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FOREWORD

Twin transformation aims at synergetic interaction and mutual reinforcement of the digital and sustainable transformation of manufacturing enterprises and associated value-added chains. This introduces several challenges and opportunities for cross- and interdisciplinary research on establishing sustainable, smart, resilient and human-centered manufacturing and supply chain of the future.

Information Control Problems in Manufacturing (INCOM) is a triennial symposium organized by the International Federation on Automatic Control (IFAC). The IFAC Coordinating Committee on Cyber-Physical Manufacturing Enterprises (CC 5) sponsors INCOM, which equally involves Technical Committees on Manufacturing Plant Control (TC 5.1), Management and Control in Manufacturing and Logistics (TC 5.2), Integration and Interoperability of Enterprise Systems (TC 5.3), and Large Scale Complex Systems (TC 5.4).

Technische Universität Wien (TU Wien) and Fraunhofer Austria are delighted to organize the 18th edition of INCOM in Vienna, Austria in August 28-30, 2024. Hosted by the Austrian Federal Economic Chamber (WKÖ), INCOM 2024 has provided a great forum and unique opportunity for exchanging knowledge and discussing theoretical advances, emerging topics and industrial experiences under the **flagship** topic of "**sustainable transformation towards autonomous manufacturing systems**".

Academic and industrial experts joined the event and shared their research results and empirical insights focusing among others on: digital twin, green factories and logistic networks, federated manufacturing platforms, virtualization, global manufacturing, autonomous and self-learnable systems, data-driven industrial engineering, Industry 4.0/5.0's strategies, models, and technologies, human interaction in robotics and cyber-physical systems as well as new advances in additive manufacturing, Physical internet, predictive maintenance, robotics and conversational AI applications in manufacturing and supply chain. At INCOM 2024, five outstanding keynote talks were delivered:

- Prof. Torbjørn H. Netland, ETH Zürich, Switzerland, "Augmented Intelligence for Next-Level Manufacturing Excellence"
- Prof. Dmitry Ivanov, Berlin School of Economics and Law, Germany, "The Future of Supply Chain Simulation and Digital Twins"
- Prof. Alexandre Dolgui, IMT Atlantique, France, "Information Control Problems in Manufacturing: History of IFAC INCOM Symposium"
- Prof. Andreas Kugi, TU Wien and AIT Austrian Institute of Technology, Austria, "Advanced Control for Sustainable Autonomous Manufacturing"
- Caroline Viarouge, EIT Manufacturing, France, "How European Manufacturing is shaping our Greener and Digital Future?"

INCOM 2024 intended to foster synergies among all participants and establish dialogues. To this end, two panels have been organized. The first panel focused on "Smart and Sustainable Manufacturing", with participation of academic experts from IFAC community, and also industrial experts from UNIDO, Infineon Technologies Austria, and EIT Manufacturing. The second panel was dedicated to CC5 involving TC chairs, where the discussion focused on "Resilient, Digital and Sustainable Manufacturing and Supply Chain". Offering a Doctoral Workshop on "Advances in Manufacturing and Logistics Management and Control Problems" as a pre-conference event on August 27, 2024, INCOM 2024 also highly acknowledged the value of next generation scientists and industrial experts. This is also reinforced by delivering Young Author Awards and Best Paper Awards.

To sum up, 360 submissions were reviewed, out of which 218 were accepted and presented at the symposium (acceptance rate: 60.5%). The paper were presented from 39 nations in front of the audience of 340 people. The conference received 42 session proposals, out of which 28 proposals with at least five accepted papers have been appeared on the symposium program. Further, the Doctoral Workshop involved 31 PhD candidates presenting their research proposals and progress to 10 senior advisors.

The current proceeding stores all the papers presented during the INCOM 2024 symposium, representing the current trends and evolution in twin transformation of manufacturing and supply chain. The INCOM 2024's editors would like to acknowledge the efforts of all contributors, namely authors, reviewers, technical associate editors, session organizers and chairs, as well as all IPC and NOC members. During the review process and planning the symposium program, we have been committed and humbly put efforts to assure scientific quality and significant contributions of the IFAC community to the body of knowledge in manufacturing and supply chain.

