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ORIGINAL ARTICLE

Digital toolkit for human-centered machine design: development and testing of an innovative system integrating virtual reality and HMI digital prototypes

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Abstract
Industry 5.0 (I5.0) emphasizes the importance of humans in modern manufacturing, particularly the need for efficient human-machine interaction. However, current design processes often neglect human factors in the early stages of machine design. Despite the growing recognition of human-centered design (HCD), existing methodologies still lack integrated solutions that fully leverage digital technologies for usability testing in industrial machines. As a result, traditional design and testing approaches remain rigid, limiting the potential of simulation in capturing complex human-machine interactions. This forces designers to rely on incomplete data, often leading to machines optimized for performance but lacking the usability needed for seamless human operation. This paper presents an innovative system that integrates humans into the design phase through two interconnected applications: a Virtual Reality (VR) application, where it is possible to interact with the machine digital model, and a desktop application that mimics the human-machine interface (HMI) to simulate operations on the machine. The two applications are synchronized and allow real-time interaction between the HMI and the virtual machine, enabling a human-centric virtual commissioning and testing of procedures that involve both the physical machine and the HMI. This approach enables iterative refinements before physical prototyping, reducing development costs while enhancing operational efficiency. By combining immersive engagement with the virtual machine and HMI simulation, it facilitates iterative refinements before physical prototyping, optimizing human-machine interaction and ensuring user-centered solutions. The industrial case study demonstrates the potential benefits of the proposed toolkit to optimize machine design according to I5.0 principles, improving both safety and usability.

Keywords Human-Centered design · Virtual reality · Human-Machine interaction (HMI) · Machine design optimization · Industry 5.0 · Virtual commissioning

1 Introduction

In recent years, the industrial sector has witnessed the rise of Industry 4.0 [1], which is characterized by automation, digitization, and smart manufacturing technologies. While these advances have improved efficiency and productivity, they have also reduced the direct involvement of human operators in the production process. This change has raised concerns about the loss of the human role, especially in decision-making positions [2]. In response, I5.0 has emerged as a new paradigm that aims to reintroduce humans into the heart of industrial processes and foster collaboration between humans and intelligent systems [3]. This approach emphasizes the value of human creativity, intuition and problem solving in combination with the innovative technologies proposed by I4.0. I5.0 envisions a future in which humans and machines work synergistically, allowing machines to handle repetitive or dangerous tasks while humans focus on more complex, value-added tasks [4]. A central aspect of I5.0 is HCD, which ensures that the systems developed not only

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incorporate cutting-edge technologies, and also consider the needs and limitations of the human operators who will interact with them. To achieve this, Human-in-the-Loop (HITL) optimization emerges as a key methodology. HITL places human feedback and decision-making at the core of system design and operation, enabling iterative improvements that account for both technical performance and human usability [5]. By integrating humans into the testing and development cycle, HITL ensures that systems are dynamically adjusted to align with real-world operational needs and user preferences [6, 7]. This inclusion is particularly important in machine design, where usability, safety, and efficiency are all affected by the interaction between operators and machines. Consequently, new tools and methodologies are required to incorporate human factors in the early stages of machine development [8, 9].

The complexity of modern industrial machines has increased significantly, necessitating more sophisticated and integrated design processes as well as effective and comprehensive virtual commissioning [10]. Conventional methodologies for machine design have predominantly concentrated on optimizing technical functionality, frequently overlooking the indispensable function of the human operator [11]. Virtual Commissioning (VC), defined as the simulation and testing of systems in a virtual environment, is a well-known tool to address the challenges of integrating and validating complex systems efficiently and effectively. However, current VC models usually neglect the human presence [12].

As manufacturing becomes more complex, the interaction between operators and machines becomes increasingly important and cannot be neglected. Moreover, interaction is now distributed in time and space, taking place on both machine and HMI, in a synchronous or asynchronous way. In addition, modern machines have a greater electronic control that moves a lot of regulations and settings from the physical machines to the graphical interface, making interaction with industrial systems more and more varied and complicated. As a consequence, mere machine virtual models are not able to highlight future system inefficiencies, operational errors, and safety risks, particularly because human operators are not taken into account during the design and simulation stages [13].

To address these issues, designing modern machine must prioritize human-machine interaction, encompassing the simulation of both the physical machine and user interface. This approach ensures that machines are not only technically advanced, but also intuitive and straightforward to operate. This is particularly crucial in industries that rely on manual input or decision-making by operators. Machines that are difficult to use or understand have the potential to cause delays in production, increase the likelihood of human error, and even result in accidents [14]. Consequently, there is an increasing necessity for design methodologies that integrate usability testing at the outset of the development process. This guarantees that machines are adapted to the requirements of the individuals who will operate them, resulting in systems that are more efficient and easier to use. In industrial machine design, traditional usability testing methods include heuristic evaluations, cognitive walkthroughs, think-aloud protocols, and task analyses. These approaches aim to identify usability issues early in the design process, allowing for iterative improvements and ensuring that the final product meets user needs. However, these conventional techniques for assessing machine usability are frequently inadequate because they lack the flexibility to fully replicate real-world interactions. Moreover, they often involve physical prototypes and can be resource-intensive.

Therefore, despite the growing recognition of the importance of human inclusion in machine design, current design methodologies often fail to fully integrate human factors in the early stages of the process [15]. While automation and digital tools have enabled more efficient and precise machine design, these systems tend to prioritize technical performance over usability and human interaction. As a result, machines are often designed without fully accounting for how operators will interact with them, creating a disconnect between the machine's functionality and the needs of its users [16]. This lack of human inclusion is particularly problematic in the context of I5.0, which emphasizes the need for greater collaboration between humans and machines. To achieve this, it is essential to involve operators in the design phase, ensuring that their feedback and needs are incorporated into the final product [17].

However, traditional design and testing methods lack the flexibility to simulate complex human-machine interactions in a realistic and dynamic way. Without a system that can effectively simulate these interactions, designers are often forced to rely on incomplete data, resulting in machines that may be efficient in terms of performance but lack the usability required for optimal human operation. To address this gap, this research proposes a toolkit that integrates a VR application and a 2D HMI app, connected with the VR model, allowing for the flexible simulation of combined human-machine interactions. The VR application provides a digital model of the machine, while the HMI represents the real-world control interface. These two systems are synchronized, enabling operators to interact with the machine via the HMI and see the results in real-time in the VR environment and vice versa. This system is inherently aligned with HITL principles, as it provides a platform for continuous feedback from operators during the design and testing phases, enabling iterative improvements and ensuring that the final product is both efficient and user-friendly.

Building on this approach, this study aims to address the following goals:

G1: Evaluate the ability of the proposed system to replicate real-world human-machine interaction as accurately as possible.
G2: Test the system within an industrial case study to assess both the procedural workflow and the overall human-machine interaction.

The paper is structured as follows: Sect. 2 provides an overview of the research background, focusing on the role of VR simulation and HMI usability assessment in machine design. Section 3 describes the development of the proposed toolkit, detailing its architecture, the VR and HMI applications, and their integration. Section 4 presents the case study, outlining the experimental setup and data collection methodology, the discussion of the results, the limitations and the future developments. Finally, Sect. 5 concludes the paper by summarizing the findings.

2 Research background

In recent years, the integration of advanced digital tools has reshaped industrial design processes, particularly in the field of machine design, where VR simulation and digital usability assessment play an increasingly central role. VR enables a more immersive and interactive approach that can promote a HCD philosophy, while usability assessment on digital interactive HMIs allows to predict the user interaction between operators and complex systems [18].

