easy to use also to less skilled operators. In this paper, we present a general framework for the design of HMIs that adapt to the skills and capabilities of the operator, with the ultimate aim of enabling a smooth and efficient interaction and improving user’s situation awareness. Adaptation is achieved considering three different levels: perception (i.e., how information is presented), cognition (i.e., what information is presented), and interaction (i.e., how interaction is enabled). For each level, general guidelines for adaptation are provided, thus defining a meta-HMI independent of the application. Finally, some examples of how the proposed adaptation patterns can be applied to the case of procedural and extraordinary maintenance tasks are presented.

Note to Practitioners — This paper was motivated by the problem of facilitating the interaction of human operators with human-machine interfaces (HMIs) of complex industrial systems. Standard industrial HMIs are static and do not take into account user’s characteristics. As a consequence, least skilled operators are prevented from their use and/or have poor performance. In this paper, we suggest a novel methodology to the design of adaptive industrial HMIs that adapt to the skills and capabilities of operators and compensate their limitations (e.g. due to age or inexperience). In particular, we propose a methodological framework that consists in general rules to accommodate user’s characteristics. Adaptation is achieved at three different levels: perception (i.e., how information is presented), cognition (i.e., what information is presented), and interaction (i.e., how interaction is enabled). The presented rules are independent of the target application. Nevertheless, we establish a relationship between such design rules and user’s impairments and capabilities and kind of working tasks. Hence, designers of HMIs are called to instantiate them considering the specific requirements and characteristics of the users and the working tasks of the application at hand.

¹V. Villani, L. Sabattini and C. Fantuzzi are with the Department of Sciences and Methods for Engineering (DISMI), University of Modena and Reggio Emilia, Reggio Emilia, Italy {valeria.villani, lorenzo.sabattini, cesare.fantuzzi}@unimore.it

²F. Loch and B. Vogel-Heuser are with the Institute of Automation and Information Systems, Technical University of Munich, Munich, Germany {frieder.loch, vogel-heuser}@tum.de

This work has been supported by the INCLUSIVE collaborative project, which has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under grant agreement No 723373.

I. INTRODUCTION

In recent years, the complexity of modern production systems has dramatically increased, to comply with diversified needs of market, flexible production and competitiveness. The introduction of Industry 4.0 and cyber-physical production systems has changed the traditional manufacturing industry, allowing for customization and production of small batches [1].

Despite technological progress, the presence of human operators is still fundamental in production plants. However, new trends in production and management have introduced changes in employment conditions and requirements. Firstly, operators’ role has changed from operating the machines, to supervising them and monitoring processes, promptly taking action in case of machine faults or changes in production. While displacing some of the least-skilled labor, greater automation requires higher-skilled labor for monitoring and managing new automation systems [1]. Moreover, the ongoing demographic change requires future manufacturing systems to be accessible to aging employees with declining physiological and cognitive capabilities [2]. In spite of that, elderly operators represent a valuable resource for complex tasks (e.g., supervision of wide and diversified plants) given their working experience. Hence, efforts should be made to leverage such capabilities, while compensating limitations due to aging.

In addition, today’s production schemes often force operators to work under very fast pace determinant with consequent effects on the cognitive demand and on the quality of the output. As surveyed in [3], plant and machine operators report challenging work conditions, such as noisy environments, tight schedules, atypical working time arrangements (such as nights and weekends), fear of losing job, and/or psychological pressure due to direct control of the boss. Such strenuous conditions are amplified when vulnerable users, such as those cognitively or physically impaired as well as elderly and low educated operators, are involved in the interaction. In typical operative scenarios, these classes of workers are barred from job positions that necessitate the meticulous attention to detail required to interact with a complex factory plant. Alternatively, in the case that these workers are granted any such occupations, their responsibilities and duties are severely limited.

To invert such a policy, complex product systems need to be simplified. In this scenario, being the point of contact between the operator and the machine, human-machine interfaces (HMIs) have become a critical part of the system, since they determine, to the greatest extent, the feasibility and efficiency of acting and interacting with the machine. Designing “good”

user interfaces is, hence, an important and challenging part of the design of efficient production systems.

A. State of the art on adaptive user-centred HMIs

To improve the usability of HMIs, approaches based on anthropocentric design [4] have been proposed. The novelty introduced by this methodology is that the design of HMIs should focus on achieving not only efficiency in the process, but also satisfaction in the user, who is relieved of discomfort and stress caused by the interaction. To this end, these approaches prescribe that HMIs should be designed around user's needs and capabilities, rather than starting the design from technical requirements of the process at hand. However, in real industrial scenarios, standard HMIs are static and do not take into account user's characteristics. If operator's login is required, it is used to enable or disable advanced functions according to standard user profiles, or to simply track operator's activity. As a result, user's specific expertise or contingent difficulties are not leveraged or compensated, thus leading to inefficiency and frustration. On the contrary, if information about user's capabilities and characteristics are collected, it is possible to adapt the interaction accordingly, assisting her/him when needed.

Some approaches to the design of industrial adaptive HMIs have been proposed in the literature. This is the case, for example, of monitoring systems [5], process industries [6] and cognitive production environments [7]. In [8] a cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance is proposed, which aims to support adaptive scheduling taking into consideration monitoring data from shop-floor and data related to maintenance. Model-based frameworks for user interfaces design, such as the Cameleon Reference Framework [9] and ConcurTaskTrees [10], have also been suggested. However, these methods mainly consider adaptation related to operative context (e.g., tasks, environmental conditions, hardware): user's capabilities and comfort during the interaction are typically not considered.

Recently, an integrated approach to the design of adaptive interaction systems has been proposed [11]. The approach is called *MATE* since it relies on three pillars, namely *Measurement* of user's capabilities, *Adaptation* of HMI, and *TEaching* of the lacking competence. To this end, user's capabilities and characteristics and current emotional condition need to be thoroughly measured [12]. Based on this, the interaction is adapted and facilitated, and, if this does not prove sufficient, additional off-line and on-line training support is provided, possibly by means of virtual or augmented reality [13]. The ultimate goal of this approach is to allow an inclusive work environment that can be accessed also by vulnerable and least-skilled operators, which opens up to a number of socioethical implications, as discussed in [11]. In this context, in [14] an adaptive virtual training system for industrial procedures has been discussed with specific regards of elderly workers.

Finally, it is worthwhile noting that human-in-the-loop cyber-physical systems (HiLCPSs) have been proposed as part of new-generation intelligent manufacturing [15], [16].

A typical HiLCPS allows interaction with an embedded system (the cyber component) and the physical environment by recognizing human cognitive activity and, hence, enabling transparent interaction. Human's intention is detected by collecting physiological measurements, which enable an easy and customized interaction with complex systems.

B. Contribution and organization of the paper

The aim of this paper is the definition of a general methodological approach to design adaptive operator interfaces for complex automatic systems. Our goal is that of devising universal adaptation patterns that have general validity and can be used to guide the design of application-dependent adaptive HMIs.

Adaptation is intended mainly towards the user and her/his characteristics in order to allow a smooth interaction also in the presence of constitutional (e.g., lack of experience or presence of impairments) or situational (e.g., fatigue or rushed working conditions) difficulties.

