A User-Friendly Open-Source Framework for Virtual Layout Planning

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Abstract: This paper presents an open source and user-friendly framework that can be used to visualize and modify factory layouts using virtual reality (VR) technologies. By creating a virtual environment that simulates the real-world factory layout, users can move machines around and visualize the flow of components and products with ease. The framework is mainly intended for small and medium-sized enterprises, who need efficient facilities to remain competitive, while they lack resources to conduct large scale factory layout planning projects. The major contribution in this paper is a design specification for a virtual layout planning tool and that all functionalities can be accessed by the user without exiting the virtual environment. User tests have been utilized throughout the process to improve the framework and a link to the final version is appended to this paper.

Keywords: Virtual Layout Planning, Factory Layout Planning, Virtual Reality, Production

1 Introduction

Factory layout Planning (FLP) is a critical aspect of industrial engineering and manufacturing. It is essential to improve production efficiency and reduce operational costs. Virtual Reality (VR) technology offers promising opportunities to visualize factory layouts and analyze the flow of components and products in a simulated environment. Additionally, this Virtual Layout Planning (VLP) ideally includes functionality for moving machines and other objects directly inside the virtual world without having to exit VR.

Several studies and applications of Virtual Layout Planning have been presented before, but it is still not utilized much by small and medium-sized enterprises (SMEs). However, it is of great importance for SMEs to design or redesign their factory layouts properly since they have dynamic demands and competitive markets (Constantinescu, 2008, Al-Zubaidi et al., 2021). Earlier studies show that it is possible to reduce the operating cost of a factory by up to 50% (Tompkins et al. 2003) or reduce the material handling costs by 10-30% (Francis et al. 1992) if the layout of the factory is optimized. While this level of improvement may seem ambitious for smaller-scale factories, the significance of layout optimization transcends mere cost reduction, encompassing aspects such as safety, ergonomics, and logistical efficiency.

Two primary challenges impede the widespread accessibility of VLP for SMEs – namely, the procurement or creation of requisite 3D models (Gong et al., 2019, Bellalouna 2020), and the identification of suitable VLP tools after obtaining said models. The laborious nature of crafting 3D models essential for fostering a realistic VR environment often emerges as a significant bottleneck (Gong et al., 2019), particularly for resource-constrained SMEs striving to sustain competitiveness. Hence, there exists a palpable demand for a cost-effective and user-friendly VLP framework (Chandra Sekaran et al. 2021).

Bellalouna (2020) has developed a framework for VLP with functionalities such as a VR assets library, creation of factory infrastructure, collision detection and a numerical measure presenting the ratio of the occupied versus free surface of the factory. However, it is neither freely available nor has functionalities such as distance measuring and visualization of flows in the factory.

To tackle this challenge, this paper introduces a freely available and user-friendly downloadable framework, implemented in Unreal Engine, complemented by a comprehensive video guide. This framework aims to democratize access to VLP, particularly for SMEs. Users are required to create or leverage existing 3D models, which can then be seamlessly imported into the framework. Subsequently, within the VR environment, users can effortlessly manipulate objects and ascertain inter-object distances.

Furthermore, this paper presents a detailed design specification for an intuitive VLP framework, derived from thorough background research and user interviews. Additionally, insights gleaned from user testing and interviews conducted during the framework's development phase are elucidated.

The structure of this paper is organized as follows: The subsequent section reviews the related work, providing a comprehensive background and situating this study within the existing body of research. This is followed by an exposition of the overall methodology employed in this project, detailing the approaches and techniques utilized to investigate the research questions. The subsequent section presents the results derived from the project, offering a detailed analysis and interpretation of the findings. The paper culminates in a discussion that synthesizes the insights gained from the study and concludes with a summary of the key conclusions and implications for future research.

2 Related Work

This section presents key terms and work related to the content of this project.