2.1 Virtual reality simulation to support machine design

During the last decade, VR has become an effective instrument in enhancing machine design by enabling the simulation of complex interactions with physical interfaces within a secure and controlled setting, thereby reducing the necessity for physical prototypes [19]. In the field of machine design, VR enables engineers and designers to develop digital machine models that human operators can test and assess in real-time. This approach facilitates the identification of design issues early in the development process, reducing the reliance on physical prototypes and enhancing collaboration among team members [20]. VR is also helpful in focusing on human tasks and providing a comprehensive assessment of the future machine commissioning on the field [21]. In both cases, such immersive simulations provide valuable insights into how machines will perform in real-world conditions, including human interventions, allowing designers and engineers to identify usability issues and refine their designs accordingly [22, 23]. Moreover, VR opens up new possibilities in the field of product development by accelerating the pace and improving quality and usability. Prototypes and products can be tested 'virtually' before final verification is performed with physical prototypes. This is particularly useful for complex systems where engineers need to consider a lot of information and many signals, such as in a factory environment [19]. The main goal of VR in machine design is to simulate physical interactions, which includes human-machine interaction analysis and physical ergonomics optimization [24]. This capability makes VR a valuable asset for industries seeking to incorporate human factors into machine design [25].

Some examples from the literature regarding the use of VR in the design field: Peruzzini et al. [26]. emphasize the role of VR in allowing engineers and designers to immerse themselves in a virtual environment containing the digital model of the machine; such an environment facilitates the identification of ergonomic problems and potential design inefficiencies prior to building physical prototypes. By simulating machine operation in VR, the study shows that design flaws can be identified and corrected early in the development process, reducing the cost and time associated with iterative physical prototyping. Prati et al. [27]. discuss the application of VR in machine design with a focus on user-centered evaluations. The study shows that VR helps uncover usability and security issues early on as it allows end users (e.g. operators) to interact and provide feedback on the design before it is finalized. The results of this study show a significant improvement in training efficiency: operators trained with VR perform tasks with fewer errors than those trained with traditional methods. Caputo et al. [28] highlight how VR environments help engineers visualize spatial configurations and check for potential conflicts and access issues. This allows for a more efficient design process, as potential space, accessibility, and component layout issues can be addressed up front. For maintenance applications, the study found a reduction in maintenance time after VR training, as personnel can virtually practice troubleshooting and part replacement. Li et al. [29] have shown that using VR for HCD design allows for a deeper understanding of user preferences, capturing the subtle shades of their feedback that would otherwise be difficult to detect with traditional design methods. Ultimately, the use of VR in concept validation leads to improvements that are better aligned with end-user expectations, resulting in a product that is more likely to meet user needs and provide greater satisfaction. Similarly, Fuchs et al. [30] proposed a collaborative knowledge-based method for the interactive development of cabin systems in VR, enabling a cabin systems layout based on preliminary aircraft design data. Their approach uses an ontology-driven XML data structure to consolidate properties, system relationships, and requirements, ensuring data consistency and accessibility for all experts involved. This data is visualized in a 3D virtual mock-up, where users can interact with cabin components, evaluate designs, and optimize layouts in a cost-effective and immersive environment. The method fosters interdisciplinary collaboration and streamlines communication among stakeholders, allowing for iterative development and early-stage validation of concepts before transitioning to physical prototypes. Manghisi et al. [31] developed ErgoVR, a VR-based tool designed to evaluate the Rapid Upper Limb Assessment (RULA) metric both in real time and offline. This innovative approach enables the evaluation of workstation ergonomics during the design phase by allowing operators to interact with virtual mock-ups of their workstations. As a result, ErgoVR makes it possible to perform ergonomic analyses early in the development phase of the workstation. De Freitas et al. [32] conducted a comprehensive review of patents and literature to identify the benefits and challenges of VR-based industrial usability testing and design reviews. Their study highlights the potential of VR to innovate product development processes while also emphasizing the constraints that must be addressed to fully harness this technology's possibilities.

2.2 Usability assessment on digital HMIs

HMI is a critical component of the machine, serving as the medium through which operators interact with its controls and access to its data. A well-designed HMI can significantly improve usability, operational efficiency, and safety by providing clear, intuitive controls that are easy for operators to understand and manipulate. In contrast, poorly designed interfaces can lead to operational errors, reduce productivity, and increase the risk of accidents [33]. However, current methodologies for testing and evaluating HMIs are often limited, as they typically focus on isolated aspects of interaction rather than a holistic view of the human-machine system.

Aranburu et al. [34] conducted a study highlighting the importance of HMI usability testing for monitoring and control tasks. Through this study, the authors highlighted that a well-designed HMI enables operators to effectively operate complex machinery by reducing cognitive load and minimizing errors during critical operations. The findings highlight the importance of including usability assessments early in the design process to ensure that interfaces are aligned with operator needs and industry standards, ultimately improving both productivity and safety in machine operations. Similarly, Wilson et al. [35] studied HMI usability by focusing on ergonomic aspects and their influence on operator performance. Their research demonstrated that incorporating usability principles into HMI design reduces operators' physical effort and cognitive fatigue. This study reinforces the idea that ergonomic HMI designs are essential to optimize machine interactions, as they enable operators to perform tasks more intuitively and reliably. Jura et al. [36]. developed a method to improve the quality of industrial HMIs by estimating usability through a quantitative analysis of users' reaction times in response to specific tasks, combined with a qualitative analysis using eye tracking. The results demonstrate that this approach can significantly enhance usability, reliability, and efficiency, while also identifying and eliminating graphic design errors that could lead to operator mistakes. Chauhan et al. [37]. introduced a comprehensive methodology for developing industrial HMIs optimized for usability and efficiency in operational environments. This approach involves a sequence of steps including user research, task analysis, prototype design, usability testing, data collection and analysis, iterative prototyping, and integration of optimization algorithms. The methodology uses three fundamental optimization techniques Fitts' Law optimization for ergonomic positioning of controls, a genetic algorithm for layout and color optimization to improve user satisfaction, and an adaptive HMI decision tree classifier that adapts the interface based on individual user interactions. By combining user-centered design, rigorous usability testing, data-driven optimization, and adaptive tuning, this methodology improves the safety, productivity, usability, and cost-effectiveness of industrial HMI design. Lorenz et al. [38] conducted a study to evaluate a next-generation excavator HMI using usability and user experience (UUX) metrics to meet the needs of digitized construction environments. The HMI concept included a touch-based interface with advanced features and interaction modes to improve efficiency and safety. The main objectives were to compare joystick and touch-based interactions, measure performance during testing, compare UUX measures, and explore correlations between UUX metrics. Results showed no significant differences between interaction modes for UUX, although time per action varied within groups. This study highlights the value of user-centered design in industrial applications, especially as digitalization creates new integration challenges. Villani et al. [39] conducted a comprehensive survey on usability assessment methods for industrial user interfaces, categorizing them into subjective and objective approaches (Fig. 1). The figure illustrates these categories and highlights the distinction between qualitative and quantitative methods, with subjective evaluations focusing on user perceptions and satisfaction, and objective methods based on measurable performance indicators. This classification provides

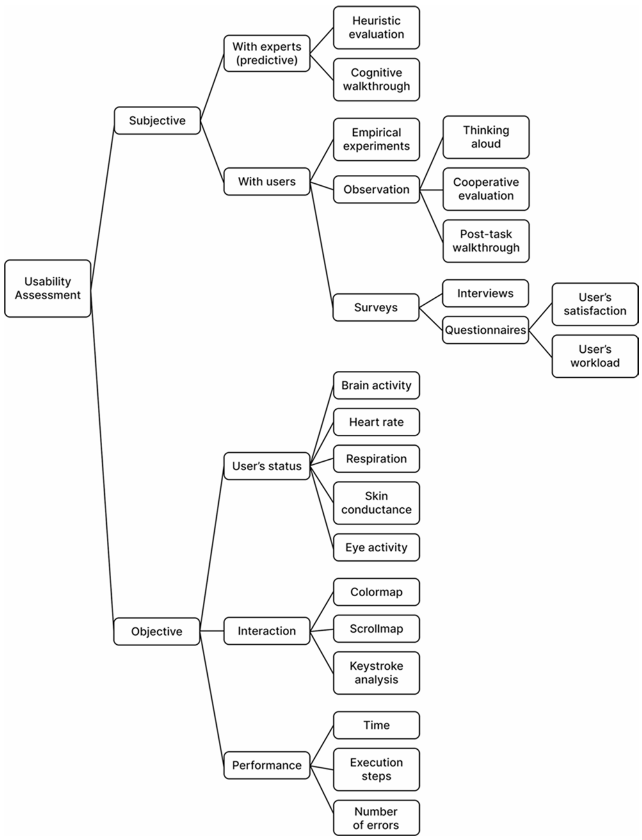

Fig. 1 Usability assessment metrics, adapted from [39]

a well-rounded framework for evaluating industrial HMI usability by addressing key aspects such as user mental fatigue, clarity of presented information, and production efficiency. These insights served as a foundational reference for this research, guiding the development of the usability evaluation approach. However, while the figure effectively synthesizes these usability approaches, it also raises important considerations. Objective methods, for instance, may offer more reproducible and quantifiable insights, yet they might overlook critical aspects of User Experience (UX) that are better captured through subjective assessments. Conversely, subjective evaluations, though valuable for understanding user feedback, could be influenced by individual biases. By integrating both qualitative and quantitative measures, this dual approach enhances the accuracy and applicability of usability evaluations in diverse industrial environments.