To deliver general guidelines for the design of adaptive HMIs, in Sec. II we start from the analysis of the relevant literature to select the general principles for the design of usable and effective HMIs. These principles serve as reference, on the one side, for the design of any HMI and, on the other side, to select which features should be empowered to provide optimal support to the target users, by means of adaptation. The proposed approach is introduced in Sec. III and, more specifically, we discuss:

- how the above mentioned principles can accommodate sensorial impairments to provide adaptation to user's perceptive capabilities (Sec. IV);
- how the usability principles can be implemented to accommodate user's experience in the task, computer alphabetization and current affect during interaction (i.e., mental fatigue and anxiety) (Sec. V);
- how the interaction means properly fit user's capabilities (Sec. VI).

Finally, in Sec. VII we consider the application of the proposed approach to some industrial use cases and discuss related benefits.

II. GENERAL PRINCIPLES FOR THE DESIGN OF HMIs

A wide body of the literature has been devoted to identifying best practices for the design of clear and consistent HMIs that provide effective feedback for operator's actions. These principles are generally devoted to automatic machines, are independent of the case study and users, and, hence, have general validity. As a consequence, they should be used as a reference for the design of any operator interface for automatic machines, and, formerly, serve as a reference for the proposed approach.

In this section, we review the main principles in the literature on this topic. In particular, in Table I we recalled the main principles for the design of HMIs for machine operators [17]–[20], with respect to their effect on how the user is aided in perceiving and understanding what is happening at

TABLE I
DESIGN PRINCIPLES FOR HMIs: GUIDELINES TO THE ENHANCEMENT OF
USERS' INTERACTION, PERCEPTION AND COGNITION CAPABILITIES
(FROM [17]–[21])

Interaction	Perception	Cognition
Display technology consistent with HMI system environment	Colour scheme simplicity	Information simplicity
	Use of images	
	Showing trends	
Spatial interaction	Consistent visual and colour coding	Consistency with the operator's mental model
		Functional separation
Spare use of motion and sound		Information hierarchy
		Grouping of data together
		Multi-language considerations
		Multi-letter acronyms and abbreviations
		Using analog representations
		Feedback

the machine and how the interaction means can accommodate user's senses.

As regards the guidelines for means of interaction, defining input requirements will help decide which control technology is best suited for an application. Display technology choices should be dictated by the HMI system environment. In particular, the selection between legacy and touchscreen technologies has to be determined by factors such as exposure to shock, operator clothing, ambient illumination, and colour requirements. As well, appropriateness of control technologies (mainly cursor control and switches) depends on the HMI system, equipment, and application.

Spatial interaction refers to the fact that, by means of tangible computing, ubiquitous computing and augmented reality, a behavioural mapping can be established between the manipulation of the physical input device (e.g., the point and click of the mouse) and the resulting digital representation on the output device (the screen). On the contrary, in classical graphical user interfaces such mapping is relatively indirect and loosely coupled [22].

As regards motion and sound, their use should be limited since they drain the operator's attention, with the consequent risk that s/he will not be able to focus on what is important. The same applies to the use of colour.

As regards the need for simplicity, it applies to both perception and cognition. Simplicity in perception is finalized to make important information (such as abnormal conditions) stand out. As regards content, dialogues should not contain information that is irrelevant or rarely needed. Also the use of images affects both perception and cognition, since pictures and illustrations are a great way to quickly draw a user's attention. A well-designed visual element can communicate quickly and clearly complex ideas and information, which are retained for a long time by the user. The use of trends allows to improve level SA-3 since they help operators predict the future. Trends make it possible to see what is likely to happen next and predict whether the current state is continuing in the right direction or headed for a problem.

Furthermore, consistency is one of the most important usability principles for the design of HMIs. Consistency requires that dialogue syntax (language, colour, size, location, etc.) and semantics (behaviours associated to objects) are coherent in the interface. In other words, similar things should look and act similar; different things should look different. The strength of consistency lies in the fact that a consistent interface makes it easy for the operator to understand the system and know how to take actions or respond to problems.

Functional separation refers to the importance of allowing flexible use, thus making it possible to operate the user interface with different knowledge. The interface should be tailored for the user who is using the device most of the day, in order to help her/him to be as efficient as possible. In addition to functional separation, building an information hierarchy helps the operator to create a process overview and easily locate the needed level of details. Further, grouping information that belongs together helps the operator perceive important connections, thus facilitating the comprehension of the information shown on the display. As regards multi-language considerations, as far as possible, dialogues should be in the users' native language and not in a foreign language. This applies also to nonverbal elements like icons. Multi-letter acronyms and other abbreviations only work when all users understand their meaning. If not, the operator is presented a mismatch between the system and her/his own language and knowledge. The system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Using analog representations of data helps reducing cognitive load, since it relieves the user of doing the math and provides visible comparisons between measured values and normal ranges.

Finally, as regards feedback, the system should always inform the user about what it is doing and how it is interpreting the user's input. Specifically, feedback should not wait until an error situation has occurred: positive feedback should be provided as well, together with partial feedback, as information becomes available.

III. PROPOSED FRAMEWORK FOR ADAPTIVE INTERACTION SYSTEMS

The rationale behind the proposed approach is to allow the interaction system to fully adapt to the human operator, taking into account as much information as possible about the user, the environment and the current situation. To this end, we propose to provide adaptation according to three different levels, namely:

- perception: sensorial capabilities of the user are accommodated and information is presented accordingly. Thus, this level of adaptation refers to *how information* is presented.
- cognition: user's ability to understand information is considered. This is influenced by user's skills and current emotional status and the kind of interaction task. This level of adaptation refers to *what information* is presented to the user.
- interaction: depending on user's sensorial and physical capabilities, the best interaction means is selected to allow

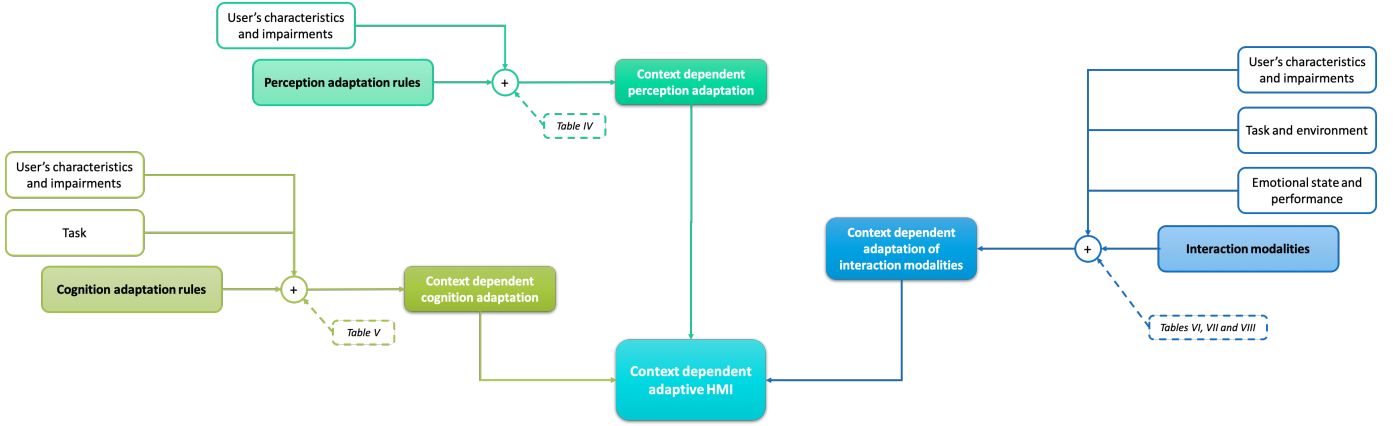


Fig. 1. Overview of the proposed approach to the design of adaptive industrial operator interfaces. Adaptation can be provided in terms of accommodation of user's perception and cognition capabilities and selection of the optimal interaction modality. General rules are provided such that they can be instantiated considering the characteristics of users and tasks to provide a context dependent adaptive HMI. References to the tables in the paper where the adaptation rules are listed are provided.

a smooth interaction. This level of adaptation refers to *how interaction* is enabled.