We, on behalf of all contributors of INCOM 2024, sincerely hope that the present proceedings inspires you on creating, sharing and implementing new ideas towards shaping manufacturing and supply chain of the future. We wish you a pleasant reading.

Vienna, August 2024

Fazel Ansari (AT)
INCOM 2024's Editor and NOC Chair

Sebastian Schlund (AT)
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Design and test of a Human-Machine Interface for assembly lines in a learning factory

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Abstract: Human-Machine Interfaces are pivotal in modern manufacturing, serving as the critical link between human operators and complex machinery. This paper explores the evolution of HMIs, emphasizing their importance in enhancing efficiency, safety, and productivity within manufacturing environments. While HMIs offer real-time monitoring and control functionalities, their effectiveness hinges on human-centric design principles. Incorporating insights from human-centred design, this research presents a case study conducted at the SLIM laboratory of the University of Bergamo. The study encompasses theoretical exploration, HMI re-design, and user evaluation within an automatic assembly line setting. The research identifies key factors influencing HMI usability through critical analysis and user feedback and offers valuable insights for optimizing HMIs and empowering operators in the digital manufacturing landscape.

Keywords: Human Machine Interface (HMI), Human-Computer Interface (HCI), HCI/HMI design principles, HMI Graphic Design rules, Human Factors, Usability, Human Centered Design.

1. INTRODUCTION

Human-Machine Interface (HMI) plays a pivotal role in the realm of manufacturing systems, acting as the crucial bridge between human operators and complex machinery. In recent years, HMIs have evolved by introducing new information types and interaction methods, transforming how humans control and cooperate with industrial processes (Kumar & Lee, 2022). As technology advances, the importance of HMI becomes increasingly evident, impacting efficiency, safety, and overall productivity within manufacturing environments.

In the current industrial landscape, HMIs provide intuitive platforms for users to oversee and manage various aspects of the manufacturing process. Among the most widespread functionalities are real-time monitoring, control, data visualization, and alarm management, which allow for the swift exchange of information critical for decision-making (Ardanza et al., 2019). Additionally, HMI systems can be integrated with programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) and other automation technologies, enabling a comprehensive and interconnected approach to industrial operations (Basu et al., 2023). In particular, in the Industry 5.0 context, HMI contributes to improve the interaction between humans and robots and is expected to facilitate the implementation of advanced technologies such as artificial intelligence (AI) and extended reality (Mourtzis et al., 2023).

However, to acknowledge the effectiveness of HMIs, which depends on their ability to accommodate the needs and preferences of human operators, the human-centric design represents a critical element (Nguyen Ngoc et al., 2022). A well-designed HMI system promotes user-friendly interactions, reducing the likelihood of errors and enhancing the overall user experience. As manufacturing environments become more complex, the importance of intuitive and user-centric design principles in HMI cannot be overstated. This aims to improve productivity and contribute to workers' safety and well-being by minimizing cognitive load and facilitating quicker decision-making (Romero et al., 2016).

This paper addresses the topic of design and test of human-centred Human-Machine Interfaces through the development of a case study in the SLIM laboratory of the University of Bergamo. The research moves from a theoretical exploration of the most relevant rules and principles to be followed for developing human-centred HMIs to developing an application case on the automatic assembly line located in the University laboratory. The case consists of the re-design of the HMI related to the first two stations of the line and an evaluation test of them provided by an external sample of users.

The relevance of this research grounds on the critical analysis of the most relevant factors that affect the usability of HMI for monitoring and controlling automatic systems. The case study results provide insightful guidelines about the main aspects to consider to achieve the human-centred design of industrial HMI and highlight the significance of creating interfaces that empower operators and contribute to the overall success of manufacturing enterprises in an increasingly digital and interconnected world.

The remainder of the paper is organized as follows. Section 2 describes the adopted methodology, while Section 3 presents the result of the literature review on HMI design. The description of the case study and the developed HMI are presented in Section 4. Section 5 discusses the results of the test. Concluding remarks, limitations, and further development are finally discussed in Section 6.