Factory Layout Planning

FLP is an essential aspect of industrial engineering and operations management, aiming to design optimal spatial configurations for manufacturing facilities to enhance efficiency, flexibility, and worker safety, amongst others. Historically, FLP has been conceptualized as a mathematical optimization challenge, wherein a variety of optimization algorithms and heuristics were employed to identify superior factory layouts. In contemporary practice, methodologies have expanded to include Computer-Aided Design (CAD) and simulation tools, enhancing the precision and applicability of layout planning.

Al-Zubaidi et al. (2021) provide a comprehensive review that endeavors to classify various drivers behind the implementation of FLP. Furthermore, they enumerate several strategies for addressing FLP issues through mathematical optimization, offering a critical evaluation of the methodologies' efficacy and scope. Klar et al. (2021) introduce a novel approach by applying reinforcement learning to ascertain optimal factory layouts, diverging from traditional reliance on optimization algorithms and heuristics. While this method primarily focuses on minimizing the transportation time of goods as the optimization objective, it underscores the significant potential of integrating machine learning techniques into FLP solutions.

Advancements in digital twin technology and virtual reality have ushered in new avenues for FLP, enabling more interactive and immersive planning processes. These technologies facilitate the incorporation of Virtual Layout Planning (VLP) into traditional FLP frameworks, potentially revolutionizing the manner in which factory layouts are conceived and implemented.

Virtual Layout Planning

Virtual Layout Planning (VLP) is increasingly recognized as a pivotal adjunct to Factory Layout Planning (FLP), attributed to its capability to pre-visualize factory layouts prior to their actual implementation. This pre-visualization significantly enhances comprehension of the proposed factory layout. Smith and Heim (1999) identify three principal benefits of employing VLP in FLP:

1. Upon establishing a functional framework, it facilitates the ease of modifications within the factory layout.
2. It engenders a comprehensive understanding among stakeholders involved in FLP of the various layout alternatives and their consequential impacts.
3. The decision-making process is substantially improved through leveraging the flexibility and graphical prowess of three-dimensional (3D) environments.

The advent of Virtual Reality (VR) technologies has democratized 3D visualization, making it accessible to individuals without specialized knowledge in computer rendering or programming (Kline & Volegov, 2021). Gong et al. (2019) address the challenge associated with the creation of 3D geometry for VLP by exploring point cloud-based virtual factory modeling. They propose an integration of existing Computer-Aided Design (CAD) models with 3D laser scanning of the factory premises to streamline the geometry creation process. Furthermore, the application of Mixed or Augmented Reality (AR) in layout planning is among the most scrutinized uses of AR within the construction domain (Ciuffini et al., 2016), primarily facilitating the planning of factory locations and dimensions. Nonetheless, it holds potential for presenting an AR depiction of the factory interior, encompassing all objects within.

The establishment of digital twins for factories is identified as a fundamental requirement for the realization of Industry 4.0 (Chandra Sekaran et al., 2021; Yildiz & Møller, 2021), facilitating seamless integration between the factory and enterprise systems (Soori, 2023). VR is advocated for its utility in modeling virtual manufacturing, FLP, robot path planning, virtual prototyping, and training. Additionally, the integration of VR tools with other simulation technologies is recommended to enable real-time virtual factory simulations (Chandra Sekaran et al., 2021).

3 Methodology

The procedural methodology of the project is delineated in Figure 1, illustrating the comprehensive flowchart of activities undertaken. The project's inception was marked by a concurrent background study and interviews with three prospective users, a dual approach designed to gather foundational insights. The interviewees would all prefer to conduct VLP in their professions and were asked to list and rank desired functionalities in a VLP framework. These initial activities culminated in the formulation of a design specification, as documented in Table 1.

Subsequent to the establishment of the design specification, the project transitioned into an iterative development phase, characterized by a tripartite division of tasks: the development of the framework architecture, the creation of the user interface, and the visualization of operational flows within the factory setting. This phase was punctuated by iterative user testing sessions, during which a cohort of users engaged with the framework. Post-use, these participants were interviewed to garner feedback on several aspects of the framework, including its functionality, user interface, and the efficacy of flow visualization. This iterative process was executed over four cycles, leading to the selection of the final design.

