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Development of a VR-Based Digital Factory Planning Platform for Dynamic 3D Layout Editing

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Abstract

Factory planning plays a critical role in the optimization of manufacturing processes. Recent technological advances, especially in Virtual Reality, offer potential to enhance planning efficiency and to meet evolving planning standards and requirements. Current challenges persist due to technological gaps in virtual environments for factory planning. These challenges encompass mismatches between digital models and actual systems, difficulties in managing dynamic layout edition, scalable factory designs, real-time simulations, and more. This study addresses these challenges by introducing the VR-based Digital Factory Planning Platform, which utilizes Unreal Engine for rendering, VR support, and programming interfaces. The Digital Factory Planning Platform features three key functionalities: dynamic 3D layout editing, a data exchange connection for mathematical optimization solutions, and VR visualization of scalable layouts. We validate these functionalities through two case studies. The platform evaluation process with factory planning experts encompasses usability, accuracy, and practicality metrics, providing insights into the impact on factory planning processes. Using VR and Unreal Engine capabilities in developing the Digital Factory Planning Platform supports improved decision-making and resource utilization in manufacturing.
This research contributes to the industrial application of virtual environments, particularly the use of VR for factory planning, thereby paving the way for enhanced planning of manufacturing processes. The Digital Factory Planning Platform aims to enhance planning efficiency by aligning VR technology with industry needs and addressing the specific challenges in factory planning tasks.

Keywords: Factory Planning; Manufacturing Digitalization; Automated Layout Design; Virtual Reality; Planning Optimization; Unreal Engine

1. Introduction

In the modern manufacturing environment, factory planning (FP) is crucial for dimensioning and designing production facilities and to enhance operational efficiency in the associated production processes. The introduction of the Industry 4.0 initiative, encompassing technologies as the Industrial Internet of Things, Big Data, Artificial Intelligence, and Virtual Reality (VR), significantly enhances FP by offering new tools for optimization and efficiency. However, traditional approaches in FP often suffer from manual, time-consuming processes susceptible to human errors. Addressing challenges in FP, particularly through virtual reality and virtual environments, emphasizes the importance of digitization and innovation. For Small and Medium-Sized Enterprises (SMEs), essential in supplying larger factories, the need for digital solutions and innovative technologies is critical. These sectors must rapidly adapt to significant business changes, highlighting the need to reevaluate organizational structures to integrate digital tools in FP effectively [1-3].

The challenges that concern to FP in virtual environments include mismatches between digital models and actual systems, difficulties in managing dynamic layout edition, challenges in software integration, inadequate response times for time-critical simulation [4-6]. Addressing these challenges is crucial

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for improving planning efficiency, productivity, and overall performance in the manufacturing sector, for example, in the serial production of electrolyzes.

The motivation for this research results from the manufacturing sector's pressing need for digitization, aiming to enhance efficiency and productivity. The integration of digital technologies is crucial in transitioning traditional factory operations into automated, data-driven processes, aligning with Industry 4.0 principles [4]. As such, FP must prioritize optimization and continuous development through the timely adoption of new industry technologies.

To address these challenges, this research proposes the development of a DFP Platform utilizing UE. The platform will feature dynamic 3D layout editing, integration with production optimization algorithms, and VR visualization capabilities. By using UE's features, factory planners can make informed decisions, optimize production processes, and adapt rapidly to changing demands.

2. State of the art

2.1. Dynamic scalable factory layouts challenges

The trend towards mass personalization requires manufacturing operations that are flexible and capable of producing custom products at demand-based batch sizes efficiently, yet, many current manufacturing environments lack the adaptability needed for dynamic production needs, struggling to modify production and layout structures without negatively affecting the overall performance [7, 8]. Moreover, attaining requirements such as interoperability, modularity, scalability, as well as real-time and knowledge-based responsiveness is essential to overcome challenges faced in the Digital Factory [9]. To fulfill these requirements and adapt to the rapidly evolving industry, companies have turned to immersive technologies, as well as connectivity technologies, to develop Digital Factory solutions, such as the Digital Twin [7, 10-12]. Digital Factory approaches focus on standardizing and optimizing the complete production and logistics of a facility, enhancing the overall planning, execution, and management of factory operations, giving competitive edge to the companies that implement these methodologies and tools. "Digital Factory" is a recognized term, reflecting a comprehensive strategy that integrates digital technologies to create more efficient, connected, and adaptable manufacturing environments [1, 13, 14].