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2. METHODOLOGY

The research methodology is divided into two phases: the first phase focuses on the analysis of the literature in order to identify principles and rules that could be used in the second phase of the experimental application, where the new HMI proposals have been designed and implemented. In the end, to give further value to the study's results, once the new HMI configurations were completed, they were subjected to an evaluation test by an external sample of users to collect observations and suggestions for further improvements.

2.1 Literature review

The first research phase consisted of the literature analysis to identify principles and rules regarding the design of HMI. It was addressed by using the Scopus database and ensuring that the information found could be adapted to a manufacturing industry context. The main keywords used to drive the research were "Human- Machine Interface" OR HMI combined with "guidelines" OR "principle*" or "design rule*". Based on the number and validity of the resulting papers, it was evaluated whether to filter further based on the publication type, considering only articles and conference papers, and limiting the subject areas to engineering, computer science, business and social sciences. From this phase, 30 articles relating to the topic were selected and subsequently used in the practical case.

2.2 Case study development and test

The practical application to a case study has been developed in the SLIM laboratory of the University of Bergamo, a learning factory in which an SMC SIF-400 automatic assembly line is installed (https://slim.unibg.it/). In particular, the study focused on the first two stations of the line, where HMIs were already present. First, the functionalities of the current HMIs were studied and, based on the human-centric design rules identified in the literature review, new configurations for the HMIs were proposed and developed. Furthermore, they have been implemented in the software Crew, which is devoted explicitly to HMI design and programming and was already used by the assembly line supplier for the first HMI design.

These new proposals were then evaluated using a questionnaire by a sample of seven people: researchers, doctoral students, and graduate students working in the SLIM laboratory. The questionnaire consisted of fifteen questions, divided into four modules: the first related to the clarity and arrangement of HMIs, the second focused on their ease of use, the third related to communication between man and machine and the fourth to general considerations.

The questionnaire results were then discussed in Focus Group in which the interviewees have been required to discuss the strengths and weaknesses of the new HMIs and to reason concerning possible improvements.

3. STATE OF THE ART

3.1 HMI

Historically, the concept of Human-Computer Interaction (HCI) began to spread as early as the early 1980s until it was established with the emergence of the computer, or more generally, of the machine itself. The reason is due to the fact that the goal of the HCI is precisely to improve the interaction between users and computing devices, trying to make it more user-friendly and better adapted to the needs and capabilities of users and the capabilities of the device (Karray et al., 2008). According to the international community of the ACM Special Interest Group on Computer-Human Interaction, HCI can be defined as "a discipline that deals with the design, evaluation and implementation of interactive computer systems for human use and with the study of the main phenomena that surround them" (Despont-Gros et al., 2005). In the context of HCI, the HMI is what the users see and work with to use a device (Villani et al., 2017). The design and development phases of HMIs are of particular importance. To this purpose, the International Organization for Standardization (ISO), starting from the ISO13407 standard deployed in 1999, pointed out two relevant topics: human-centred design and usability (Jokela et al., 2003). For the first, the standard provided a structure of the activities needed to design and test solutions based on user requirements. The second key concept of usability has been further defined by ISO 9241 as "the extent to which specific users can use a product to achieve specific objectives effectively, efficiently and satisfactorily in a given context of use" (ISO, 2019).

Concurrently, scholars developed human factors engineering, also known as Human Factors (HF) and Ergonomics, as the discipline that focuses on understanding the needs and limitations of human capabilities and applying this understanding to the design of human-machine systems (Lewis, 2011). Since the actual effectiveness of a system is achieved when there is the right balance between functionality and usability, HMIs require a design that should produce an adaptation between the user, the machine and the required services to achieve a specific performance in terms of quality and optimization of services (Ebert et al., 2012).