Effective HMI can significantly improve operator performance and reduce cognitive load, making machine operations safer and more intuitive. Despite these advances, however, current systems still have limitations, particularly regarding testing and validation. Existing approaches often lack the flexibility to deal with the different scenarios that occur in real industrial environments, where interactions are often not exclusively physical or digital, but a combination of both.

In the context of virtual machine design, the possibility to carry out usability analysis on digital HMI prototypes plays a vital role in improving the overall system design. In modern industries, HMIs are becoming increasingly complex as machines grow more advanced. As a result, the analysis of HMI has gained importance, with a focus on designing interfaces that are both user-friendly and capable of handling the complexities of modern machines [40]. Digital usability assessment allows a preventive analysis and a more comprehensive approach to HMI analysis by incorporating usability testing from the early stages of machine design and supports the simulation of realistic scenarios. This approach would ensure that HMIs are not only technically robust but also tailored to the practical needs of human operators, optimizing them for real-world application.

In this direction, the study proposes an innovative approach that leverages both VR and HMI in a unified test environment, this research aims to address these limitations. This solution proposal focuses on developing a comprehensive and adaptable framework that improves the accuracy of usability testing and enables deeper analysis of human-machine interaction, aligning with the goals of I5.0 and HCD.

3 Human-centric digital toolkit

The following sections provide an overview of the developed toolkit, followed by a detailed breakdown of the two developed applications: the VR app and the HMI app. The discussion covers their integration and concludes with an explanation of how the system has been used for testing purposes.

3.1 Toolkit architecture

The toolkit has been developed using Unity [41], a versatile and widely adopted game engine and development platform that enables the creation of immersive and interactive virtual environments. Unity provides the tools and frameworks needed to build complex simulations that integrate 3D models and real-time user interactions, making it particularly suitable for industrial applications.

The toolkit integrates two sub-systems, namely a VR app and a bi-dimensional HMI app, as presented in Fig. 2. The VR app manages the tri-dimensional model of the system under investigation and the user immersive visualization as well as the human tracking into the virtual space. The 3D

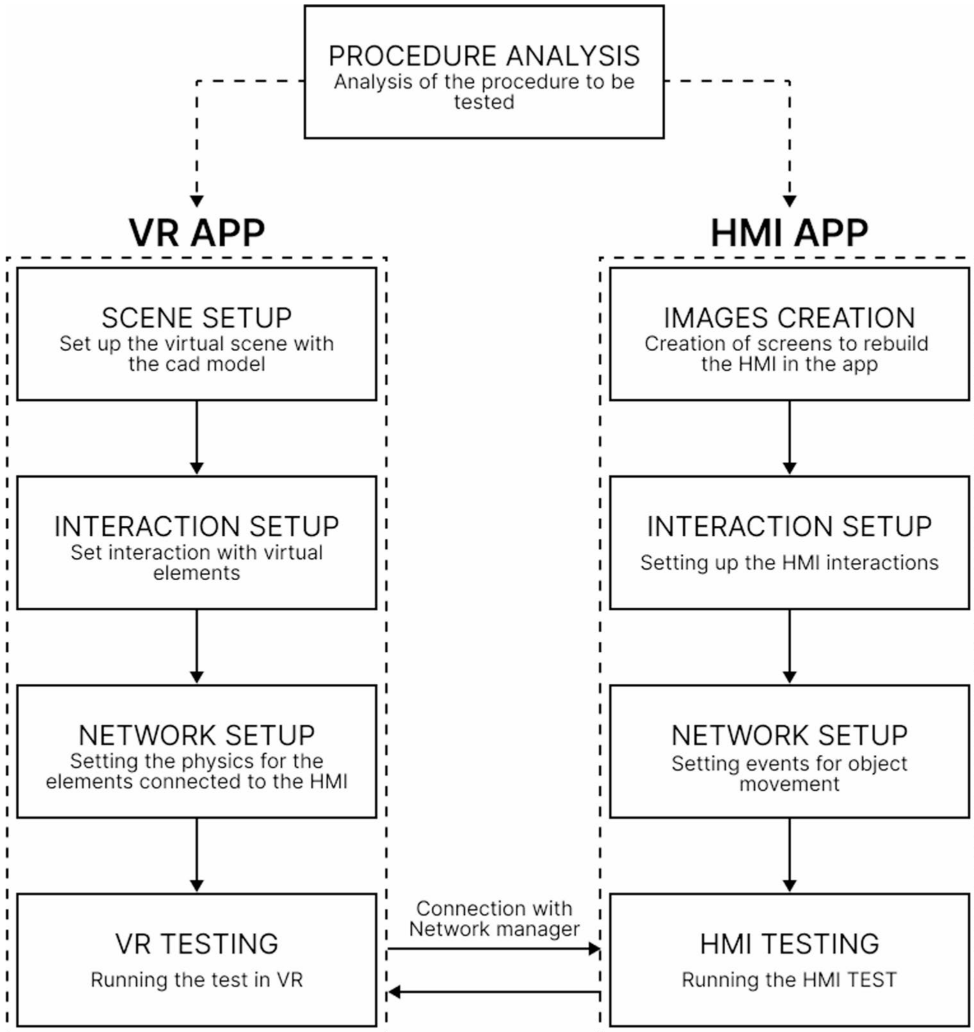

Fig. 2 Human-centric digital toolkit architecture

machine virtual model can be manipulated and tested in a fully immersive environment, simulating real-world physical interaction without requiring a physical prototype (visibility, reachability, collisions, maneuvering spaces). The HMI app manages the interactivity among the HMI digital pages and items, by providing a mimic of the machine HMI by a fully interactive prototype. The HMI allows users to simulate operating procedures, providing feedback on user interactions.

The main contribution of the toolkit is the real-time synchronization between the two apps, which allows the simulation of the realistic behaviours of both machine and HMI, considering the occurring of specific events. The toolkit allows users to operate the digital machine in the VR directly from the interface and to see real time synergic behaviours into the virtual space. When the user operates the HMI in the 2D application, commands are sent to the VR application, where the digital machine performs operations in a virtual environment. This allows testing of procedures that combine physical interaction in VR and HMI-based control. Such scenario allows to evaluate machine usability and human-machine interaction within a realistic industrial setting, representing both virtual and physical interactions between the user and the system.

Such toolkit aims to incorporate human factors into the design and validation phase of industrial machinery, for the evaluation of complex procedures involving user interaction with both the graphical HMI and the physical aspects of the machine (e.g., leverages, buttons, doors, supporting tools). This provides valuable insights into areas requiring optimization, including the user interface the geometry and the layout of the machine, and even the spatial and temporal sequence of procedural steps.

3.2 VR app

The VR app is organized with a modular structure to ensure scalability and adaptability to different machine models and test scenarios. Each component of the environment is built to represent a specific part of the machine or user interaction process, enabling realistic and flexible simulation of machine usability. In Unity, objects and components are arranged hierarchically, with parent-child relationships reflecting the actual dependencies of the physical and operational parts of the machine. The generalized structure of the application is shown below:

Main scene The central virtual environment in which the simulation takes place. This scene serves as the main container for all *GameObjects* and is designed to replicate the real-world industrial workspace. It provides a fully immersive environment in which the user can move around, manipulate and test the digital machine model. The Main Scene contains.