Further innovations include a four-step model designed to assist SMEs in planning flexible, interoperable, digital, and data-driven business models that integrates Digital Twins by designing the manufacturing technology, material flow, ICT management systems, and an Asset Administration Shell [10]. To address affordability, labor intensity, and accuracy in FP for SMEs, Sommer et al. proposed a method for creating a Digital Twin. This involves using rapid scans to generate a digital point cloud of the shop floor, processed through AI for object recognition, thus transforming the physical layout into a digital model. This method facilitates value stream analysis and bottleneck identification, enabling layout improvements [14]. Fan et al. proposed a framework involving digital twins and modular AI to allow manufacturing systems to dynamically adjust, aligning with shifts in market demands or customer needs by following a knowledge-based approach that allows rapid adaptation of factory configuration [15]. Balla et al. presented an approach where the game engine Unity3D was used alongside the Game4Automation framework for the development of digital twins; bidirectional data flow between the PLCs of real and their digital system through the Siemens TIA portal, allow realistic simulations at a lower cost [16].

2.2. 3D virtual environments for factory planning

FP encompasses more than just designing the layout; it involves a comprehensive approach to optimizing both digital and physical elements within a facility to enhance productivity. Layout planning is a significant component of this process, focusing on the strategic arrangement of these elements for improved efficiency and performance [10]. FP aims to design layouts with optimal resource allocation where the machinery and all elements that make up the production process yield a coordinated workflow while considering performance, costs, ergonomics, and safety regulations [11, 17]. However, traditional FP methods struggle to fully capture and assess the complexities of production settings, making it hard to make fast-informed decisions [9].

Additionally, traditional 2D planning approaches tend to be inaccurate due to unintended human error and inaccuracy [18]. Therefore, the development of digital solutions that integrate Industry 4.0 technologies are key for the transformation towards smarter factories, where tasks become ever more autonomous, leading to better configurations of manufacturing environments [19, 20]. For a factory to stand out competitively, access to digital FP solutions such as virtual environments, where people can collaborate in the comprehensive planning process of a factory system, has been suggested [21]. The use of 3D virtual environments and advanced technologies for the design and evaluation of factory layouts, without the need for physical prototypes or real-world testing, is then known to reduce costs, save time, and improve the overall accuracy and efficiency of FP [2]. The creation of virtual environments that mirror the physical world is a key step towards developing digital twins, offering a more comprehensive understanding and control over the changes in the manufacturing processes' impact [22].

2.3. Virtual reality for factory planning

In the context of digital factories under Industry 4.0, simulation plays a crucial role by enabling high-fidelity representations of manufacturing environments. These simulations support advanced production design and decision-making by mirroring physical systems within a digital framework. While VR is not merely a form of simulation, it complements these simulations by providing immersive, real-time visualizations that enhance understanding and interaction with digital twins of physical factories [23]. Specifically, VR is acknowledged as a crucial factor in achieving the goals of Industry 4.0, enhancing manufacturing settings by facilitating smart factories and digitalized production [2, 4, 10, 24, 25, 26]. VR can provide immersive experiences that allow for effective factory layout planning, enabling rapid adjustments to market demands with minimal risk at low costs [17, 27, 28]. Particularly, the introduction of the head-mounted display and the development of advanced VR hardware has increased the accessibility and widespread use of VR technology as a solution to FP challenges [13].