Figure 1 shows how the three levels of adaptation take into account several different aspects of the interaction scenario. In particular, as regards the human operator, her/his constitutional characteristics (e.g., age, language, education), possible impairments and emotional condition (e.g., being tired or fatigued or in panic) are all considered to tailor adaptation. Moreover, it is important to take into account also further information that, although not being strictly related to the user, influence her/his interaction and performances: this is the case of the kind of task the operator is working at and environmental conditions. These aspects affect the way adaptation of cognition and interaction modalities are selected.

To define a methodological approach that has general validity for any industrial application, general guidelines for each level of adaptation are discussed in this paper, building upon established principles for the design of HMIs known in the literature. This allows our framework to be valid for any application scenario in the industrial context. In practical applications, such rules need to be customized and/or selected considering the characteristics of operators and tasks as shown in Fig. 1, thus leading to a context dependent adaptive HMI. The collection of the universal patterns leads to a meta-HMI: in the paper, we use this term to denote a set of hardware and application independent rules and methods that describe how a HMI can be adapted to the characteristics and capabilities of the user. In other words, the meta-HMI collects the methodological background that guides the design of a smart HMI that adapts to the measured capabilities of the user and the current situation. The specific requirements and characteristics of each single application and operator instantiate the concrete implementation of the interface, as shown in Fig. 1. As a consequence, the meta-HMI is delivered in terms of a set of rules for the design of an adaptive user interface for a manufacturing system.

A. Measurement of user's capabilities

A key prerequisite of the proposed approach to the design of adaptive HMIs is that information about the user needs to be collected. The greater amount of information is available, the more customized can be the interface. Specifically, three main characteristics of the user should be monitored, since they affect the interaction with socio-technological systems, as discussed in [12]. Such characteristics include:

- innate and evolved skills and capabilities, such as age, education, working experience, computer skills, physical and cognitive impairments;
- the actual strain of the operator whilst working at the system, including mental fatigue and emotional information of the situational characteristics, when currently conducting the operating task;
- decay of performance of the operator (e.g., increasing number of errors and time to take decisions).

The first set of characteristics can be measured beforehand since they provide an off-line assessment of general characteristics of the user. The other two sets of characteristics need to be measured on-line, since they are modified by the interaction task. Further details can be found in [12] and [23]. In particular, in [12] user's characteristics that are relevant for the interaction have been identified, together with methods to measure them. Moreover, in [23] groups of users have been defined such that users of a group, despite having different individual capabilities and features, have common needs and response to the interaction with complex production systems. As a consequence, this defines clusters of users that have the same need for adaptation. Then, the adaptation rules discussed in the next paragraphs can be defined by considering such users' clusters, rather than addressing specific individual user's needs.

The user's characteristics determine all together the way the HMI should be adapted to the current condition. As will be clarified in the next sections, constitutional characteristics influence all the three levels of adaptation since they determine how and what information should be presented and which is

TABLE II
RELATIONSHIP BETWEEN USER'S CHARACTERISTICS AND THE THREE
LEVELS OF ADAPTATION.

	Perception adaptation	Cognition adaptation	Interaction adaptation
Constitution	✓	✓	✓
Strain and emotions	✓	✓	✓
Performance		✓	✓

the best interaction modality. Such settings can be updated during the interaction if mental strain or a decay of performance is detected, as summarized in Table II.

B. Relationship with situation awareness

It is worthwhile remarking that the design of adaptive HMIs according to the proposed three-level scheme allows to improve operator's situation awareness. Indeed, user interfaces are a key component in facilitating situation awareness, which refers to user's understanding of current situation and promptness to take proper action when needed.

Situation awareness can be formally expressed in terms of three steps that the operator must go through [24]:

- SA-1** S/he must perceive important data;
- SA-2** S/he must comprehend the current situation;
- SA-3** S/he must predict the future status.

By adapting the HMI in terms of adaptation of perception, cognition and interaction modalities as presented in Fig. 1, the needs of the three levels of situation awareness are accommodated. In particular, adaptation at perception and interaction levels helps the user to perceive the important data in the HMI in clearer and easier way, thus increasing level SA-1. To infer relevant information from presented data (level SA-2), the HMI should provide a clear depiction of the current state of the machine so that the user can easily understand what is going on and what s/he is expected to do (level SA-3). This is done at the cognition adaptation level. The relationship between the three levels of situation awareness and the proposed approach is summarized in Fig. 2.

Ultimately, the proposed framework is intended to guide the design of adaptive HMIs that, accommodating user's capabilities and skills, enjoy two interconnected advantages. On the one side, the three-level scheme for adaptation allows to improve the situation awareness of operators while interacting with the machine, thus ultimately improving their efficiency. On the other side, it is expected that a better interaction is perceived by the user, thus increasing the usability of the interaction system. As a result, interaction tasks can be accomplished in an easier and not frustrating way for the user. Moreover, also vulnerable users, such as the elderly or those with low education or physical and/or cognitive impairments are enabled to use them.

IV. PERCEPTION ADAPTATION

Two main causes might affect the perception of important information in the HMI: i) erroneous presentation of content, and ii) limitations in user's perceptive capabilities. Both these phenomena lead to a decay of operator's performance during

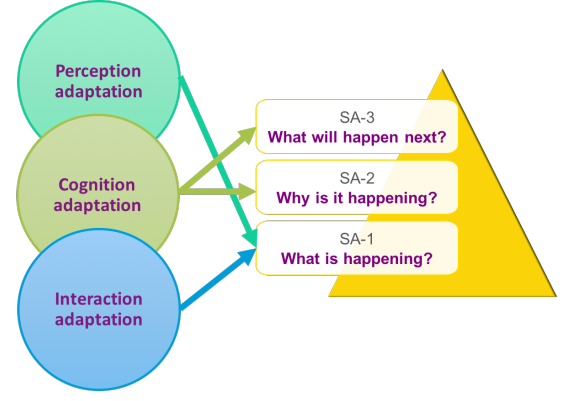


Fig. 2. How the intended adaptation scheme affects the three levels of situation awareness.

the interaction, since level SA-1 cannot be properly achieved. To avoid these adverse conditions, two different levels of design should be considered:

- 1) the perception related principles considered in Sec. II should be implemented to address the first issue;
- 2) user's perception capabilities should be explicitly taken into account, in order to accommodate her/his sensorial impairments.