Machine model: it is the 3D representation of the simulated industrial machine. This model is composed of various subcomponents that mimic the mechanical and functional elements of the real machine. The model includes mechanical parts (e.g., levers, gears, buttons or switches) and interactive elements. These include any moving or operational parts that require user input (e.g., handles, touch points, or control panels). Each interactive element is configured to respond to user actions in real time, triggering corresponding changes in machine behaviour within the virtual environment.

User Interface elements: the scene includes a number of elements that help guide the operator through the virtual environment to enhance the experience. These elements, which are non-invasive but critical for navigation and feedback, are often represented by visual indicators (highlighted or illuminated areas that show the parts of the machine that the user can interact with), instructional prompts (text or symbols that provide guidance on the next steps or tasks to be performed by the user), and virtual controls (HUD elements or virtual buttons that allow the user to execute commands without leaving the VR environment).

Physics and Collision Systems: the Unity's physics engine is used to simulate the realistic physical behaviors of machine parts, providing accurate feedback on interactions such as pressing buttons, rotating levers, or moving larger machine components. "Rigid bodies" and 'colliders' are used on each machine component to simulate real-world physical interactions. The collision detection system ensures that user interactions with various machine components are accurately detected and registered. This system also helps prevent unrealistic actions, such as passing through solid parts of the machine.

User Interaction Handlers: they are designed to detect and interpret user actions, such as hand movements, controller inputs, or other tracked inputs from external devices and managed by the toolkit e.g., Leap Motion [42], different types of controllers [43]). The User Interaction Handlers are implemented through the Unity input system and custom scripts, and they ensure that the user's interactions with the machine are recognized and translated into real-time responses by the digital machine model. They also ensure that the machine's responses (e.g., moving parts or visual feedback) are consistent with the user's input. For example, pulling a lever should activate a specific part of the machine, such as rotating a component or starting an operational process.

The left side of Fig. 2 illustrates the essential logical framework for the effective use of the VR application. It begins with the "Scene Setup" block, which involves importing the CAD model of the machine and all other necessary models, such as tools and various workstation elements, into the virtual environment. Once the models have been imported, the physical configuration of these objects is carried out. This includes defining physical properties such as mass, friction, and collision behaviours. Next, interactions with each virtual element must be established. This phase involves programming how users will interact with the objects, including controls for grasping, moving, or manipulating tools and components within the virtual space. The next phase focuses on setting up the Network Object. This involves creating events that can trigger the movements defined in the initial step, which will be triggered by the interactions of the desktop HMI application. Proper configuration of these events is critical, as it ensures continuous communication between the VR and HMI applications, facilitating real-time responses to user input. In addition, establishing the Network Manager is essential. This component is responsible for the reliable transmission of data between the two applications. It may involve configuring protocols and establishing connections that enable synchronized actions between the VR environment and the HMI application. Once these components have been thoroughly configured and tested, the simulation can be started. This marks the transition from the preparation phase to active testing, allowing users to interact with the system and evaluate the usability of the machine in a controlled environment.

3.3 HMI app

The HMI application differs from the VR app for the 2D items (i.e., interface elements such as buttons, menus, text fields, and graphical indicators managed within the system) that are managed, but they both have a similar structure. The main HMI elements are built using Canvas components, which are specific Unity objects for rendering and interacting with 2D content. The Canvas system provides a structure that facilitates the display of graphical elements such as buttons, images, and text. Using Unity's scripting capabilities, each Canvas element can be dynamically manipulated to respond to the user inputs, simulate real-time changes, and mirror the behaviour of a physical machine interface. The HMI app operates as a standalone application on the same PC as the VR app, with the two applications communicating via a shared network system. This ensures that user inputs in the HMI app trigger corresponding actions in the VR app, maintaining real-time synchronization between the user interface and the virtual machine simulation. Unity's network tools and resource libraries facilitate this integration, making it straightforward to connect the applications for seamless interaction. During testing, users control the HMI using a standard input device, such as a keyboard, mouse, or touchscreen. Although the VR headset is typically worn throughout the simulation, users may need to remove the headset when operating the HMI. This approach reflects real-world scenarios where operators interact with both a physical control interface and the machine itself. Tasks are carefully structured to allow for transitions between the HMI and VR as needed, ensuring usability and workflow remain smooth. This architecture allows the HMI app and VR app to function as tightly integrated systems while remaining distinct in purpose and execution. It provides a realistic simulation environment where both physical and digital interactions are accurately represented.

The structure of the HMI application is organized around three main managers: Canvas Manager (responsible for rendering and interacting with 2D interface elements), CSV Manager (handles data storage and export using the widely adopted. csv file format), and Network Manager (enables real-time communication with the VR simulation). These managers are responsible for controlling the application interface elements, managing the data, and connecting to the VR simulation.

Canvas manager This manager serves as the backbone of the application's user interface, housing all the elements required for interaction. The Canvas Manager oversees several sub-managers, each of which is responsible for specific UI components and tasks.

Task manager It is responsible for presenting the user with a list of available tasks (or procedures) to perform. Each task represents a macro-level procedure that the user must complete. This functionality mimics the typical workflow an operator would follow in a real industrial environment, where they would select a specific operation to perform on a machine.

Instruction manager Once a task is selected, the Instruction Manager handles the guidance process, ensuring the operator follows the required procedure. From a technical standpoint, this functionality is implemented through a side panel within the user interface. The panel lists all the subtasks sequentially, dynamically updating to reflect the current step in the process. As each subtask is completed, it is visually marked, providing real-time feedback on progress. In terms of user interaction, the design of the interface aims to present the steps in a clear and intuitive manner. The subtasks are displayed in a structured, step-by-step format, which ensures the operator is consistently aware of the next action required. This approach not only facilitates smooth task execution but also aligns with the analysis goals, as it provides a controlled way to evaluate how operators interact with and follow the defined procedure.

Flow manager It is responsible for orchestrating the user's interactions with the interface in a structured and sequential manner. It controls the visibility and availability of UI elements based on the current process step. For example, if a task requires the user to press a specific button, the Flow Manager ensures that the button is only activated at the appropriate time and guides the user through the process in a logical manner.

Statistics manager As tasks are performed, the Statistics Manager tracks the user's performance. It monitors key performance indicators such as the time taken to complete each task and the number of errors made. This data is critical for evaluating the usability of the interface and the efficiency of the operator, providing a basis for performance analysis and potential improvements in both HMI design and operator training.

Network manager At facilitates the real-time synchronization between the HMI application and the VR application by properly managing the *Newtork Objects*. The Network Manager ensures that any action taken on the HMI (e.g., pressing a button or completing a task) is reflected in the VR environment where the digital machine is operating. The Network Object plays a key role in synchronizing the scenes and facilitating the exchange of events between the two applications. Conversely, any feedback or changes in machine state within the VR environment are sent back to the HMI, creating a closed-loop interaction system. This synchronization is critical for realistic simulation, as it ensures that the operator's input on the HMI directly corresponds to the machine's behaviour.

CSV manager Manages data collection and export. It maintains the structure of the data collected during the test, ensuring that all relevant performance metrics and physiological parameters are properly recorded. At the end of the test session, CSV Manager writes this data into a CSV file that can be easily exported for further analysis. This file contains detailed records of the operator's actions, allowing for post-test review and identification of areas that may require further optimization.