Various methodologies have been proposed to leverage VR and digital technologies in FP, enhancing planning efficiency, decision-making, and collaboration while optimizing layouts and production processes. Nåfors et al. proposed a 3D laser scanning approach for brownfield layouts with knowledge-building cycles integration to create an immersive VR environment where data management is enhanced for a faster and more accurate FP process [29]. 3D laser scanning and VR were also combined by Hingst et al. to develop a virtual environment that improves digital FP training, offering reliable data acquisition and enriched learning [30]. Bellalouna introduced an interactive VR-based method in Unity3D for proactive FP, enabling immersive simulation and evaluation of layouts, surface use, and material flows, which has shown promising results in enhancing user experience, efficiency, and safety in factory design, even before construction begins [13]. Havard et al. developed a vPerf that allows interactive virtual collaboration in the creation manipulation, and reconfiguration of factory layouts in real-time with production insights like KPIs [27]. Tecnomatix Plant Simulation and VR technology were used by Hovanec et al. to replicate real process conditions and optimize factory layouts digitally before physical changes are made, complemented by VR technology to foster collaboration and visualization of the improved material flow, ergonomics, and workforce efficiency within the Digital Factory [4].

Bracht et al. introduced Factory Planning 5.0, an integrated VR approach enabling optimized layout planning through simulation and immersive interaction with virtual models. This system allows planners to manipulate and assess various layout options in VR, providing key data on material flows and logistics, supported by a real-time communication channel for enhanced simulation accuracy, paving the way for digital twin integration in FP [31].

Angeli et al. presented an approach that integrates ERP systems and visTABLE software for enhanced data exchange and layout optimization. This method streamlines material flow analysis and layout efficiency, incorporating steps from initial layout recreation to final implementation planning, complemented by VR for layout validation. While the approach boosts collaboration and efficiency, the authors advocate for cloud-based ERP data storage to streamline processes further [17]. Current industry applications include the pioneering virtual FP approach from BMW Group; NVIDIA Omniverse Enterprise has allowed BMW to completely plan, validate and optimize their Debrecen plant on a virtual environment before the actual construction, revolutionizing the FP process [32].

Regarding the utilization of UE as a tool for the Digital Factory, Apala et al. introduced a collaborative digital factory metaverse using UE, allowing real-time team collaboration in a virtual environment for the Industry 4.0 technology training for staff members [25]. As well, Ding et al. employed UE to create a virtual workshop were fault monitoring model based on neural networks along with digital twin technology for data exchange, real-time monitoring, and operational control, demonstrating the engine's potential in simulating and optimizing manufacturing processes by dynamically rescheduling the processes [33].

The integration of advanced software and tools, such as Unreal Engine, enhances the planning, execution, and adaptability of manufacturing systems. While many successful approaches have been described, there remains a research gap in identifying comprehensive strategies to address the needs for action. This underscores the need for further development of functionalities to address specific challenges in scalable factory designs and real-time simulations. However, to guide the future development of software solutions, the usability and effectiveness of possible functionalities needs to be assessed. Therefore, we set out to significantly enhance the efficiency and flexibility of FP tasks, particularly in dynamic scalable factory layouts, such as those required for the serial production of electrolyzers.

3. Development of the VR-Based DFP Platform

To address the research gap, we focus on the development of a VR-based DFP Platform, providing a basis to assess the implemented functionalities. For this purpose, the DFP Platform's architecture and functionalities, including dynamic 3D layout editing, mathematical optimization, and VR visualization, are outlined in the following. Subsequently, the application of the platform is demonstrated through two case studies on Demonstrations Factory Aachen and a virtual e-bike production, including the experimental setup. Lastly, the user evaluation process is detailed, focusing on assessing usability, accuracy, and practicality in real-world scenarios through semi-structured interviews, thereby connecting the platform's development design with its practical application.

3.1. DFP platform functionalities and architecture

The DFP Platform, aimed at optimizing FP and streamlining processes, combines a structured architecture with advanced solutions to address manufacturing complexities. It offers a comprehensive toolkit to enhance efficiency and decision-making, with the following developed functionalities:

1. *3D layout edition and manipulation:* Users can add buildable objects to the layout, control their placement, rotation, and deletion, ensuring validity and precision. Smart path functionalities enable automatic placement of machines for defined processes.
2. *Data exchange and machine selection optimization*: Users define production goals and parameters, connect to an external server for data exchange, and receive optimized machine selection results. Manual or automatic placement of optimal machines is facilitated.
3. *VR visualization*: Layouts can be saved and loaded into the platform, allowing users to visualize different factory layout scenarios in a virtual 3D space. Navigation around newly placed machines is supported for enhanced visualization.