Thus, the first level is independent of operators' capabilities and features, and no specific adaptation can be foreseen. Indeed, the principles listed in Table I guide the design of operator interfaces for production or process control systems. Although they take into account the users' needs and point of view, according to the anthropocentric design approach, they are general with respect to any user and do not tackle the specific needs of users, in particular of vulnerable ones. The second level requires that the optimal way of presenting information should be tailored on the user, thus providing user targeted adaptation. Specifically, by perception adaptation we refer to the need of accommodating to operator's sensorial impairments in order to allow her/him to interact with the HMI with a limited (or null, in the optimal case) decay of performance due to impairments. As a consequence, the amount of perception adaptation strictly depends on the capabilities of each and every user.

In this regard, guidelines more specific than those in Table I are required. To this end, the universal design approach turns out to be useful. In particular, universal design aims at devising systems and environments that can be *inherently* accessed, understood and used to the greatest extent possible by all people regardless of their age, size, ability or disability [25]. Specifically, in the framework of universal design, a set of seven principles has been derived "to evaluate existing designs, guide the design process and educate both designers and consumers about the characteristics of more usable products and environments" [25]. Each of these principles comes with a set of guidelines that translates them into practical actions to take in order to make interaction systems accessible to all users. Table III reports the universal design principles and the associated guidelines for implementation.

With respect to perception adaptation, the following guide-

TABLE III

PRINCIPLES FOR UNIVERSAL DESIGN AND ASSOCIATED GUIDELINES FOR IMPLEMENTATION [26].

Principle	Guidelines
Equitable Use The design is useful and marketable to people with diverse abilities	<ol style="list-style-type: none"> 1. Provide the same means of use for all users: identical whenever possible; equivalent when not. 2. Avoid segregating or stigmatizing any users. 3. Provisions for privacy, security, and safety should be equally available to all users. 4. Make the design appealing to all users.
Flexibility in Use The design accommodates a wide range of individual preferences and abilities	<ol style="list-style-type: none"> 1. Provide choice in methods of use. 2. Accommodate right- or left-handed access and use. 3. Facilitate the user's accuracy and precision. 4. Provide adaptability to the user's pace.
Simple and Intuitive Use Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level	<ol style="list-style-type: none"> 1. Eliminate unnecessary complexity. 2. Be consistent with user expectations and intuition. 3. Accommodate a wide range of literacy and language skills. 4. Arrange information consistent with its importance. 5. Provide effective prompting and feedback during and after task completion.
Perceptible Information The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities	<ol style="list-style-type: none"> 1. Use different modes (pictorial, verbal, tactile) for redundant presentation of essential information. 2. Provide adequate contrast between essential information and its surroundings. 3. Maximize "legibility" of essential information. 4. Differentiate elements in ways that can be described (i.e., make it easy to give instructions or directions). 5. Provide compatibility with a variety of techniques or devices used by people with sensory limitations.
Tolerance for Error The design minimizes hazards and the adverse consequences of accidental or unintended actions	<ol style="list-style-type: none"> 1. Arrange elements to minimize hazards and errors: most used elements, most accessible; hazardous elements eliminated, isolated, or shielded. 2. Provide warnings of hazards and errors. 3. Provide fail safe features. 4. Discourage unconscious action in tasks that require vigilance.
Low Physical Effort The design can be used efficiently and comfortably and with a minimum of fatigue	<ol style="list-style-type: none"> 1. Allow user to maintain a neutral body position. 2. Use reasonable operating forces. 3. Minimize repetitive actions. 4. Minimize sustained physical effort.
Size and Space for Approach and Use Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility	<ol style="list-style-type: none"> 1. Provide a clear line of sight to important elements for any seated or standing user. 2. Make reach to all components comfortable for any seated or standing user. 3. Accommodate variations in hand and grip size. 4. Provide adequate space for the use of assistive devices or personal assistance.

lines of universal design call for deliberate consideration:

- Accommodate right- or left-handed access and use,
- Facilitate the user's accuracy and precision,
- Provide adaptability to the user's pace,
- Use different modes (pictorial, verbal, tactile) for redundant presentation of essential information,
- Provide adequate contrast between essential information and its surroundings,
- Maximize "legibility" of essential information,
- Provide compatibility with a variety of techniques or devices used by people with sensory limitations,
- Allow user to maintain a neutral body position,
- Use reasonable operating forces,
- Minimize sustained physical effort,
- Provide a clear line of sight to important elements for any seated or standing user,

TABLE IV

DESIGN PRINCIPLES FOR PERCEPTION ADAPTATION FOR COMMON PHYSICAL IMPAIRMENTS.

	Motoric impairments	Visual impairments	Auditive impairments
Accommodate right- or left-handed access and use	✓		
Facilitate the user's accuracy and precision	✓	✓	✓
Provide adaptability to the user's pace	✓		
Use different modes (pictorial, verbal, tactile) for redundant presentation of essential information		✓	✓
Provide adequate contrast between essential information and its surroundings		✓	✓
Maximize "legibility" of essential information		✓	✓
Provide compatibility with a variety of techniques or devices used by people with sensory limitations	✓	✓	✓
Allow user to maintain a neutral body position	✓		
Use reasonable operating forces	✓		
Provide a clear line of sight to important elements for any seated or standing user	✓	✓	
Make reach to all components comfortable for any seated or standing user	✓		
Accommodate variations in hand and grip size	✓		
Provide adequate space for the use of assistive devices or personal assistance	✓		

- Make reach to all components comfortable for any seated or standing user,
- Accommodate variations in hand and grip size,
- Provide adequate space for the use of assistive devices or personal assistance.

Such rules should be applied depending on user's impairments and their severity. Although a thorough classification of possible perception impairments cannot be provided, the most common impairments affecting operators working in industrial plants are motoric limitations, and visual and auditive deficits [11]. Table IV summarizes which principles of universal design should be implemented to address the special needs of subjects with such physical impairments.

V. COGNITION ADAPTATION

This section presents the rules and methodologies for adapting the HMIs to the cognitive capabilities of the user. Specifically, this refers to the fact that different users might have different abilities to understand a given piece of information, or the abilities of each user might change over time, based on her/his current emotional state, on the task s/he is performing, or on her/his level of experience. As anticipated in Fig. 1 and Table II, the way the HMI adapts to cognitive capabilities depends on the interaction task, constitutional characteristics (mainly education, experience and cognitive impairments) and incoming mental fatigue or decay of performance.

Adapting the way information is presented to the (current) cognitive capabilities of the user represents then an effective measure to increase the possibility, for the user, to correctly understand and elaborate such information (level SA-2 and level SA-3), thus increasing the effectiveness of the overall interaction system.

In the following, we will first introduce the proposed adaptation rules. The suitability of these rules depends on the characteristics of the task at hand. Hence, a high-level classification of interaction tasks is needed to show how the rules for cognition adaptation can be applied in industrial practice.

A. Rules for cognition adaptation

Starting from the general design principles for HMIs, described in Sec. II, we derived a set of four rules for cognition adaptation.