A key feature of the HMI app is the ability to collect detailed performance metrics as the user interacts with the system. For each subtask, metrics such as execution time and number of errors are recorded. This granular data allows for in-depth analysis of the operator's performance at each step of the task, identifying where errors occur and how efficiently the operator is able to complete the required actions. The design of the application allows these metrics to be aggregated at multiple levels. For example, by aggregating performance data across all subtasks, an overall assessment can be made of the user's ability to complete the entire procedure. This not only helps evaluate the effectiveness of the interface but also provides insight into the cognitive load and operational complexity of each task. The application collects several key usability metrics to evaluate the interaction between the user and the system. These metrics are as follows:

- **Errors**: This metric measures the number of mistakes users make while executing each task. It provides insight into task difficulty and highlights areas where the interface may require improvements.
- **Task Success**: Each task is assessed on a scale of 1 to 5, providing a qualitative evaluation of task completion. This rating takes into account the number of errors made, with higher scores indicating smoother and more accurate execution.
- **Time on Task**: This metric records the duration each user takes to complete individual tasks. Tracking task completion times is essential for understanding workflow efficiency and identifying tasks that may require further optimization.
- **Efficiency**: Efficiency is calculated by comparing the actions performed by the user with the minimum actions necessary to complete the task. This metric helps identify whether users are taking unnecessary steps, pointing to areas for streamlining.
- **Range of Physical Task**: This metric estimates the physical distance covered by the user during task execution, using task duration as a rough indicator. It differentiates tasks that are physically demanding due to complexity from those requiring extended movement across the workspace.
- **Visual Shifts**: This metric counts the number of times users shift their focus between the HMI and the physical machine. A high frequency of visual shifts may indicate a need to simplify the flow of information or improve the layout of the interface.
- **Movements**: This measures the number of times users physically move between the HMI and the machine. Frequent movements can reveal whether tasks are physically demanding or whether the workspace layout is inefficiently organized.
- **Machine/HMI Time**: This metric compares the time spent interacting with the physical machine to the time spent using the HMI. It provides insights into the balance of interaction and can highlight areas where adjustments might improve usability.

By integrating the aforementioned metrics, it is possible to derive critical insights for optimizing the UX. Specifically, the combined analysis of *Time on Task*, *Errors*, and *Task Success* facilitates the identification of the most critical steps within the procedure: high values for the first two variables coupled with a low score for the third indicate potential bottlenecks that may hinder operational efficiency. To further investigate the underlying causes of a physically demanding task, it is essential to assess *Movements*, *Range of Physical Task*, *Time on Task*, and *Efficiency*. For instance, a task characterized by high values across all four metrics may indicate that, despite being conceptually simple, it requires an excessive number of physical movements. In such cases, procedural optimization should be considered by refining both the HMI layout and the physical configuration of the machine to reduce unnecessary effort. Moreover, examining the balance between time spent on physical tasks and HMI interactions provides valuable insights into potential procedural inefficiencies. A significant imbalance may indicate workflow disruptions or suboptimal task allocation. Identifying the root causes of these discrepancies requires cross-referencing multiple usability metrics to pinpoint areas of improvement. Although this metric might seem secondary, it plays a crucial role in evaluating the operator's workload and overall working conditions. Ultimately, the goal is to refine the procedural flow, enhance machine design, and improve HMI usability, ensuring a more intuitive and efficient UX. Finally, evaluating *Visual Shifts* and *Movements* provides insights into whether frequent shifts in attention between the machine and the HMI indicate a strong dependency on real-time machine feedback during task execution. A high frequency of such shifts may suggest the need for a more intuitive information flow within the HMI or a reduction in the number of required physical interactions, thereby improving both usability and operational efficiency.

The right side of the block diagram in Fig. 2 illustrates the structured process for effectively using the HMI app to analyze and test human-machine interfaces. Unlike a simple HMI application, this tool allows users to recreate interfaces starting from images. The process begins with the Images Setup block, where the HMI interface is initialized by importing a series of screenshots. These screenshots serve as the foundation for recreating the interface layout within the application. This step is essential when analyzing an interface, as it enables users to accurately replicate its structure in the HMI app. Once the images are set up correctly, the next step is the Interaction Setup phase. In this stage, the Flow Manager is utilized to embed interactive elements into the interface. These elements are configured to perform specific roles, which are carefully aligned with each subtask in the procedure. For instance, a button might be linked to activating a machine component, while a slider might control a specific parameter. Task definitions are added at this stage, specifying the actions to be performed and analyzed. This systematic configuration ensures that the recreated interface supports a sequential and logical workflow, enabling users to navigate and interact seamlessly with the system. Following the interaction setup, the Network Setup phase comes into play. Here, the necessary network objects are configured to establish a connection with the VR application. Events are created and linked to the interactive elements, facilitating communication between the HMI and the VR application. This integration ensures that any interaction with the HMI triggers corresponding actions within the virtual machine, maintaining synchronization between the two systems. Once all setup phases are complete, the Testing phase begins. During this phase, the HMI app displays a full-screen interface: on the left side, a column lists all the subtasks to be executed, while on the right side, the actual HMI interface is presented, partially interactive. Users execute the tasks following the instructions provided in the subtask list while interacting with the reconstructed HMI. Throughout the testing process, performance metrics, such as task completion time and error count, are collected. Additionally, user interactions are observed directly to gain insights into user behavior, cognitive load, and potential usability issues. This observational approach complements the quantitative data, allowing for a deeper understanding of the interface's usability. Finally, the data gathered during testing is compiled by the CSV Manager for further analysis. This comprehensive dataset provides the foundation for evaluating both the HMI interface design and the overall interaction between the user and the system. The results enable iterative improvements to enhance both usability and system performance.

3.4 App integration and synchronization

In order to facilitate interconnection between the apps, it is necessary to configure specific components within the Unity environment for both applications. This dialogue is realized by the *Network Manager* and involves the *Network Objects*. These components are essential for enabling the two applications to communicate and synchronize events in real time. The *Network Manager* acts as the central controller, managing all communication between the VR and HMI applications. It must be configured with specific parameters, such as port number and IP address, to establish a proper communication path. The port number is particularly important in establishing the channel through which the data can be exchanged. In addition, the IP address is used to define the destination for the flow of data, thereby linking the server to the devices involved in the connection. Once the *Network Manager* is configured with the appropriate port and address, it takes over the responsibility of transmitting the packets, thus ensuring that the communication between the two applications is uninterrupted and reliable. On the other hand, the *Network Object* manages the transferred data and ensure that user input from the HMI is reflected in the VR application in real time. It also manages event transfer, where various events triggered in one application (such as user actions) trigger corresponding changes in the other application. In addition, synchronization ensures that both environments remain in sync, providing users with an integrated and coherent experience when interacting with both applications.

Once the network components have been established, it is necessary to define and structure events to facilitate interaction between the two systems. These events are created to correspond to specific user actions within the HMI. To illustrate, when the user completes a task or presses a button, an event is created and sent from the HMI application to the VR application. The event creation process involves identifying critical points of interaction between the HMI and VR systems. The custom events are designed to trigger appropriate actions in the VR environment, such as initiating machine operations or other procedural steps. The *Network Object* is responsible for ensuring that the transmission is successful, and that the VR application can receive the event and perform the appropriate action.

3.5 Toolkit setup

This section summarizes the workflow for setting up the toolkit, according to the phases highlighted into the block diagram. The workflow is then divided into two distinct parts, each focusing on one of the applications involved:

1. VR App:

    The virtual scene is initialized by setting up the 3D environment using a simplified, meshed version of the 3D CAD model of the machine, suitable for VR uses; Interactions with virtual elements are configured into the VR app to ensure that all operational components within the scene respond to user input;

Network elements are then set up to enable seamless communication between the VR and HMI applications, allowing real-time data exchange and event synchronization.

2. HMI App:

   The interface is established by loading the appropriate set of digital 3D images into the system. This step replicates the actual machine panel in the digital environment;
   Interactions with the HMI are configured to allow the user to interact with the interface as they would in a real environment. This includes operational controls such as buttons and switches that are replicated in the application;
   Like the VR application, the necessary network objects are set up to ensure proper communication between the two applications, linking user input from the HMI to the VR environment.

3. Testing Phase: Once both applications are fully set up, the simulation can be initiated. The user performs the assigned tasks in both the VR and HMI applications simultaneously, providing a comprehensive test of the system's functionality and usability. During this phase, performance metrics are collected for use in post-test analysis.