The DFP Platform architecture comprises several key elements that facilitate its functionality, as shown in Figure 1.

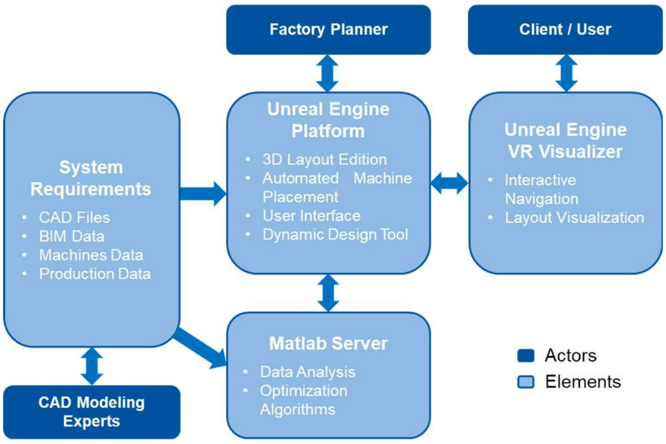

Figure 1. DFP Platform general architecture.

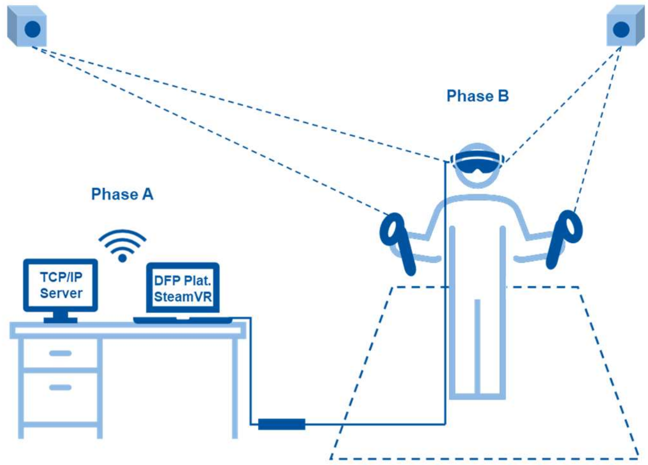

Figure 2. DFP Platform experimental setup.

At the core of the architecture lies the Unreal Engine Platform, offering factory planners a virtual environment for 3D manipulation of objects to create and edit factory layouts. This platform establishes a connection with an external server, the MATLAB server, enabling data exchange for optimization based on user production specifications. The DFP Platform relies on relevant data provided by CAD modeling experts from the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, including production flow information, product type variants, machine/workspace specifications, production parameters, and building models. This data informs the programming of functionalities within the platform. The MATLAB server processes optimization requests, employing mathematical models and functions to optimize machine selection based on user inputs and predefined specifications. Once optimized, results are sent back to the platform. Additionally, the DFP Platform integrates an Unreal Engine VR visualizer, enabling the immersion of factory planners in their layouts and facilitating client demonstrations for effective project communication.

3.2. Case studies and experimental setup

The first case study revolves around the Demonstration factory Aachen (DFA), an RWTH Aachen University facility in Germany dedicated to applied research and testing new production technologies. DFA provides a real-world factory environment for collaborative research in areas such as Digitalization and Industry 4.0. The study involves creating a 3D model of the DFA building to implement functionalities focusing on editability and interactivity.

The second case study centers on designing layouts for an e-bike manufacturing facility, emphasizing machine selection optimization based on space utilization. Developed by the digital factory planning team at the WZL institute, the "e-Bike Production" scenario offers a foundational example for developing and showcasing digital FP solutions. It includes stages requiring manual intervention to explore production limits and economic decisions regarding in-house production versus external procurement of components. This simplified scenario provides an ideal starting point before applying these technologies to more complex industrial cases.