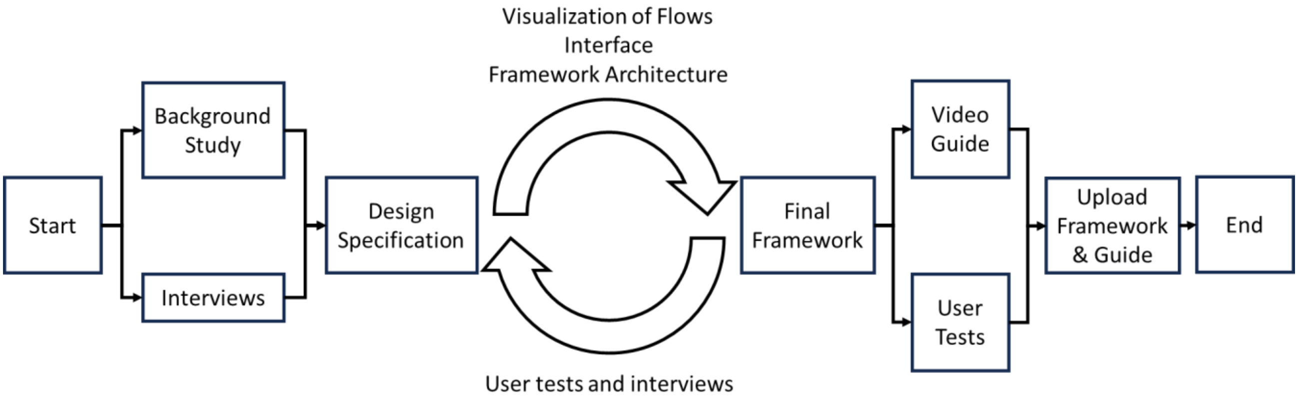

Figure 1. A flowchart of the workflow used during the project.

The project reached its culmination with the production of a video tutorial for the framework, followed by a series of user tests aimed at enhancing the tutorial's quality. Conclusively, both the guide and the framework were disseminated via YouTube and Google Drive, respectively.

User Tests and Interviews

User tests and interviews were conducted iteratively throughout the project to improve the developed framework and its potential as an appropriate tool for VLP. To support the background study, interviews were held with three prospective users of a VLP tool. All three had experience in FLP but only one had previously used tools for VLP. The interviewees were asked to list desired functionalities in a VLP as well as ranking their importance. These functionalities were then aggregated, and each final potential functionality was given a rank based on the sum of the ranks from the different interviewees.

During the iterative development of the framework, user tests and interviews were mainly held to receive feedback on different concepts for functionalities to guide the development work for the next iteration. Each iteration was evaluated by three to five different testers that were not involved in the development of the framework. All testers had engineering background but varying VR experiences. Some testers were involved in the testing of more than one iteration of the framework, enabling them to evaluate the progress of the framework. Consequently, they had a large impact on the final framework.

The tests were structured such that the testers were instructed to perform certain actions and then interviewed regarding the ease of performing the action, the interface, and the visualization of the virtual factory. Predominantly, the tester was asked to compare different concepts for the same action as well as the visualization of the result. In the first case, this meant evaluating the intuitiveness and ease of navigating in the interface.

During the tests, the testers were asked the following questions:

- What were the advantages and disadvantages of this concept?

- Do you prefer this or the previous concept?

- What do you think about the speed and color of the animation?

Finally, the results from each test were compiled and the concept preferred by most testers implemented into the next iteration of the framework.

4 Results

The results consist of five parts – the identification of requirements translated into a design specification, the architecture of the framework, the user interface, the visualization of flows inside the factory, and the guide. These components are elaborated upon in the subsequent subsections, which also incorporate feedback derived from the user testing sessions.

Design Specification

The initial phase of the research, encompassing a background study coupled with interviews conducted with three prospective users, yielded a comprehensive set of requirements. Additionally, the interviewees ranked the requirements according to importance. These requirements were meticulously aggregated and receiving an overall rank, serving as the foundational basis for the framework's design specification. The derivation of this design specification, along with its corresponding fulfillment, is systematically presented in Table 1.