3.6 Comparative analysis of usability testing approaches

Usability testing plays a critical role in industrial machine design, ensuring that operators can efficiently and safely interact with systems. Traditional usability evaluation methods are generally divided into subjective methods, which rely on user feedback and expert analysis, and objective methods, which assess performance metrics and physiological data. These approaches have been widely applied in industrial contexts and can be combined to provide a comprehensive understanding of usability. However, they still present limitations when applied to early-stage machine design and evaluation.

Traditional usability testing is often conducted after physical prototyping, making late-stage design changes costly and time-consuming. Furthermore, HMI usability and machine operation are frequently evaluated separately, leading to a fragmented understanding of how users interact with the interface and the physical system simultaneously. While subjective methods (such as interviews, questionnaires, and heuristic evaluations) provide valuable insights into user perception, they lack reproducibility and can be influenced by bias. On the other hand, objective methods (such as task completion time, error rates, and eye-tracking) generate quantifiable data but may fail to fully capture cognitive workload, stress, or real-time decision-making processes. Although traditional methods can be combined to address some of these challenges, they still lack real-time, iterative feedback mechanisms and often require physical prototypes to validate usability aspects comprehensively. This results in higher costs, longer development cycles, and limited flexibility in modifying and optimizing machine interfaces before production.

The proposed VR-HMI system overcomes these limitations by integrating VR and HMI usability testing into a synchronized, real-time simulation framework. This approach allows operators to interact with a digital twin of the machine through a functional HMI prototype, enabling an integrated, iterative, and user-centered evaluation process before physical prototyping.

To sum up, the key advantages of the proposed VR-HMI System are:

- Early-stage usability testing: the system enables usability assessment at the earliest design phases, reducing the risk of costly late-stage modifications.
- Seamless integration of HMI and machine operation: the synchronized VR and HMI environment mirrors real-world conditions, ensuring a more holistic usability evaluation.
- Iterative and real-time testing: operators provide immediate feedback, enabling rapid refinements to both the interface and operational workflow.
- Cost-effectiveness: by eliminating the need for physical prototyping, companies can accelerate the design process while reducing costs.
- Comprehensive user performance assessment: the system integrates usability metrics, interaction tracking, and potential physiological monitoring, providing deeper insights into user cognitive workload and interaction behavior.

The table below (Table 1) provides a detailed comparison between traditional usability testing methods and the proposed VR-HMI methodology, emphasizing the advantages and improvements introduced by the new approach:

Regarding the limitation of the presented approach, the lack of realistic tactile feedback in VR can hinder accurate assessments of physical interactions, potentially compromising the validity of the findings. Additionally, users unfamiliar with VR technology might experience discomfort or disorientation, which could influence their performance during evaluations. These factors necessitate careful consideration when integrating VR into UX assessments to ensure reliable and applicable results.

4 Case study

4.1 Case study description

The case study is provided by a Italian company, worldwide leader in the design and production of industrial machinery across various business units (e.g., sanitaryware, ceramics, etc.). The case study focuses on a highly automated production line for the manufacturing of ceramic slabs and tiles. Human interaction with the machines is usually conducted through dedicated onboard HMIs, except for specific operations such as maintenance tasks. This case study is particularly relevant as it presents numerous challenges related to the combined use of HMI interfaces and physical interaction with the machines. The production line (Fig. 3) consists of a series of advanced systems, each playing a key role in manufacturing ceramic slabs and tiles. It begins with the Automatic Powder Bed (APB) system, which deposit coloured ceramic powder layers on the conveyor for design flexibility. The Digital Material Sprayer (DMS) system then applies decorative materials to enhance aesthetics, followed by the Digital Decoration Device (DDD), which decorates the surface for finer details. The Powder Compaction Roller (PCR) compacts the powder layer, creating a solid base, while the Transverse Precision Vertical (TPV) performs precise, continuous cuts. The Rectifying and Relaying System (RRS) transports and trims the slabs for uniformity, and the Measurement and Density X-ray (MDX) measures the density of each green slab to ensure quality and adherence to specifications. The case study procedure focuses exclusively on the TPV machine and includes a maintenance process. This process requires configuring specific settings on the HMI and performing checks on the TPV's vertical cutters to perform their calibration. Consequently, the procedure involves interaction with both the physical components of the machine and its digital interface, highlighting the need for seamless integration between the HMI and the practical operation of the machine. The initial data required to perform the test includes the CAD model of the machine, the procedure to be tested, and images of the interface.

4.2 HMI app setup

The first step is to divide the procedure into macro-tasks and further subdivide them into subtasks. For each subtask, it is necessary to define the textual instructions for the user (both for the operations to be performed on the HMI and to indicate to the operator that this is the time to perform the operation in VR), to specify the areas of the interface that require interaction, and to capture the interface images for each step of the procedure. Once this preparation is complete, the following components can be configured:

Table 1 Comparison of traditional and VR-HMI usability testing approaches

Criteria	Traditional Usability Testing	Proposed VR-HMI Testing
Timing of Evaluation	Conducted post-prototyping, making early changes difficult	Enables usability testing from the early design stages
Integration of HMI & Machine	HMI and machine usability are evaluated separately, leading to fragmented insights	Fully integrated, allowing simultaneous HMI and machine interaction analysis
Iteration Capability	Limited; changes require modifications to physical prototypes	High; refinements can be implemented in real time
Real-time Interaction	Not available; usability feedback is collected post-experiment	Available; users interact dynamically with the system and receive immediate feedback
Cost of Prototyping	High; requires multiple iterations of physical models	Low; usability testing occurs in a fully digital and simulated environment, but requires VR hardware
User Cognitive Assessment	Indirect, based on surveys and expert evaluations	Integrated, with usability metrics, interaction tracking, and potential physiological monitoring
Testing Environment	Conducted in physical labs or real production sites	Conducted in an immersive VR environment, replicating real-world conditions, but some real-world constraints may not be perfectly replicated
Scalability	Limited; each evaluation requires a dedicated setup per machine	Highly scalable; can be applied to different machine types with minimal adjustments
Data Collection & Analysis	Manual observation, requiring subjective interpretation	Automated data logging, allowing precise performance analysis and usability insights
Flexibility in Test Scenarios	Limited to predefined conditions; difficult to modify test cases dynamically	High flexibility, enabling real-time scenario modifications for adaptive testing
Risk Identification & Prevention	Often detected late in the development cycle	Early identification and mitigation of usability risks before physical prototyping
Operator Engagement	Passive observation and post-test reporting	Active involvement in real-time usability testing, but VR adoption may require initial training

- Task Manager: the entire procedure is divided into three separate macro-tasks to organize the workflow, which are the general navigation of the home page, the thickness gauge check of the disk-to-conveyor belt distance, and the safety sensor check;
- Instruction Manager: instructions for each previously defined subtask are added to a list that guides the user through each step;

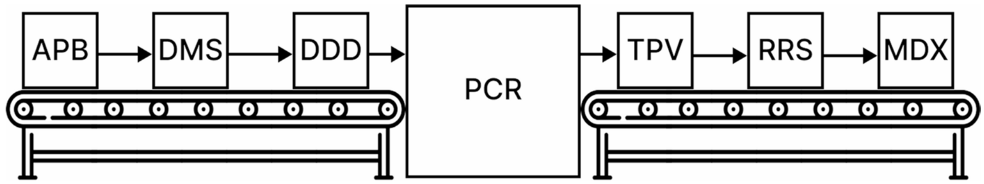

Fig. 3 Automatic line layout

- Flow Manager: interface images are loaded, and interactive interface elements are defined by adding *Buttons GameObject*;
- Statistics Manager: elements that trigger errors and track the time spent on each subtask are configured, with different buttons for each step of the procedure. Based on the settings of the Statistics Manager, the CSV Manager is used to configure the data to be exported.

Next, custom script-driven events were created and linked to the various buttons designed to trigger them. These events include velocity and acceleration values, which are assigned to objects within the virtual scene to execute specific movements. The Fig. 4 provides a generic example of the application's usage:

4.3 VR scene construction and setup

The scene construction follows the guidelines outlined in the methodology chapter precisely. Figure 5 shows the object hierarchy within the scene.