The described case studies serve as practical examples of the platform's capabilities, which can be extrapolated to further applications, such as the serial production of electrolyzers. This extension demonstrates the platform's versatility in adapting a range of industrial processes and planning scenarios.

The experimental setup was placed in a controlled environment within an office at the WZL institute. FP experts utilized the latest version of the DFP Platform and evaluated their experience. The experimental phase consisted of two parts: Phase A involved testing functionalities for both case studies to design a layout in the virtual environment of the DFP Platform, while Phase B focused on visualizing the saved layout in VR. Figure 2 illustrates the components necessary for testing the DFP Platform. In Phase A, the DFP Platform runs on UE version 5.1 and connects to an active TCP/IP server in MATLAB R2023a for data exchange during the optimization process. In Phase B, VR hardware accesses the DFP Platform's VR visualizer via the SteamVR platform, utilizing an HTC VIVE VR headset, two motion controllers, and two tracking sensors to ensure an immersive and accurate VR visualization experience.

3.3. User evaluation

This section introduces the semi-structure interviews evaluation method utilized to gather insights and feedback on the DFP Platform's practicality and effectiveness. The goal is to present how these interviews serve to collect crucial data for evaluating the platform's performance and user experience, while also validating the DFP Platform against the objectives of this study.

The initial interviews gathered FP experts from the WZL institute at RWTH Aachen University, fostering discussions to identify key functionalities and potential solutions for addressing FP challenges. Through collaborative dialogue, participants outlined essential features and considerations crucial for enhancing FP processes.

Subsequently, a series of semi-structured interviews were organized, inviting the same experts to interact with and evaluate the DFP Platform firsthand. During this session, participants actively engaged with the platform, providing valuable feedback, comments, and suggestions. These insights were meticulously recorded to inform about further improvements and refinements to the platform. As part of the interviews user feedback surveys were administered to participants, allowing them to express their opinions on usability, challenges encountered, and suggestions for enhancements. The open-ended nature of the survey questions facilitated a deeper understanding of user interactions and preferences within the virtual environment. Measures were implemented to safeguard participant privacy, including anonymity and secure storage of user data. Furthermore, participants were provided with debriefing sessions to address any concerns and ensure a positive overall experience.

The results of these interviews and surveys, along with the insights gathered, will be presented in Section 4.2, offering valuable perspectives on the DFP Platform's efficacy and potential areas for improvement.

4. Study results

In this section, the results obtained from the platform's functionalities are presented, followed by the outcomes of the user evaluation. Lastly, the overall results are discussed, offering a comprehensive view of the platform's effectiveness and utility in the context of FP.

4.1. Functionality outcomes

One of the core functionalities of the DFP Platform is the dynamic 3D layout editing and manipulation feature. This functionality enables users to interact with the virtual environment, placing and adjusting various elements to create factory layouts. Figure 3 illustrates this process with four images showcasing the intuitive interface and interaction mechanisms for the case study I.

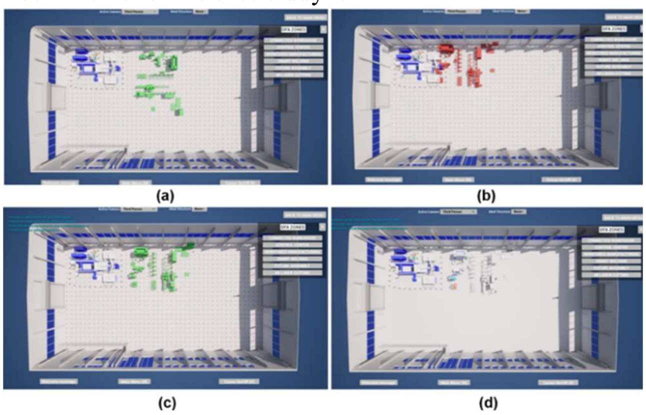

Figure 3. Addition of buildable objects to a layout and their behavior: Valid placement/undesired rotation (a), Invalid placement/desired rotation (b), Valid placement/desired rotation (c), Placed buildable object (d).