3.2 HMI design rules

Design rules imply important premises that designers should always keep in mind when designing to have an overall perspective on the entire human-machine interface. Several authors in the literature agree that the discipline of HMI design is so fragmented and extensive that it is difficult to identify a single approach method or even a set of universally accepted principles (Blair-Early & Zender, 2008). Although there is a difficulty in identifying a single model to follow for HMI design, the seminal work of Shneiderman provided a first set of Eight Golden Rules including: striving for consistency, suggesting the use of shortcuts, providing feedback, designing dialog to yield closure, handling errors, allowing backwards actions, and so on (Thamrin et al., 2023). Further, Nielsen principles are among the most frequently cited design principles in the literature. Nielsen heuristics, or "10 Heuristics for Usability Design", are a set of usability principles that can be used as guidelines for evaluating the usability of a user interface (Hinze-Hoare, 2007).

Until the late 1990s, the priority objectives for a designer were safety, utility, effectiveness, efficiency and usability. Subsequently, the term "Usability" was generalized to a synonym for “User Friendly”, thus including the other concepts (Hinze-Hoare, 2007).

Here are the principles suggested by Nielsen:

1. System Visibility
2. Familiarity and user language
3. User Control & Freedom
4. Consistency and standards
5. Error messages
6. Error Prevention
7. Reduce memory load
8. Flexibility and efficiency of use
9. Aesthetic and minimalist design
10. Help & Documentation.

Beyond the general principles for the design of HMI, the literature review enabled the identification of specific rules that would allow these principles to be met and that could be adapted to the reference context of the case study. All the selected rules were grouped initially according to the scope of use and then, as far as possible, according to the Nielsen principle to which they refer most, as can be seen in Table 1. In particular, the identified application areas were those relating to the display of information on the screen, cognitive adaptation, alarm systems, and, finally, chromatic rules and/or the sizing of characters and elements (O’Hara & Fleger, 2020).

Table 1: HMI Design Principles and Rules

Principle	Rule
Aesthetic and minimalist design	Images and graphics quickly grab a user’s attention.
Flexibility and efficiency of use	The information to be compared should be presented on the same page.
Consistency and standards	The display must use a consistent colour code for similar information for all pages.
	It is necessary to use standard colour coding to represent the severity of errors.
Error messages	A more severe alarm should attract the user’s attention via an on-screen notification.
User Control & Freedom	It is necessary to add buttons to improve navigation efficiency between screens.
Error Prevention	Allow operators to see alarm history.
System Visibility	Real-time performance measurements (e.g., execution times, errors).

4. CASE STUDY

As previously mentioned, the application case is implemented at the SLIM laboratory of the University of Bergamo (https://slim.unibg.it/). An automatic line consisting of seven stations is installed there, allowing users to assemble customizable products. These products are containers with either a square or circular base that can be filled with red, blue, or yellow granules. The assembly line has a dual operating mode, manual and integrated modes, which the operator can freely set via a specific button on the HMI screen. The integrated working mode allows the operator to control and manage the production progress directly from a tablet or an external PC through an MES, where it is possible to launch the production of new products and track the positioning of those already in progress. The manual mode, on the other hand, allows the operator to control and manage the progress of production one station at a time through an HMI interface directly installed on each station. This HMI has been the objective of this study.

The structure of the HMI is similar for all the stations, with some standard pages. Each HMI has a home page where the specific task of every station is carried out. The default home page is shown in Figure 1.

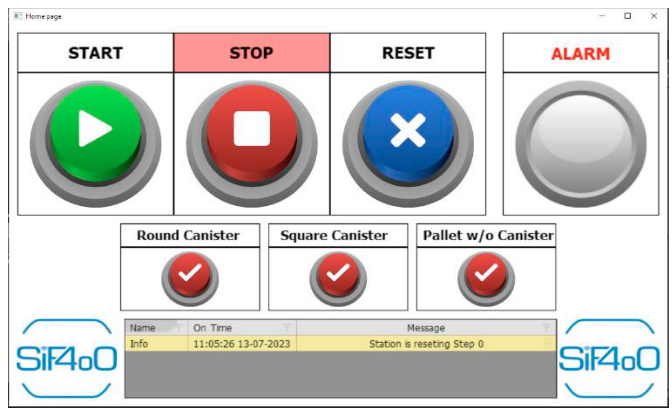

Figure 1. HMI Home page

Other standard pages are the page related to the station configurations, which allows checking the status of each station; the page for maintenance performances, thanks to which the user can measure the times of planned and unplanned stops; the page for product quality management, the page of energy consumption data that shows info about energy and air consumption and the page that allows the user to call an autonomous mobile robot that performs logistics activities.