R1 - Information selection: When considering complex systems, the amount of data that are collected and monitored is typically very large. The overall state of the system is, in fact, defined by the interplay and superposition of a large set of quantities, related to the task, to the machines, to the environment, and to the user. While all these data are important for the correct operation of the system, and/or for logging purposes, the user typically needs to have direct access to only a subset of such data, or to the results of pre-processing operations.

In particular, the quantity and the kind of information that is presented to the user needs to be selected by the system, based on her/his cognitive status. Specifically, in the presence of cognitive difficulties, the amount of data that are shown to the user needs to be reduced and, in some circumstances, pre-processed (e.g. aggregated data, averaged data, merged data, etc.). This leads to reducing the effort required to the user for understanding the most relevant information.

R2 - Alarm organization: Machines are generally equipped with self-diagnosis tools, which are able to elaborate acquired data to assess the current status of the overall system. Mal-functioning conditions are then identified: alarm and alert systems are exploited to provide the user with warning and error messages, to make her/him aware of the kind of problem that is currently taking place.

Clearly, problems with different priority may arise, and generate an alarm or a warning: often, several minor issues can happen simultaneously, causing a large number of simultaneous alarms or warnings. The quantity and the kind of alarms that are presented to the user need to be adapted, based on her/his cognitive status. Specifically, in the presence of cognitive difficulties, low-priority alarms (i.e., those alarms representing non-critical issues) need to be hidden, to let the user focus on high-priority ones, which represent more critical situations that can not be neglected.

R3 - Guidance: When interacting with complex machines and systems, the user is often required to follow complex and long procedures and to take decisions based on the current situation.

In order to help users subject to cognitive difficulties, proper guidance procedures need to be implemented. In particular,

guidance can be implemented in different manners and on different levels, e.g. providing suggestions when decisions have to be made, indicating the next action to be performed, or providing a complete list of activities to be fulfilled. An example in this regard is provided in Sec. VII.

R4 - Functionality enabling: Complex machines and systems generally include a large variety of functionalities and operational modes, which allow to perform different operations, ranging from common activities to advanced functions or maintenance operations. While basic functionalities are typically easier to deal with, advanced functionalities are often more difficult to utilize, and are seldom necessary to access.

When the user is experiencing cognitive difficulties, the system needs to reduce the number of available functionalities, in order to avoid confusion, to simplify the task for the user, and to reduce the possibility of mistakes.

B. High-level task classification

The user can interact with the system during several kinds of interaction tasks. The application of the rules for cognition adaptation presented in Sec. V-A depends on the specific kind of activity performed by the operator. For this purpose, the following high-level classification of the interaction tasks is introduced.

Procedural: Procedural tasks include all those tasks for which an ordered sequence of activities is required, and needs to be fulfilled by the user. Examples of procedural tasks are represented by set-up operations, reconfiguration operations, or ordinary maintenance procedures.

All these activities are characterized by (often very long) lists of activities the user needs to complete. Main difficulties arise then in the necessity, for the user, to remember the correct sequence of operations, and to take decisions based on the current status of the system.

Supervision: Supervision tasks include the activities that are needed to supervise a complex, and possibly large, system, which may include more than one machine. Even when considering automated machines, human supervision is generally necessary, to assess, monitor, and control the overall status of the system.

When dealing with very complex systems, the amount of information to be considered, simultaneously, is very large. This can generate difficulties in the user, who may be overloaded with data, and may have difficulties in understanding the relevant pieces of information.

Extraordinary maintenance: Extraordinary maintenance procedures need to be performed when unpredictable and/or infrequent situations take place. Examples are represented by procedures to replace broken or malfunctioning parts, or to recover from anomalies or alarm situations.

Being these tasks not frequently executed, it can be difficult, for the user, to correctly know, remember and apply the desired sequence of actions.

C. Application of the rules for cognition adaptation

Table V shows how the rules for cognition adaptation presented in Sec. V-A can be applied to the high-level task category introduced in Sec. V-B.

TABLE V
RULES FOR COGNITION ADAPTATION FOR HIGH-LEVEL TASKS.

	R1: Information selection	R2: Alarm organization	R3: Guidance	R4: Functionality enabling
Procedural			✓	✓
Supervision	✓	✓		✓
Extraordinary maintenance	✓	✓	✓	✓

When considering *procedural* tasks, cognition adaptation consists in providing the user with a sufficient level of help in following the correct procedure. This is achieved providing information about the list of activities to be performed (R3) to guide the user, preventing wrong choices. At the same time, advanced functionalities may be enabled or disabled (R4), based on the cognitive status of the user, to forbid dangerous actions or excessively difficult operations.

When considering *supervision* tasks, cognition adaptation consists in defining the correct amount and quality of presented information, and possible actions to be taken. This is obtained properly selecting what data are shown, in each specific situation, to the user (R1), presenting opportunely aggregated data (to make them easier to understand), or hiding redundant or unnecessary information. At the same time, for users experiencing cognitive difficulties, only high priority alarms or warnings need to be shown (R2), so that the user can focus on the most relevant issues, without being distracted by the less important ones. Furthermore, when supervising a very complex system, the number of available functionalities need to be tuned (R4), reducing the possibilities for cognitively overloaded users: this simplifies the task, reducing the possibility of making mistakes.

Extraordinary maintenance tasks are inherently very complex, in particular when the user is experiencing cognitive difficulties. To help the user in these tasks, it is necessary to properly select the kind and amount of information to be shown (R1), presenting opportunely aggregated data (to make them easier to understand), or hiding redundant or unnecessary information. Along the same lines, also alarms and warnings need to be selected, showing only the high priority ones (R2), to let the user focus on the most relevant pieces of information. Since extraordinary maintenance tasks are performed infrequently by the user, proper guidance (R3) needs to be provided, helping the user to follow the correct procedures and make the correct choices. At the same time, opportunely enabling or disabling advanced functionalities (R4) reduces the choices the user has to make, thus decreasing the possibility of making mistakes.

VI. ADAPTATION OF INTERACTION MODALITIES

This section introduces the approach to adapt how the user can interact with the HMI. The interaction modalities that the operator can use have to match: i) her/his constitution and disposition as well as qualification and competence, ii) the requirements of the task and the environment, and iii) the current state of the operator (i.e., mood and mental fatigue)

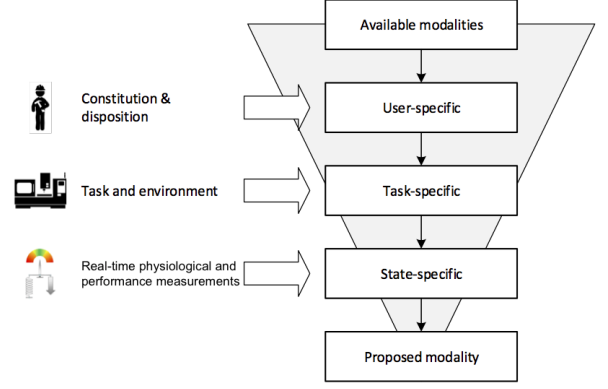


Fig. 3. Approach for the selection of interaction modalities.

and the measurements that describe the interactions with the user interface over time (e.g., performance metrics, number of errors, time to take a decision, etc.). Providing different interaction modalities ensures that a user can apply an interaction modality that allows a satisfying and efficient interaction with the HMI (see, e.g., [27]). Thereby, it is possible to realize the universal design idea to provide access to the HMI to all people regardless of age, size, and ability, or disability.