The first image depicts the selection of a specific zone for placement within the virtual environment. Upon selection, a grid appears, aiding in precise placement. Additionally, a "buildable ghost" is displayed, indicating the intended location for placement, which dynamically updates its color to signify the validity of the position.

In the subsequent images, users can observe the rotation of the buildable preview for optimal alignment and placement. The color of the ghost changes in real-time, transitioning between red and green based on collision detection with existing structures or walls. Once positioned correctly, users can confirm placement with a keyboard command, as indicated in the interface's instructions and log prompts.

The subsequent functionality involves the automatic placement of a specified group of machines, as demonstrated in case study II. Upon clicking the "Automatic machine placement" button in the Main Menu, users can specify the number of machines to be placed, as depicted in Figure 4. Initially limited to machines for the cutting process, users are then prompted to create a placement path following the instructions provided in the log. Figure 4 illustrates the process, including creating an AI finder, setting the target end point, switching to the Top Down DFA camera for optimal viewing, displaying coordinates for the shortest path, and ultimately, the automated placement of machine rows along equidistant points within the designated path.

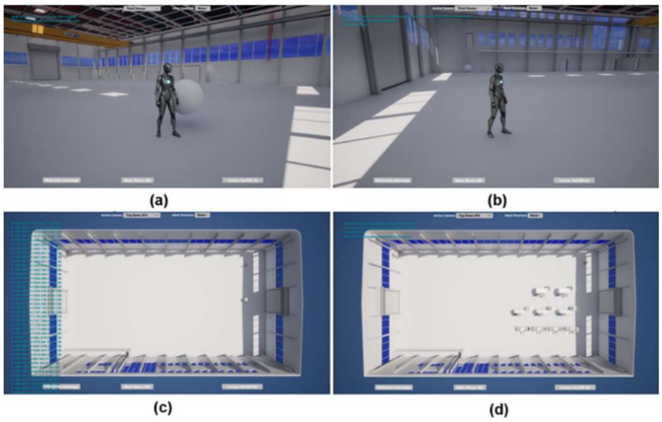

Figure 4. Automatic machine placement process: Setting initial point (a), Setting final point (b), AI path finder functionality (c), Machine placement (d)

Moreover, users have the flexibility to edit and manipulate placed objects. Selection of objects triggers confirmation prompts, allowing users to either proceed with adjustments or deselect objects if needed. This user-friendly approach enhances the precision and efficiency of layout creation within the virtual environment.

The fifth button on the Main Menu introduces the second functionality: optimizing the capacity planning through the capacity planning via data exchange with MATLAB. A crucial step in this process is ensuring connectivity with the server, as highlighted earlier in this section. Figure 5 illustrates the user interface for this functionality, prompting users to specify the desired annual production of e-bikes for each type and input relevant production parameters.

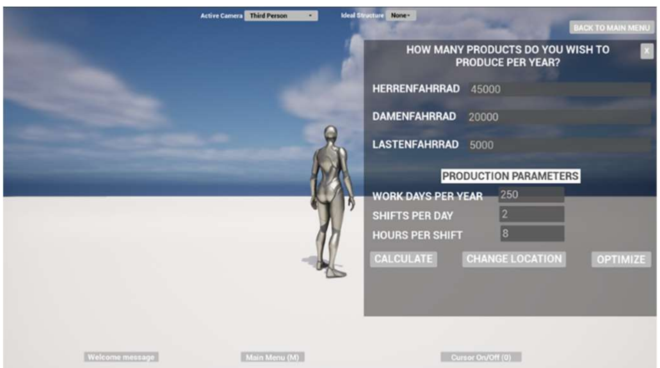

Figure 5. Machine selection optimization menu.

Following input, clicking the "Calculate" button initiates an initial output calculation for each process to achieve the production goal. Due to limited space within the DFA building, users have the option to relocate to an open space outside the building by clicking the "Change location" button. Once the location is selected, clicking "Optimize" triggers MATLAB to optimize machine selection based on production needs while minimizing space requirements. Upon completion, data optimized by MATLAB is transferred back to the DFP Platform and displayed in the log for user review. Subsequently, users have the option to place machines manually or via an adapted version of automatic placement. Once machines are placed, layouts can be saved for future use by clicking the "Save" button on the Main Menu, with confirmation displayed in the log.