For that reason, since the structure of the HMIs is similar for all the stations, and since the innovations introduced have been designed so that they could be extended to all the HMIs of the line, for the case study, the focus has shifted to the HMIs of the first and second stations, which deal respectively with the selection of the container (Station 1) and the filling of the same (Station 2).

Following the identified rules, some of which are shown in Table 1, we started with the design of the new HMIs. To improve the Error messages, an alarm notification has been inserted if severe errors occur, and a color coding has been set based on the severity of the problem. Furthermore, to improve consistency in the aesthetic, the number of colours used for all HMI pages has been reduced, trying to use the same ones for commands with similar functionality (e.g., green for “start”, red for “stop”, blue for all the other functions).

Besides other changes in positioning, sizing, colours and choice of the icon of some buttons in order to improve the readability and graphics of the HMIs, the main innovations concern the introduction of arrows to navigate between HMI pages, improving user control, and two performance indicators in order to improve the system visibility. These indicators consist of a counter (TOTAL) that calculates the total number of products launched by the station and a timer called StopTimer, which allows the user to calculate all station cumulative downtimes. The arrows for navigating from one page to another have been added to enhance user control. This is because the drag-and-drop navigation currently used in HMIs is complex and not consistently recognized by the HMI due to screen wear and tear.

As for the TOTAL counter, it increments by one every time the START button is pressed. In manual mode, each product launched corresponds to one START press. Therefore, counting the number of START presses can give us information about the total number of products launched by the station. As far as the Timer is concerned, it works so that it is activated every time the user clicks on the STOP button and is interrupted every time the user clicks on the RESET button, assuming that after each stop, the user must reset the station to restart production. The new proposed HMI is depicted in Figure 2.

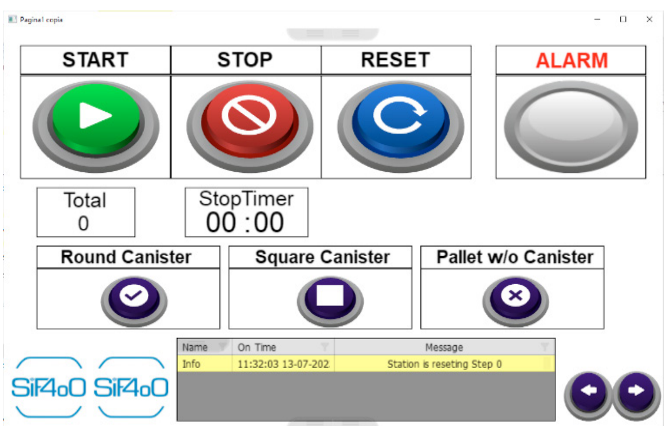

Figure 2. HMI Home page new proposal

Further changes concern the inclusion of two new pages among those available, which do not have a corresponding one in the current HMIs: one relating to the discard rate and one relating to the alarm history. The first (Figure 3) shows on the same page a comparison between the total of products launched by the station, according to the methods seen with the TOTAL counter, and the total of products rejected by the same station, using a counter like that of the total products launched with the difference that the reference button is the DISCARD button, relating to rejects. The graph below shows the two values so the user can easily compare them.

The second page (Figure 4), on the other hand, displays the history of the alarms that have been recorded by the station so that the user knows which are the main criticalities that need attention in order to plan corrective actions and which are the most frequent alarms for each station to prevent errors. These changes have been implemented on both the first and second stations of the line, but they could very easily be implemented on the remaining ones as well.