Table 1. The Design Specification is formulated upon the foundation of an extensive background study and a series of interviews. Furthermore, an evaluation regarding whether each requirement has been met is presented in the rightmost column.

Number	Requirement	Shall/Should	Fulfillment
1	The user should be able to move and rotate machines in VR.	Shall	Yes
2	The user should be able to place new machines from a database.	Shall	Yes
3	The user should be able to adjust the size of the snap fastening point that machines adhere to during movement.	Shall	Yes
4	The user should be able to duplicate and delete existing machines.	Shall	Yes
5	The user should be able to measure the distance between two points.	Shall	Yes
6	It should be possible to see which machine is selected.	Shall	Yes
7	It should be possible to save at least three different layouts in different save slots.	Should	Yes
8	There should be an undo button to undo machine movements.	Shall	Yes
9	There should be a handheld screen with a top view of the current factory layout.	Shall	Yes
10	All machines in a specific folder should automatically receive a so-called thumbnail in the menu's "catalog" and be possible to place in the factory	Shall	Yes
11	The user should be able to change the speed at which machines move during relocation.	Shall	Yes
12	Machines should have a box with information about the machine	Should	No
13	The product flow should be visualized above the actors in the factory.	Should	Yes
14	The product flow should be visualized at ground level	Should	No
15	Simulations should be able to be turned on and off in VR.	Should	Yes

The completion status of the framework, subsequent to the project's conclusion, is documented in the rightmost column of Table 1. It is observed that all specified requirements, with the exception of numbers 12 and 14, have been satisfactorily met. The integration of informational boxes associated with each machine represents a potential enhancement for future iterations of the framework. While the product flow is not depicted at the ground level, it is effectively illustrated above the factory actors and in the top-down view. This approach mitigates the necessity of representing the product flow at the ground level.

In summary, the framework has successfully met and integrated all critical requirements. This accomplishment facilitates users in generating a virtual representation of the manufacturing environment and the machinery it encompasses by importing three-dimensional (3D) models. Furthermore, the framework allows for the addition of machinery, along with the capability to adjust their positions and orientations directly within a Virtual Reality (VR) setting. Notably, the visualization of operational flows within the factory is dynamically updated in response to the repositioning of machinery.

Framework Architecture

The development of the framework was executed within the Unreal Engine environment, utilizing blueprint scripting for the implementation of its functions. Central to the framework is the utilization of a pre-configured VR pawn within Unreal Engine, which inherently supports user navigation, teleportation, and orientation capabilities. Figure 2, on its left side, delineates the interaction between the VR pawn and other blueprints, essential for activating the functionalities enumerated in the product specification.