In this case, the main scene is titled 'TPV – Interaction Analysis,' and the Machine Model object contains several key components of the machine. Specifically, these include the Conveyor Belt, the Vertical Cutters, and a prefab labelled 'DIGITAL MODEL' representing the remaining machine elements. This setup was designed to optimize scene performance: the prefab was minimized to the smallest possible size without compromising human-machine interaction, while the Conveyor Belt and Vertical Cutters were optimized but not fully reduced in weight. These two components contain elements that are interactive and animated during the simulation, and therefore require a higher level of detail. During the optimization process (carried out with Pixyz software [45]) many elements are 'merged' together, which limits the ability to manage them independently. By maintaining the Conveyor Belt and Vertical Cutters as separate entities, the model retains its interactive functionality without sacrificing performance. For the User Interaction Handlers, OpenXR is employed in this case to interpret user actions, without any custom scripts added. User Interface Elements were kept minimal, with only contact indicators (see Fig. 6) to highlight when two objects make contact. The interactable elements include the Gauge Feeler, which is used during the procedure, and the vertical cutter discs, which need to rotate upon contact with the Gauge Feeler. Additional movable components are found in the vertical cutter, represented by prismatic joints. In this specific case study, the decision was made to use the XDE physics engine developed by CEA List, as XDE enables efficient animation of complex scenes with multiple rigid bodies interconnected by mechanical joints [46, 47]. XDE Physics provides precise collision handling and highly accurate simulation of dynamic effects, all at a rate compatible with haptic rendering [48].

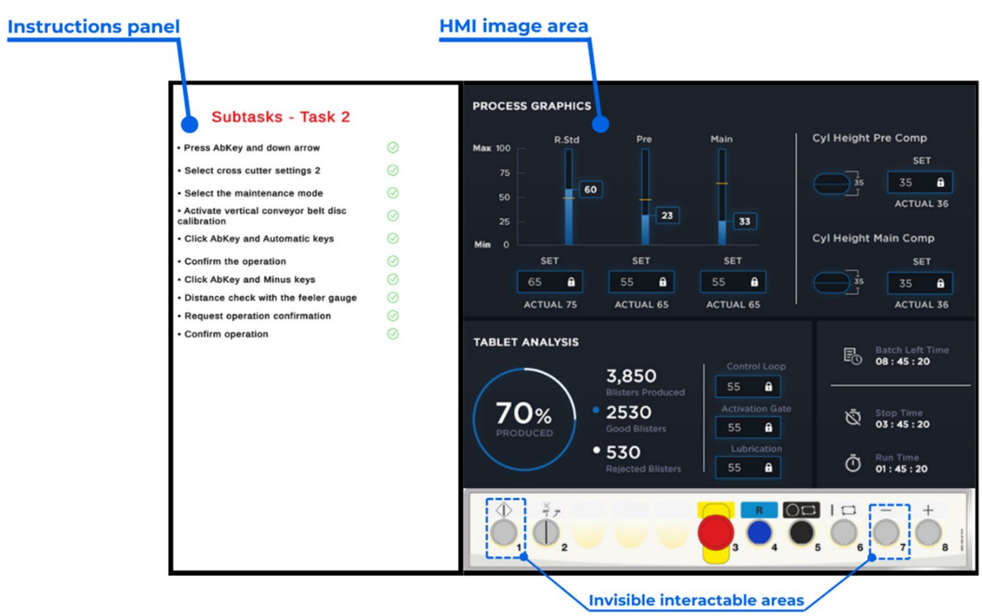

Fig. 4 Example of the HMI application interface, with an indication of the three instruction zones, the area in which images are present, and the interaction zones. The interface image was taken from [44]

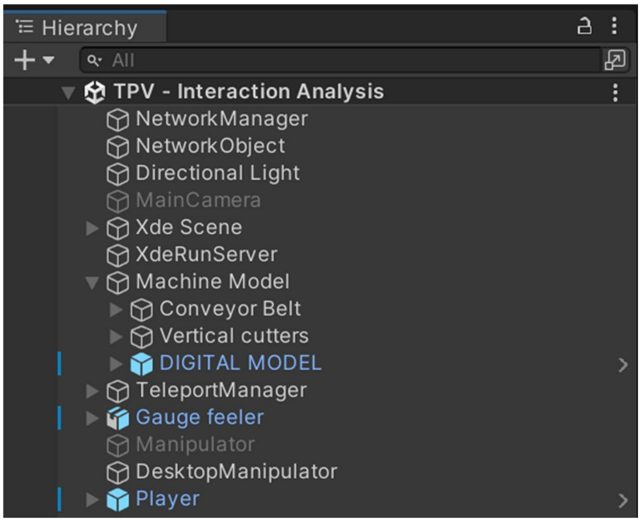

Fig. 5 Object hierarchy in unity VR app

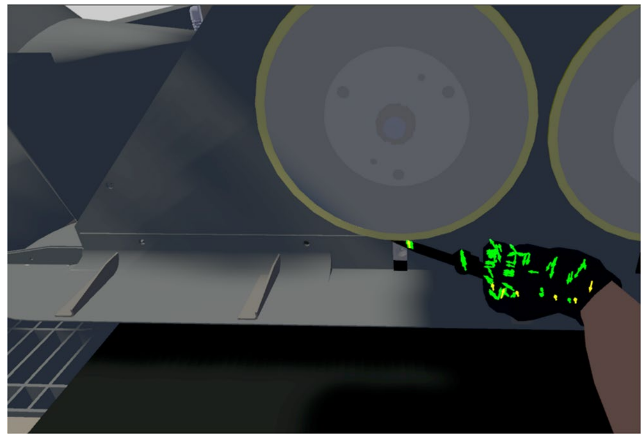

Fig. 6 Simulation of contact between the Gauge Feeler and the disc. The arrows indicate the contact points between the objects, including the hand and the Gauge Feeler

Custom scripts were developed to handle specific events, primarily to control the vertical movement of the cutting discs. The movement control is set up as a range-bound displacement between a lower and an upper limit. The created events provide velocity and acceleration to the moving object, which continues to move until it reaches its designated limit and then stops. The scene hierarchy also includes the Player component, which represents the user's perspective in the simulation, complete with interaction and collision detection capabilities. This setup allows for a highly immersive experience, as users can engage with objects within the scene, simulating real-world interactions. For debugging purposes, two manipulators were included. These tools enable developers to interact with objects without requiring the VR headset, making the debugging process more efficient and flexible. Additionally, a TeleportManager was integrated to facilitate user movement over larger distances within the scene. This feature provides a convenient way to navigate the virtual space, especially when testing requires covering multiple areas. To manage the overall simulation, two crucial components were added: Xde Scene and XdeRunServer. These elements work in conjunction with the XDE physics engine, handling the physics-based interactions and simulations within the virtual environment.

4.4 Toolkit testing

The testing phase was conducted using a Meta Quest 2 [43] headset al.ongside a touchscreen monitor (Fig. 7). This preliminary test had two main objectives: first, to evaluate the overall functionality of the system and its ability

Fig. 7 Execution of the test by a user: the top section shows an example of interaction with the HMI, while the bottom section displays the user interacting in VR

to accurately reproduce the tested procedure, ensuring a realistic simulation of the UX; second, to conduct an initial assessment of the overall human-machine interaction within the case study, analyzing both the interaction with the HMI and the physical interaction with the machine.

During this phase, three users with an industrial engineering background participated in the testing sessions. This choice was made to emulate real machine operators, who typically possess a solid understanding of industrial manufacturing environments. Additionally, their familiarity with VR technology was a key factor, as this preliminary testing phase aimed to focus on evaluating the system itself while minimizing potential issues related to a lack of experience with VR. Several key metrics were collected to provide insight into user interaction and performance (Tables 2 and 3).

The data presented in Tables 2 and 3 are a simplified version of the actual data collected, as the original data were divided into subtasks. In this case, only the macro-tasks (T1, T2, T3) have been considered, and the values shown represent an aggregation of the subtasks. Not all of these metrics were collected automatically. Specifically, metrics related to visual shifts, physical movements and the range of physical task were manually observed and recorded by the expert administering the test. These observations provide valuable qualitative insights that complement the quantitative data, offering a complete picture of UX during task execution.