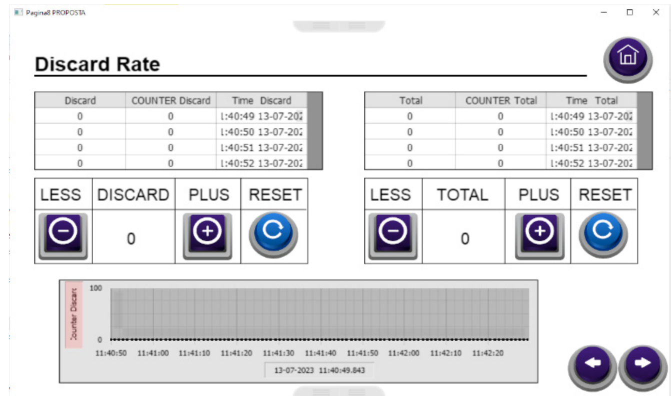

Figure 3. HMI page – Discard rate

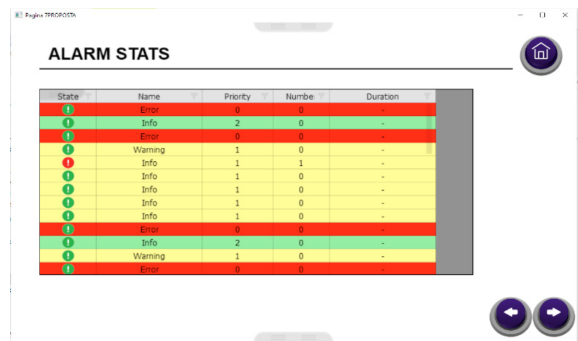

Figure 4. HMI page – Alarm Stats

5. TEST AND RESULTS OF NEW INTERFACES

Once the new interface proposals had been finalized and defined, they were subjected to an evaluation questionnaire by an external sample of seven people: researchers, PhD students and Engineering master's students working at the SLIM laboratory. The sample involved in the test was limited due to the choice of including only people that already knew the equipment and the functioning of the line, in order to avoid the need of preliminary training. The test was performed by showing the new interfaces to the sample of users in the Crew software, in which it was possible to simulate their functioning. In the first phase, the users were not informed in detail about the differences between the new and old interfaces to prevent any bias in their evaluation. The interfaces have been shown for a particular time, in which users could ask specific questions about functions, buttons or information whose content and use were not intuitive.

After this demonstration, the users were asked to complete a questionnaire in which specific aspects of the new HMI design were investigated. Considering the more general questions: "Is the new HMI easier to use compared to the existing one?" and "Has the new HMI brought significant improvements in terms of usability?", asked to evaluate a 4-level scale (from absolutely not to absolutely yes), all the respondents were completely or almost completely satisfied (level 3 or 4) with both the ease of use of the new HMIs and the innovations introduced. In particular, none of the aspects of each module met disapproval. On the contrary, in general, many aspects were quite successful. Concerning the clarity and aesthetic of the HMI, positive confirmations came concerning the choice of colours, which five people fully appreciated, while the remaining two, even if not completely, were still satisfied, and the choice of font size and fonts, which four people fully approved out of seven.

On the other hand, there was more uncertainty regarding the choice of button icons, the size and positioning of the buttons themselves, and the sequence of pages. At least one person was not satisfied with the button choices, and two out of seven people did not notice much improvement in the sequence of pages. Concerning usability, both questions relating to the ease of use of the new features introduced and the intuitiveness of the sequence of actions to be performed obtained total or sufficient approval. In contrast, in the question asking to evaluate the effective presence of feedback to help the user, one person was not overly satisfied with the support generated. Concerning communication between man and machine, consisting of two questions, in a similar manner to the previous ones one focusing on the ease of obtaining and understanding output information and the other on the effectiveness of the alarm system in attracting the user's attention, positive responses came from the respondents: respectively five and four users out of seven totally approved the new proposal. The remainder, even if not completely, were still satisfied. In particular, assessing the convenience of the different proposed methods for navigation between pages, the arrows for moving to the next or previous page were the tools that received the most positive votes, six out of seven, to the detriment of the other proposals, although it has to be said that for each of these, there was at least one person who was not too enthusiastic about it. The drag-and-drop mode to the right or left, which is the one currently offered in existing HMIs, is the one that least convinced the respondents due to various difficulties caused mainly by a small and worn screen display, which is not always able to detect the user's touch correctly. These difficulties with the touch screen of the HMI display and with dragging and dropping are the same reasons why the proposals of double-clicking on the screen and the tab appearing at the bottom of the page also failed to convince respondents.