In the following, we consider three factors for the selection of the interaction modality. First, static factors that are determined by the user's constitution and disposition and the task and environmental requirements are taken into account to filter modalities that are not applicable for the present user and task. This subset is further narrowed down by dynamic measurements about the user's emotional state (real-time physiological measurements) and performance (real-time performance measurements). Figure 3 provides a schematic overview of the approach for the selection of interaction modalities.

A. Interaction modalities

Interaction techniques are typically separated into modalities that classify a communication channel between the user and the computer [28]. Three main modalities, i.e., visual, physical, and auditive, are considered.

IM1 - Visual interaction modalities: They rely on a camera that records the environment and recognizes and interprets patterns. A common example is gesture-based interaction where movements of the user are recorded and detected. Gesture-based interaction has not found widespread application in industrial settings yet. A research application from the domain of human-robot interaction where gestures are used to select a package that a lifting device should pick up is presented in [29]. As regards output, visual interaction mainly relies on monitors and lights.

IM2 - Physical interaction modalities: They recognize physical manipulations of the interaction device. Exemplary input devices are hardware buttons, pointing devices (e.g., mouse, trackball, touchscreen, or stylus) or keyboards. This modality represents the most frequently applied modality in

industrial HMIs. Today's machinery is mostly controlled by hardware buttons and touchscreens, as it is recommended by industrial standardization committees. Additionally, haptic devices can be used to provide tactile and force in- and output.

IM2 - Auditive interaction modalities: Auditive interaction is based on acoustic information. This typically includes speech-based interfaces that allow controlling an interaction system using speech in- and output. Such systems are applied in specific industrial applications such as commissioning [30]. Many research works target this interaction technique, especially for operator support during manual tasks like maintenance [31].

B. User's characteristics and impairments

The interaction modality has to match the disposition and constitution of the operator. Possible limitations of the operator may preclude the effective application of some interaction modalities and yield a bad user interface. Operators with vision declines, for instance, cannot use a touch interface effectively. A speech-based interface may be offered for this user group instead.

The capabilities of the user can be mapped to the requirements of the interaction modalities to arrive at suggestions for each user group. Table VI shows the interaction modalities mostly suited for vulnerable users having different limited capabilities. As regards visual interaction, the use of input methods that require physical movements is not advisable for elderly, since their movement capabilities decline, making precise movements more difficult and more arduous [32]. Moreover, in- and output techniques that rely on the sense of touch are not suitable for operators with disabilities of the upper limbs. Keyboards with textual input are not advisable for operators with low literacy and problems of performing accurate movements using a mouse are suggested by the declining motoric capabilities of elderly [2]. Of course, in- and output techniques that rely on the sense of seeing are not suitable for blind operators. Finally, as regards auditive interaction, it is evident that in- and output techniques that rely on the sense of hearing are not suitable for deaf operators. Additionally, since the sense of hearing of elderly people declines [32], using auditory output is not advisable or needs to be adapted to the capabilities of the individual. Speech input is an advisable input modality for people with low literacy. Moreover, the use of auditory output is a vital alternative for the rendition of content that blind or dyslectic users cannot perceive.

C. Task and environment

The characteristics of the task and the environment also affect the selection of an appropriate interaction modality. With respect to the selection of the best interaction modality, it is relevant to consider the following types of tasks.

Manual tasks: They require manipulations of the physical components of the machine. Such tasks require visual attention of the operator.

Observational tasks: These tasks require the operator to observe the machine condition in response to a physical action.

Setup tasks: They concern the programming and setup of the machine, mostly using the HMI.

Supervision tasks: These tasks concern ensuring whether the machine operates in normal boundaries.

Each task has distinct requirements regarding the appropriate interaction modality. In Table VII we suggest different interaction modalities for manual, observational, setup and supervision tasks.

For manual tasks where the operator is involved in physical activities, the provision of an auditive interface is recommendable. Providing an auditive interface ensures no distraction from the manual task and allows the operator to, for instance, stay at her/his location at the machine and interact from a distance. Input on a touchscreen can be offered if the provision of graphical information is necessary. However, this modality may interfere with the manual tasks of the operator. Similar constraints are present for observational tasks. In that case visual output may be required by the task and cannot be replaced with auditive information. Supervision tasks impose no restrictions on the interaction modality.

Environmental characteristics need to be considered as well to choose the correct interaction modality. Typically, environmental characteristics include climate, noise and lighting, vibration, and the presence of dust, smoke or other emissions. A high level of noise impedes robust speech in- and output. A hazardous environment that demands visual attention motivates the use of speech-based interaction to minimize distraction. Furthermore, the presence of vibrations precludes the application of interaction devices like touchscreens or a mouse. Further requirements of the environmental conditions on the choice of a suitable interaction method are described by norms (e.g., [33]).

D. Emotional state and performance

The third influence on the interaction adaptation is the current emotional state of the user and her/his performance during interaction with the machine. This can be tracked by measuring performance indicators such as time for decisions, executions steps for the task, mistakes, and redundancies. Different interaction techniques have a different sensitivity for stressful states. Furthermore, interaction techniques that were error-prone with a given user in the past should be discouraged in critical states.

1) *Emotional state:* If operator's fatigue and mood can be measured non invasively during interaction (see, e.g., [11]), then it should be considered in the choice of an appropriate interaction modality. Gesture-based interaction should only be considered in situations with low fatigue of the operator. High mental stress precludes input techniques like speech since the error rate with such techniques increases with mental fatigue. Physical interaction is appropriate in all states of the operator. In Table VIII we summarize the levels of mental fatigue and the proposed adaptations of the interaction modalities.

2) *Performance:* The real-time performance measurements (e.g., execution time or mistakes) indicate the performance of a user with the HMI and an interaction modality. The effectiveness of different interaction techniques can be compared measuring performances during interaction. Based on

TABLE VI
SELECTION OF INTERACTION MODALITY FOR THE USER'S CAPABILITIES
(✓ = RECOMMENDED, ✗ = NOT RECOMMENDED, 0 = PARTIALLY RECOMMENDED).

	Elderly	Illiterate	Low computer skills	Impairments		
				Motoric	Visual	Auditive
IM1: Visual interaction	✗	✓	0	✓	✗	✓
IM2: Physical interaction	0	0	✓	✗	✓	✓
IM3: Auditive interaction	0	✓	✓	✓	✓	✗

TABLE VII
SELECTION OF INTERACTION MODALITY BY TASK TYPE
(✓ = RECOMMENDED, ✗ = NOT RECOMMENDED, 0 = PARTIALLY RECOMMENDED).

	Manual tasks	Observational tasks	Setup tasks	Supervision tasks
IM1: Visual interaction	✗	✓	0	✓
IM2: Physical interaction	0	✓	✓	✓
IM3: Auditive interaction	✓	✓	✓	✓

this, interaction modalities that have proven to be error-prone in comparable situations can be discouraged for future interactions of a user with the HMI.