Finally, with the third functionality users have the option to visualize their layout designs in a VR environment. After saving the layout design, users follow a simple integration process into the VR Visualizer. This involves transferring the saved file from the DFP Platform project to the VR Visualizer project folder. Once initialized, users can don a VR headset to immerse themselves in a virtual replica of the DFA Building, as depicted in Figure 6.

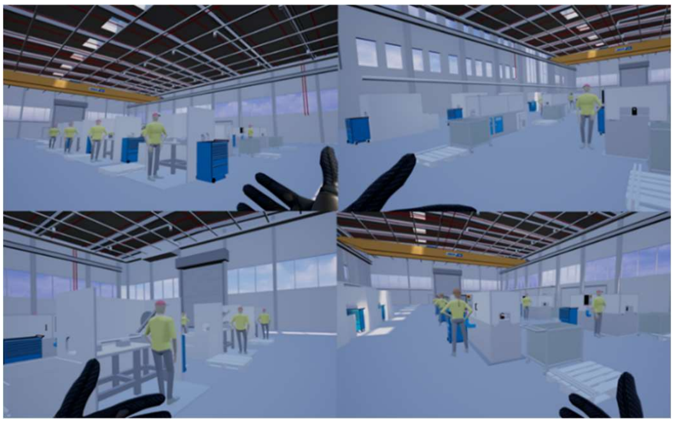

Figure 6. Loaded Layout in VR Visualizer from different perspectives.

This immersive experience allows users to navigate around the layout, inspecting each element closely. Additionally, the VR visualizer serves as a powerful tool for project presentations, enabling stakeholders such as clients and colleagues to engage with the proposed factory layout and make informed decisions.

4.2. User evaluation results

In the user evaluation semi-structured interviews conducted with FP experts, participants were asked to rate their experience with the four key elements of the interactive system developed, as detailed in section 3.3. These elements were evaluated on a scale of 1 to 5, with 1 representing "bad" and 5 representing "very good." The results, summarized in Figure 7, revealed that all elements received above-average ratings. Specifically,

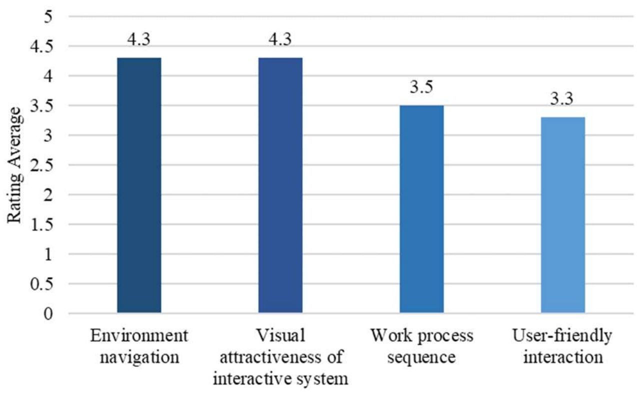

Figure 7. User experience rating of the interactive platform.

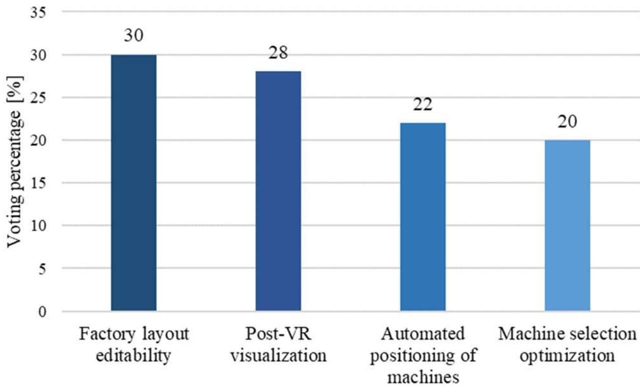

Figure 8. Most attractive feature of the DFP Platform.

"Environment navigation" and "Visual attractiveness of the interactive system" received the highest rating of 4.3 out of 5, followed by "Work process sequence" with 3.5 out of 5, and "User-friendly interaction" with 3.3 out of 5.