Asking the users for detailed feedback, it was observed that, among the aspects to be improved, classified according to the Nielsen principles, the most critical ones are user control, understood in terms of navigation and interaction with the system, selected by no less than four users out of seven, followed by system status visibility, understood as feedback elements to keep track of performance and alarms, and user language familiarity, both selected by three users out of seven. These results are perfectly consistent and concordant with the criticalities previously highlighted.

Finally, a focus group discussion was held among the respondents to share ideas and possible solutions to the identified critical issues and suggest possible future developments to refine the newly created HMIs. New possible locations were suggested for some buttons, or those buttons whose icons were not immediately intuitive were highlighted. It was suggested to modify the sequence of pages either according to their frequency of use, setting the most frequently used pages as the first ones, or dividing it into a first part consisting of only operational pages and a second one consisting of more reporting pages. Regarding feedback or user support, it was recommended to streamline the interface pages so they are not too rich in information and to insert links between pages or buttons that allow the user to reach the point of interest more quickly. With regard to navigation modes, several possible solutions have been proposed. Some suggest creating new physical buttons, similar to arrows, which perform the same function of passing between screens, sometimes directly linking the button itself with another page, as happens, for example, when clicking on the reset button of the stop timer, which takes the user directly back to the home page. Others recommend creating a home page with a menu showing all the pages in the HMI, from which it is possible to access the desired page with a simple click. A summary of the features that received positive feedback or were considered improvable is reported in Table 2.

Table 2: Case study results

Factors obtaining positive feedback	Factors that can be further improved
Choice of colours	Button placement
Font and size	Button icon
Easy to use	Page Sequence
Intuitiveness of action	Supportive feedback
Information availability	Navigation mode
Alarm system	

6. CONCLUSIONS

This paper is grounded on the human-centred design discipline, by studying the HMI design to support operators in interacting with an automatic system. The objective was to analyze literature and scientific studies concerning principles, rules, and requirements necessary for designing and developing human-machine interfaces and apply them in a case study at the assembly line in the SLIM laboratory of the University of Bergamo.

The study was articulated following a logical structure that included a first part of analysis of the literature, aimed at identifying rules and principles on HMI design, and a second part of practical application of the theories selected in the first part, first going to design on the Crew software new proposals for HMI configurations for the first two stations of the line and then evaluating them through a questionnaire that collected the points of view of users.

Overall, the proposed interfaces received a positive response from the respondents, whose feedback was helpful to understand how they perceive different aspects of the HMI usability. In detail, the new features introduced were mainly appreciated for allowing users to obtain various information without increasing their memory load but rather by reducing it. Other changes, such as the choice of colours and the choice of font and size, although they received a positive response, did not immediately leap to the attention of all observers, some of whom indeed appeared rather indifferent.

The sample of participants in the test also focused on providing effective feedback to the users and adequately arranging all the information about the system status. For instance, the sequence of HMI pages needs to be designed by keeping pages containing complementary information close together or otherwise arranging them so that the pages used most often are presented in the foreground. Better support for the users also includes the possibility of organizing HMI pages by differentiating "operational" and "reporting" interfaces.

Therefore, the research provides interesting insights on HMI design, that could be considered valid for similar equipment, such as semi-automatic production systems, where human intervention is mainly devoted to control and supervision, rather than continuous interaction. Nevertheless, this work presents some limitations. First, the proposed HMIs have been preliminary tested with a small sample of users and need extensive validation. In particular, the small sample does not offer the possibility to make statistical analysis of the results and should be extended in future studies. Also, other rules and principles could be tested, as well as different profiles of users could be involved based on different experience levels and age. Since some evidence are already present in literature concerning the different attitude of aging workforce in human-machine interaction, further investigations could be necessary in this direction. Other possible future studies may concern the implementation of the new HMIs on the line to measure relevant performance indicators in the human-machine interaction, both involving the system productivity (e.g., cycle time) and the users' well-being (e.g., error probability, cognitive load).

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