4.5 Discussion

G1: Evaluate the ability of the proposed system to replicate real-world human-machine interaction as accurately as possible.

The primary goal of this preliminary test was to assess the overall functionality of the system and its ability to accurately reproduce the tested procedure, ensuring a realistic simulation of the UX. The results indicate that the execution times observed in the virtual environment closely align with those recorded in real-world operations (both about 10 min long), reinforcing the reliability of the system in faithfully replicating the procedure. Furthermore, user observations confirm that the system provides an accurate and consistent reproduction of the test scenario, supporting its applicability for future validation studies. The choice of users with prior experience in VR was intentional, ensuring that unfamiliarity with the technology would not interfere with the testing process. However, this aspect should be considered in future studies, as participants with limited VR experience may require an initial adaptation phase, which could slightly impact execution times and overall usability.

Table 2 Results of the preliminary testing phase - part 1

User ID	Errors [*n*]			Task Success [1 ÷ 5]			Time on Task [min]			Efficiency		
	T1	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
1	1	4	2	4	4	4	1:06	6:34	3:21	0,75	0,71	0,77
2	2	4	3	4	4	3	1:14	6:48	4:13	0,60	0,71	0,70
3	1	5	1	4	3	5	1:09	7:22	2:45	0,75	0,66	0,88

Table 3 Results of the preliminary testing phase - part 2

User ID	Range of Physical Task [min]			Visual Shifts [n]			Movements [n]			Machine/HMI Time		
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3
1	0:00	3:12	2:41	0	2	1	0	5	4	0	0,97	0,75
2	0:00	4:02	3:09	0	2	1	0	7	7	0	0,61	0,75
3	0:00	3:55	2:34	0	2	2	0	7	6	0	0,97	0,96

G2: Test the system within an industrial case study to assess both the procedural workflow and the overall human-machine interaction.

The secondary goal of this preliminary test was to conduct an initial evaluation of the overall human-machine interaction within the case study, analysing both user interactions with the HMI and physical interactions with the machine. The analysis of the collected metrics identifies T2 as the most critical step, as demonstrated by significantly longer completion times (ranging from 6:34 to 7:22 min) and the highest error rates (min 4, max 5 errors recorded). Additionally, T2 exhibits the lowest efficiency scores (min 0.66, max 0.71), underscoring its complexity compared to T1 and T3. A closer examination of physical and HMI interactions reveals that T2's physical tasks are particularly challenging, with extended execution times and increased operator movements (min 5, max 7 movements per user). The physical range for T2 also stands out, spanning between 3:12 and 4:02 min, highlighting the substantial temporal and spatial demands placed on operators. Conversely, HMI interactions in T2 are marked by frequent visual shifts (2 shifts per user), likely caused by interface design issues or frequent context changes that disrupt workflow and add cognitive load. This is further reflected in the prolonged Machine/HMI engagement times (min 0.61, max 0.97), which negatively impact overall performance. T1 and T3, on the other hand, demonstrate lower criticality. These tasks require less time, involve fewer errors, and achieve higher efficiency scores. In particular, T3 achieves the highest efficiency values (min 0.75, max 0.88) and the lowest error rates, while T1 consistently features minimal operator movements and reduced physical task ranges. In summary, T2 emerges as the most demanding phase of the procedure, warranting targeted improvements in physical task design and HMI optimization. Addressing these issues can help minimize unnecessary movements, shorten task durations, and improve overall efficiency.

4.6 Limitations and future developments

It is essential to acknowledge certain limitations observed during the preliminary evaluation. While the results provide a strong foundation, they may not fully capture the variability and complexity encountered in broader industrial scenarios. The selected case study illustrates the model's applicability within a structured industrial environment; however, it does not encompass the full range of operational conditions typically found in more dynamic manufacturing settings. Aspects such as adaptability to different machine types and performance under varying operational constraints require further investigation. To address this, future research should aim to conduct an extensive test campaign across diverse machine types and operational contexts, incorporating scenarios that better reflect the dynamic nature of industrial environments and evaluating the system's robustness across different use cases. Another significant limitation is the reliance on high-performance hardware and computational resources, particularly for running the VR application with integrated physical simulations. This presents a potential barrier for smaller enterprises that may not have access to such resources. Addressing this issue could involve exploring optimization techniques to make the system more accessible and scalable for a wider range of industrial users. One more limitation observed during the test phase was the need for users to repeatedly put on and remove the VR headset. As a potential solution, upcoming advancements will focus on testing the use of Extended Reality (XR) to overcome this issue.

Future developments could incorporate physiological data monitoring to provide a comprehensive evaluation of the operator's cognitive load and stress state during task execution [49], also aligning with the principles outlined in the Objective Evaluation of Usability Assessment (Fig. 1 [39]),. Specifically, parameters such as Heart Rate Variability (HRV), Galvanic Skin Response (GSR), and Pupil Dilation (PD) could be integrated into the toolkit to quantify mental workload and emotional states in real time. These physiological signals would complement the existing performance metrics by providing an objective assessment of stress levels, attentional shifts, and cognitive fatigue. For instance, HRV and GSR can indicate stress and autonomic nervous system activation, helping to identify tasks that induce high cognitive strain. PD could be used to detect increased mental effort during complex operations. By correlating these physiological indicators with usability metrics such as *Errors*, *Time on Task*, and *Visual Shifts*, it would be possible to pinpoint specific procedural steps that contribute to excessive cognitive demand, guiding targeted improvements in both the HMI layout and operational workflow. To implement this, wearable biosensors could be integrated into the testing environment, allowing continuous and non-intrusive monitoring of physiological responses. The collected data could then be synchronized with user interaction logs within the VR and HMI environments, enabling a multimodal analysis of human-machine interaction. This enhanced framework would not only refine usability evaluations but also support the development of adaptive interfaces capable of responding dynamically to the user's cognitive state, ultimately optimizing efficiency, reducing errors, and improving overall UX. Additionally, leveraging machine learning algorithms to analyze user interactions in real time could provide actionable insights for designers, enabling rapid iteration and optimization of the machine interface and functionalities.

5 Conclusion

The integration of VR and HMI applications as a testing system for industrial machines demonstrates significant potential in enhancing HCD processes within Industry 5.0. By enabling operators to interact with a virtual machine model and its control interface, this approach improves usability assessment and optimizes human-machine interaction from the early design stages. The findings confirm that VR-based usability testing, combined with HMI simulation, allows for early identification of design issues, reducing the need for costly late-stage modifications while enhancing operational safety and efficiency. A few limitations must be acknowledged. The current validation was conducted within a structured industrial environment, which may not fully capture the variability of more dynamic manufacturing settings. Additionally, one challenge observed during the testing phase was the repeated need for users to put on and remove the VR headset, which may impact workflow efficiency. Despite these limitations, the system's flexibility and adaptability allow it to accommodate various machine designs with minimal adjustments—an essential feature in modern industrial settings where rapid iterations are required. Moreover, embedding usability testing at the initial stages of development fosters a more user-centric design process, reducing risks, enhancing safety, and improving efficiency. Future research should explore ways to integrate physiological data monitoring to further refine usability assessments, providing deeper insights into cognitive load, stress levels, and attentional shifts during task execution. These enhancements would contribute to developing adaptive interfaces capable of dynamically responding to the user's cognitive state, further optimizing usability and workflow efficiency. Furthermore, this approach promotes collaboration among engineers, designers, and end-users, as stakeholders can interact with the machine's interface and operation before physical deployment. Beyond usability improvements, the integration of VR and HMI testing has the potential to revolutionize industrial workflows. By reducing the need for physical prototypes and allowing real-time human-machine interaction analysis, this system can shorten development cycles, lower production costs, and improve safety standards. Additionally, its adaptability makes it suitable for a wide range of industrial applications, from manufacturing automation to operator training, positioning it as a valuable tool for accelerating I5.0 transformation.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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