VII. EXAMPLES OF APPLICATION

In this section we present some examples of how the proposed meta-HMI can be applied to support users in accomplishing procedural, supervision and extraordinary maintenance tasks.

A. Procedural tasks

As an example of procedural tasks, we consider the need to set a machine up with proper equipment required to run a given working task. In particular, in the following and in Fig. 4, we refer to the case of a milling machine to be equipped with the cutting tools (which have to be mounted on the tool warehouse) needed to run the selected milling tasks. In most common milling machines, there is no direct communication between the physical warehouse and the virtual one displayed on the HMI. Thus, the operator has to physically mount the tools on the machine and, additionally, to configure the tool warehouse on the HMI, entering for each position of the warehouse the tool that is mounted on the machine.

Depending on the level of expertise of the operator, this activity can be performed with different amount of guidance by the HMI. With reference to the examples in Fig. 4, an

TABLE VIII
SELECTION OF INTERACTION MODALITY FOR THE LEVEL OF MENTAL FATIGUE (✓ = RECOMMENDED, ✗ = NOT RECOMMENDED, 0 = PARTIALLY RECOMMENDED).

	High mental fatigue	Average mental fatigue	Low mental fatigue
IM1: Visual interaction	✗	0	✓
IM2: Physical interaction	✓	✓	✓
IM3: Auditive interaction	✗	0	✓

expert operator, being familiar with the tools and their codes, might prefer to select the tools by selecting their code among those of all available tools (Fig. 4(a)). On the other side, least-experienced operators might not recognize tools by their codes and need to upload them on the HMI by selecting their features (Fig. 4(b)). Additionally, operators with physical (visive) or cognitive impairments might need further guidance in the selection and appreciate step-by-step guidance (Fig. 4(c)).

B. Supervision tasks

As an example of supervision tasks, we consider the need to manage fleets of automated guided vehicles (AGVs) operated along production lines and in partially structured and highly dynamic warehouses. In such environments, autonomous vehicles share the working area with human operators and manually guided vehicles. In this scenario, while movements of vehicles and traffic can be managed automatically by dynamically assigning tasks to agents, it is important that the supervision of the fleet is in charge of a human operator who can cope with unpredictable situations and unforeseen faults.

Different tasks, requiring different capabilities, are involved to this end, ranging from interventions on vehicles to assignment of priorities to interventions. In particular, experienced workers are able to understand the meaning of working parameters of the fleet and, hence, assess the overall status. To this end, they should be allowed to view raw values and trends of specific parameters (e.g., covered distance, working time, temperature, pressure) and, based on them, schedule extraordinary maintenance interventions, postpone incoming actions and change priorities to scheduled ones. These tasks are suited also to expert operators who are unable to perform physical interventions on vehicles, due to physical impairments or aging.

On the contrary, least expert operators, who have poor knowledge of the dynamics underlying a complex plant, should be shown only the list of interventions under their responsibility, together with an integrated support tool for guided procedures (such as the one presented hereafter).

Finally, cognitively impaired workers could be enrolled to assign interventions to operators and monitor the execution of scheduled tasks.

C. Extraordinary maintenance tasks

As regards tasks related to extraordinary maintenance and troubleshooting, they are likely to be critical since they might be accompanied by machine failure causing anxiety in the operator who is in charge of understanding which action to take. Moreover, extraordinary maintenance and troubleshooting tasks happen seldom and it is very likely that novice users are not familiar with them. On the other side, for expert users, these tasks are quite repetitive and, hence, little guidance is desired. As a consequence, in agreement with Table V, it is important to understand when operators need step-by-step guidance, depending on both their experience and emotional condition.

A proper solution in this regard is given by MyAID, an interactive troubleshooting system that consists in a guided



Fig. 4. Examples of an adaptive HMI for machine setup operations.

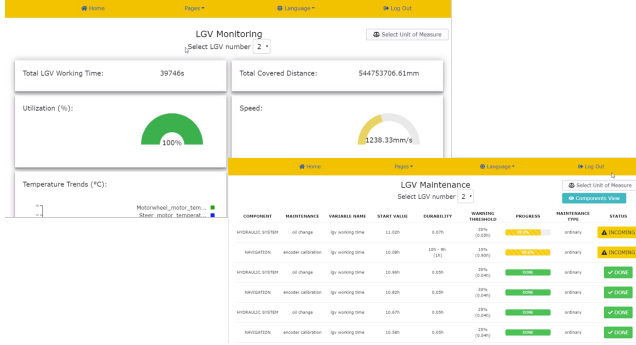


Fig. 5. Example of user interface for the management of fleets of AGVs. Rules R1 and R4 for cognition adaptation are implemented to accommodate users with different experience level (background: expert users, foreground: operators without decisional roles).

procedure for the identification of machine failures and their resolution [34]. As shown in Fig. 6(a), its aims are twofold: on the one side, it guides users to identify the current fault by means of a sequence of questions about the state of the machine; on the other side, it provides step-by-step procedures to solve the detected fault.

Integrating such a support tool in the HMI allows to address the needs of fatigued or inexperienced users; however, it should be made available upon recall, in order to not interfere with expert operators who do not need support. Different levels of assistance can be provided, depending on user's characteristics and capabilities. Operators with no experience or who are experiencing high levels of mental fatigue might benefit from using MyAID in combination with augmented reality for immersive assistance. For those with a low level of experience, running MyAID on a portable device, such as a tablet, might be sufficient, as shown in Fig. 6(b); whereas those with higher experience should be provided with shortcuts providing direct access to specific pieces of information: for example, an expert operator is able to recognize the current fault at a glance and might need to give a quick look to the solving procedure.

VIII. CONCLUSION

In this paper we presented a general approach to the design of industrial HMIs that adapt to the skills and capabilities of human operators. The goal is that of relieving the increasing complexity of modern production systems by providing operators with usable interfaces, enabling a smooth and easy interaction. The proposed approach consists of general guidelines,

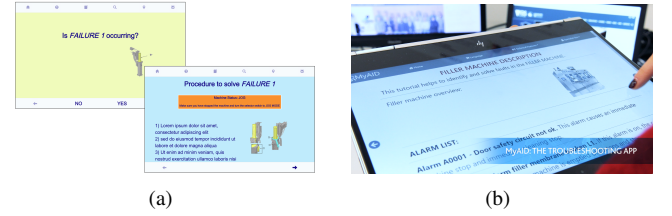


Fig. 6. MyAID is a support tool that provides varying levels of guidance to operators involved in extraordinary maintenance and troubleshooting tasks.

which are independent of the application and the hardware, thus constituting a meta-HMI. The specific requirements and characteristics of each single application and user define the specific implementation of the interface and lead to a context dependent adaptive HMI.

The proposed approach consists in three different levels: adaptation of perception, i.e., how information is presented, cognition, i.e., what information is presented, and interaction, i.e., how interaction is enabled. For each level, general guidelines for adaptation were provided, building upon principles for the design of HMIs known in the literature. This allows our framework to hold true for any application scenario in the industrial context. In practical application, the rules of the meta-HMI need to be customized and/or selected considering the characteristics of operators and tasks, thus leading to a context dependent adaptive HMI. Instructions on how such rules accommodate characteristics of the user and the task were provided. Moreover, in the paper we presented a couple of examples of how the proposed adaptation patterns can be applied to the case of procedural and extraordinary maintenance tasks.