In the next question, participants were asked to rank the four most important features developed in the DFP Platform in order of attractiveness, with 4 being the most attractive and 1 being the least. The results converted into percentage, shown in Figure 8, revealed that factory layout editability and post-VR visualization were rated the most attractive features. Participants noted that factory layout editability was highly usable in real projects, while post-VR visualization was seen as mature and practical for quick demonstrations to future staff and production makers.

In the final question, participants distributed points with 3 for most relevant, down to 1 for least. The options included three FP application scenarios: client demonstration, FP decision-making, and factory planner training. Afterward, these points were translated into percentages to clarify the preferences quantitatively. Figure 9 shows that the allocation of points reveals client demonstrations as the leading application at 43.3%, yet this suggests less than half the participants favor its use. FP decision-making follows at 33.3%, and factory planner training is considered the least relevant at 23.3%, which may reflect a critical view on the platform's current capabilities and the specific needs of the industry.

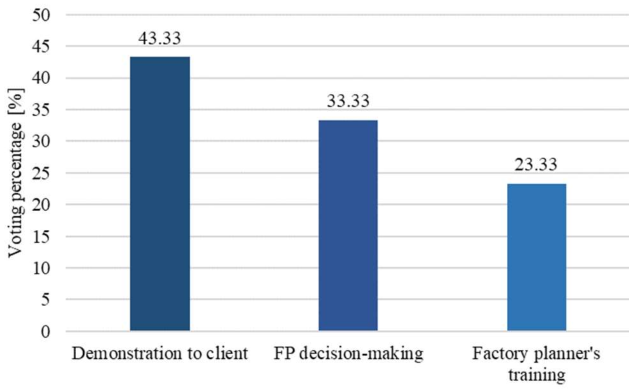

Figure 9. Voting results percentage of attractive uses of the DFP Platform

4.3. General discussions

The results from the functionalities reveal several key insights, particularly applicable to complex manufacturing processes like the serial production of electrolyzes. Firstly, the platform's capability for 3D layout editing and manipulation was highly valued for its usability in real projects. Secondly, the optimization of machine selection through data exchange with MATLAB showed promise but required more contextual information for settings. Additionally, VR visualization was praised as a valuable tool for client demonstrations. However, feedback called for enhancements in functionality clarity and intuitiveness. Future development suggestions include enriching context for machine selection, integrating data on raw materials, and refining optimization models to better suit various scenarios. These improvements aim to refine the DFP platform, ensuring it meets user needs and industry demands more effectively.

5. Conclusions

The development of the DFP Platform represents a substantial contribution to the evolving needs of the manufacturing industry, particularly for layout editing in FP. By using current technologies and integrating them into a virtual environment, this work successfully tackled challenges associated with manual processes, which cause human errors and inflexibility. The DFP Platform's main objectives are to provide factory planners with an intuitive tool for creating and editing factory layouts, optimizing machine selection, and facilitating VR visualization. Through a series of semi-structured interviews and evaluations, insights were acquired into the platform's usability and effectiveness. Overall, the DFP Platform received positive feedback, with its interaction system and layout editability being particularly well-received. The integration of Industry 4.0 initiative, including technologies such as VR, underscores the platform's potential to revolutionize industrial planning and design by offering more dynamic and adaptable solutions. Moving forward, further development and refinement of the DFP Platform will be essential to fully realize its potential and address user feedback for improved clarity and usability.

Future development of the DFP Platform will focus on enhancing the user interface for improved usability, enriching context with data on raw materials and personnel integration, and generalizing functionalities for customization. Additionally, collaboration through multi-user connections, modular design for scalability, integration with VR visualizer and AI, and automatic calculation of KPIs will further enhance the platform's capabilities. At the same time, the insights from the first presented case studies will be extrapolated to the use case of serial production of electrolyzers to support industrial ramp-up with dynamic scalable factory layout planning. These efforts aim to solidify the DFP Platform as a digital solution for FP, fostering innovation and efficiency in the manufacturing industry.

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