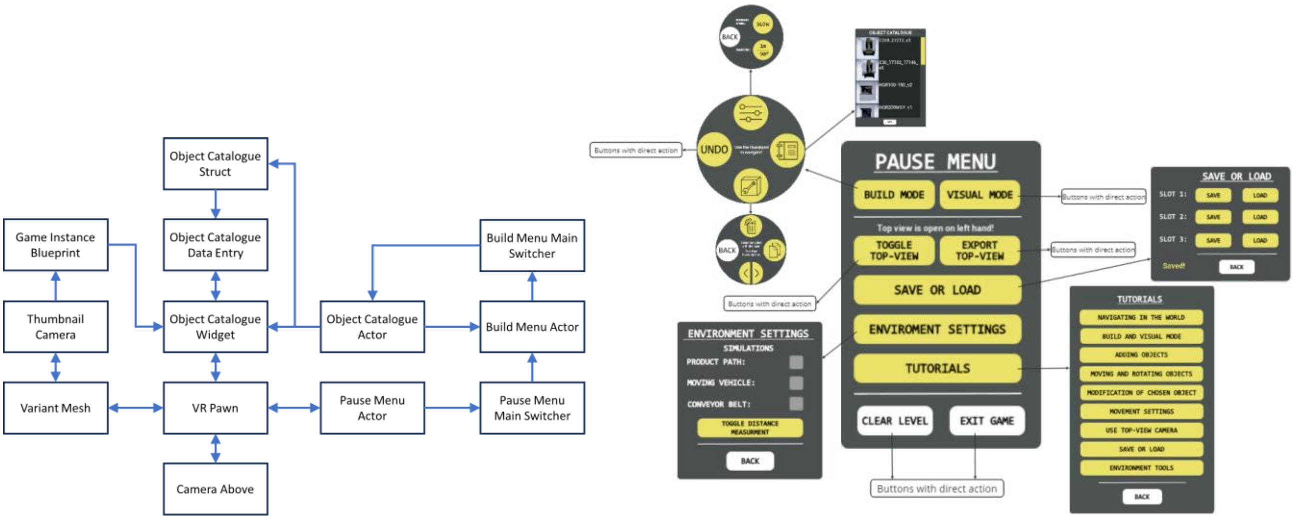

Figure 2. To the left: A schematic for the blueprint interaction with the VR pawn. To the right: A flowchart describing how the different menus are connected to each other.

The schematic representation of the interaction flow among the various functionalities within the framework is depicted on the right side of Figure 2. Central to this interaction flow is the Pause menu, which serves as the primary navigational hub, facilitating access to all other functions and menus. Interaction within the framework is categorically divided into two distinct modes: Build Mode and Visual Mode, both of which are operationalized directly within the Virtual Reality (VR) environment. Build Mode is activated for the construction phase of the factory, wherein a menu is displayed on one of the user's arms, offering functionalities such as importing objects from the database into the factory scene, object rotation, and access to an undo feature. Conversely, Visual Mode is designed for exploration purposes, allowing the user to navigate through the factory without the ability to make edits. This mode also provides access to an additional menu for altering environmental settings, thereby enabling the visualization of product paths, moving vehicles, and conveyor belts.

To enhance user autonomy and efficiency within the VR environment, a series of tutorials has been integrated, enabling users to access instructional content without the need to disengage from the VR environment.

Interface

The conceptualization phase for the interface design yielded three primary concepts, illustrated in Figure 3 and denominated, from left to right, as Regular Toaster, Clean Concrete, and Space Cowboy. The Regular Toaster concept is characterized by a rectangular design language, employing varying colors to denote different actions. The Clean Concrete concept adopts a monochromatic color scheme with buttons arranged in a circular pattern, emphasizing simplicity and elegance. Lastly, the Space Cowboy concept introduces a futuristic aesthetic, with a button interface resembling a revolver cylinder that rotates to select the desired function.