Future works include a thorough experimental validation of the proposed approach. To this end, experiments will be carried out in the framework of the EU project *Smart and adaptive interfaces for INCLUSIVE work environment (INCLUSIVE)* [35]. As part of the project, three industrial use cases have been selected as representative of a wide area of interest for industry in Europe [36], in terms of both production requirements and involved operators. Moreover, future works will regard also the development of a framework for the measurement of user's characteristics. Indeed, in order to provide the optimal level of adaption following the rules presented in this paper, it is important to achieve a complete and accurate characterization of the user. In this regard, user's characteristics that are

relevant for the interaction need to be identified, together with methods to measure them.

ACKNOWLEDGEMENT

The research is carried out within the "Smart and adaptive interfaces for INCLUSIVE work environment" project, funded by the European Unions Horizon 2020 Research and Innovation Programme under grant agreement N. 723373.

The authors would like to thank Michela Liberale and Giulia Lotti for providing the implementation of the presented examples of application.

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] N. Schneider, J. Wilkes, M. Grandt, and C. M. Schlick, "Investigation of input devices for the age-differentiated design of human-computer interaction," in *Proc. Human Factors and Ergonomics Soc. Annu. Meeting*, vol. 52, no. 2. SAGE Publications, 2008, pp. 144–148.
- [3] Eurofound, "Sixth european working conditions survey – overview report (2017 update)," Publications Office of the European Union, Luxembourg, Tech. Rep., 2017.
- [4] D. A. Norman, *The design of everyday things: Revised and expanded edition*. Basic books, 2013.
- [5] 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.
- [6] F. Jammes and H. Smit, "Service-oriented paradigms in industrial automation," *IEEE Trans. Industrial Informatics*, vol. 1, no. 1, pp. 62–70, 2005.
- [7] 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.
- [8] D. Mourtzis and E. Vlachou, "A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance," *Journal of manufacturing systems*, vol. 47, pp. 179–198, 2018.
- [9] L. Balme, A. Demeure, N. Barralon, J. Coutaz, and G. Calvary, "CAMELEON-RT: A software architecture reference model for distributed, migratable, and plastic user interfaces," in *European Symposium on Ambient Intelligence*. Springer, 2004, pp. 291–302.
- [10] F. Paternò, C. Mancini, and S. Meniconi, "ConcurTaskTrees: A diagrammatic notation for specifying task models," in *Human-Computer Interaction INTERACT'97*. Springer, 1997, pp. 362–369.
- [11] 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.
- [12] 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.
- [13] F. Loch, G. Koltun, V. Karaseva, D. Pantförder, and B. Vogel-Heuser, "Model-based training of manual procedures in automated production systems," *Mechatronics*, 2018.
- [14] F. Loch, S. Böck, and B. Vogel-Heuser, "Adapting virtual training systems for industrial procedures to the needs of older people," in *17th IEEE Int. Conf. Industrial Informatics (IEEE INDIN)*, 2019.
- [15] G. Schirner, D. Erdogmus, K. Chowdhury, and T. Padir, "The future of human-in-the-loop cyber-physical systems," *Computer*, vol. 46, no. 1, pp. 36–45, 2013.
- [16] J. Zhou, P. Li, Y. Zhou, B. Wang, J. Zang, and L. Meng, "Toward new-generation intelligent manufacturing," *Engineering*, vol. 4, no. 1, pp. 11–20, 2018.
- [17] J. Nielsen, *Usability engineering*. Elsevier, 1994.
- [18] P. Gruhn, "Human machine interface (HMI) design: the good, the bad, and the ugly (and what makes them so)," in *66th Annu. Instrumentation Symp. for the Process Industries*, vol. 25, 2011.
- [19] "Building an HMI that works: New best practices for operator interface design," Opto 22, Tech. Rep., 2014.
- [20] "Top 10 tips for operator interface design," Eaton Corp., Application Note, 2007.
- [21] "Design considerations for effective human machine interface systems." [Online]. Available: https://eao.com/fileadmin/documents/PDFs/en/08_whitepapers/EAO_WP_HMI-Systems_EN.pdf
- [22] E. Sharlin, B. Watson, Y. Kitamura, F. Kishino, and Y. Itoh, "On tangible user interfaces, humans and spatiality," *Personal and Ubiquitous Computing*, vol. 8, no. 5, pp. 338–346, 2004.
- [23] 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.
- [24] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *Human factors*, vol. 37, no. 1, pp. 32–64, 1995.
- [25] "What is Universal Design." [Online]. Available: <http://universaldesign.ie/What-is-Universal-Design/>
- [26] B. R. Connell, M. Jones, R. Mace, J. Mueller, A. Mullick, E. Ostroff, J. Sanford, E. Steinfeld, M. Story, and G. Vanderheiden, "The principles of universal design," The Center for Universal Design, NC: North Carolina State University, Tech. Rep., 1997.
- [27] L. Gaouar, A. Benamar, O. Le Goer, and F. Biennier, "HCIDL: Human-computer interface description language for multi-target, multimodal, plastic user interfaces," *Future Computing and Informatics Journal*, vol. 3, no. 1, pp. 110–130, 2018.
- [28] V. Villani, F. Pini, F. Leali, and C. Secchi, "Survey on human-robot collaboration in industrial settings: Safety, intuitive interfaces and applications," *Mechatronics*, vol. 55, pp. 248–266, 2018.
- [29] L. Overmeyer, F. Podszus, and L. Dohrmann, "Multimodal speech and gesture control of AGVs, including EEG-based measurements of cognitive workload," *CIRP Annals-Manufacturing Technology*, vol. 65, no. 1, pp. 425–428, 2016.
- [30] J. De Vries, R. de Koster, and D. Stam, "Exploring the role of picker personality in predicting picking performance with pick by voice, pick to light and RF-terminal picking," *Int. J. Production Research*, vol. 54, no. 8, pp. 2260–2274, 2016.
- [31] J. Fischer, D. Pantförder, and B. Vogel-Heuser, "Improvement of maintenance through speech interaction in cyber-physical production systems," in *IEEE 15th Int. Conf. Industrial Informatics (INDIN)*, July 2017, pp. 290–295.
- [32] K. Chen and A. H. Chan, "A review of technology acceptance by older adults," *Gerontechnology*, vol. 10, no. 1, pp. 1–12, 2011.
- [33] ISO/TC 159/SC 4, "ISO 9241-420:2011 Ergonomics of human-system interaction," ISO, Tech. Rep.
- [34] V. Villani, N. Battilani, G. Lotti, and C. Fantuzzi, "MyAID: a troubleshooting application for supporting human operators in industrial environment," *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 391 – 396, 2016.
- [35] "Smart and adaptive interfaces for INCLUSIVE work environment." [Online]. Available: <http://www.inclusive-project.eu>
- [36] L. Sabattini, V. Villani, J. N. Czerniak, A. Mertens, and C. Fantuzzi, "Methodological approach for the design of a complex inclusive human-machine system," in *13th IEEE Conf. Automation Science and Engineering (CASE)*. IEEE, 2017, pp. 145–150.