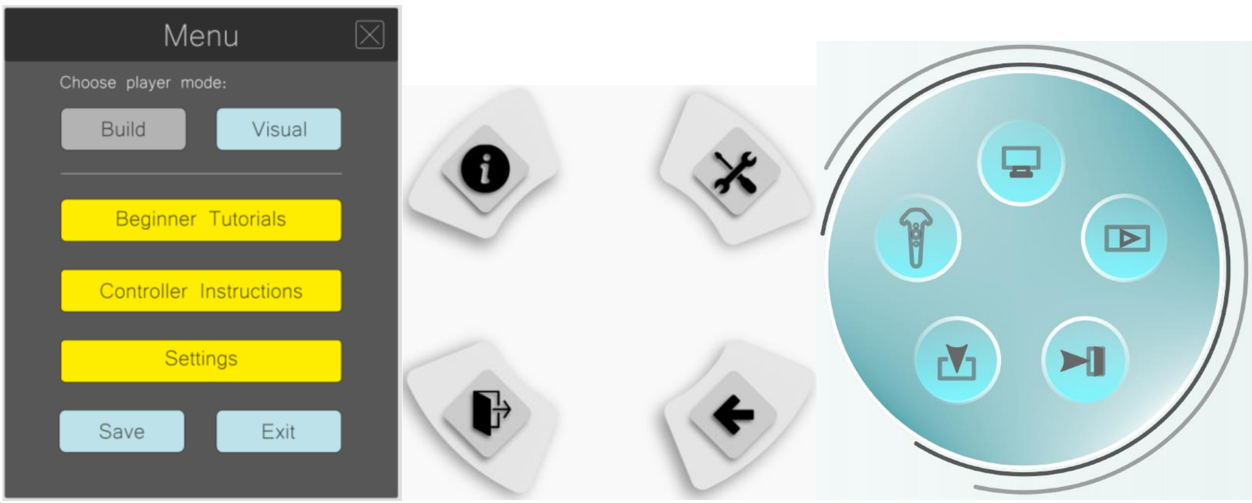

Figure 3. Three different concepts for the interface of the framework. These are named (from left to right) – Regular Toaster, Clean Concrete and Space Cowboy.

User testing sessions revealed several areas necessitating enhancements:

- It is recommended that circular menus contain no more than eight buttons to prevent user overload.
- Designing menus that foster muscle memory should be prioritized to facilitate the learning process
- Initial instructions for manipulating and orientating objects proved insufficient, leading to confusion among users. An effective resolution involved augmenting textual instructions with animations demonstrating the intended interactions with the controllers.
- To mitigate the risk of users inadvertently swapping the controllers, one controller was designated blue and the other red within the virtual environment.
- The build menu employs the controller's touchpad for navigation, in contrast to the pause menu, which relies on controller-pointing for button activation. To clarify this distinction, the build menu instructions were enhanced with illustrative images.
- Test participants expressed a preference for quickly locating specific instructions over navigating extensive text. Accordingly, instructions were sequentially numbered to improve navigability and facilitate the search for specific guidance.

The finalized interface concept is illustrated on the right side of Figure 2. This concept amalgamates elements from each initial design, predominantly drawing from the Regular Toaster concept. The pause menu is structured with a rectangular layout, while the build menu adopts a circular form. Selection within the pause menu is achieved by directing the controllers' laser pointers at the desired option and pressing the trigger button. Conversely, the build menu's selection process leverages the touchpad, with the circular interface's design intended to enhance user intuition and promote muscle memory, allowing seasoned users to navigate the menu without direct visual reference.

To ensure coherence across the framework, a consistent color scheme was employed throughout its various components. This uniformity extends to the start screen and instructional materials, all of which adhere to a unified design aesthetic. Figure 4 illustrates this consistency, with the start screen depicted on the left and selected instructional examples on the right. Notably, uniformity is maintained through the consistent application of a specific font and color palette across these elements, thereby facilitating user comprehension.

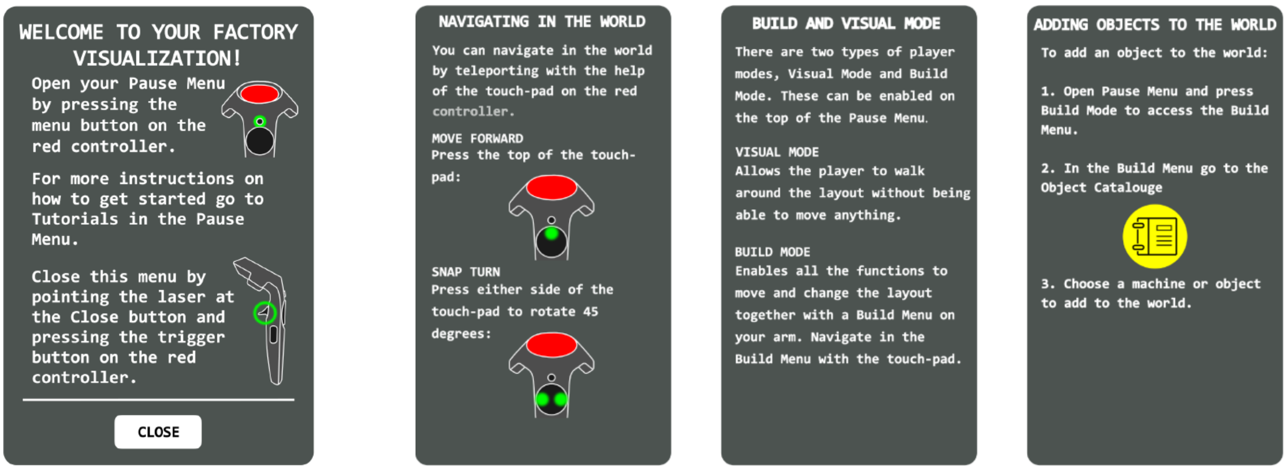

Figure 4. The leftmost figure shows the start screen, whereas the other figures are examples of instructions.

Visualization of Operational Flows within the Factory

The depiction of operational flows within the factory constitutes a critical functionality of the framework, significantly influencing both the efficiency and the working environment of the manufacturing process. To address this need, three distinct conceptual designs were developed, each representing a different approach to visualizing these flows. Figure 5 presents these concepts from a top-down perspective. Common to all designs is the sequential numbering of machines, indicating the order of operation, with connections delineated by spline curves. The two concepts on the right incorporate additional visual cues: yellow pulsing and moving lights to enhance visibility and intuitive understanding. The central concept employs directional arrows for guidance, while the concept on the far right features a light whose intensity gradually fades.

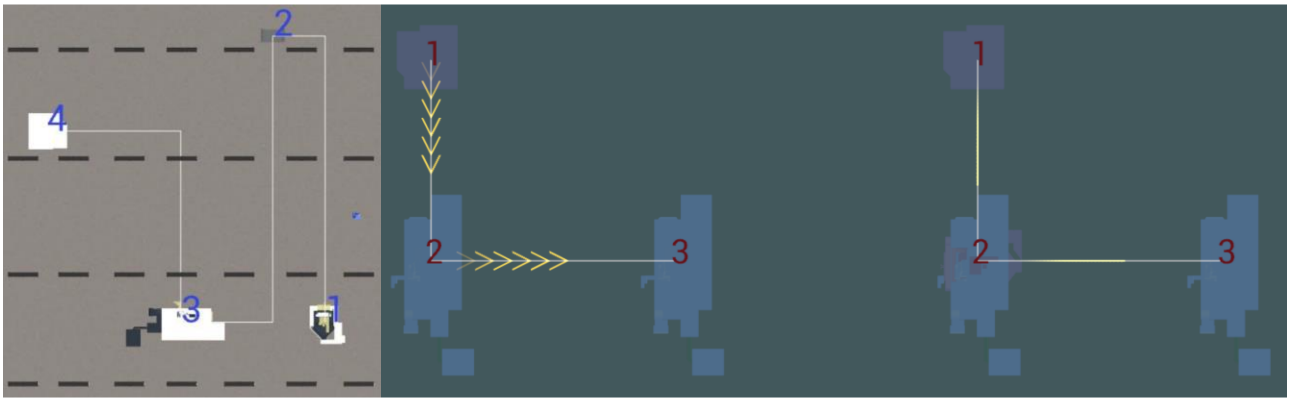

Figure 5. The first concepts for the visualization of flows in the factory. All are viewed from a top view perspective.

Participants in the testing phase were solicited to assess both the velocity and the morphological characteristics of the light signals, in addition to evaluating the impact of varying color schemes. While the utilization of yellow was generally perceived positively, it was noted to exhibit visibility challenges in certain factory environments. Alternatives proposed included the colors green and blue, selected for their potential to offer enhanced contrast relative to the factory's existing color palette. These deliberations culminated in the implementation of a solution depicted in Figure 7, where operational flows are represented by dark blue arrows in motion.

User preferences regarding the velocity of the arrows varied, leading to the introduction of a customizable feature within the framework. This adjustment allows users to modify the arrow velocity according to their individual preferences.

Figure 6. Examples of visualization of trucks and conveyer belts, plus the activation interface.

To enhance the user experience within the virtual factory environment, the framework was augmented with the incorporation of conveyor belts and trucks as optional visualizations to represent material flows. The implementation process requires the factory designer to delineate a spline within the virtual factory layout, which serves a dual purpose: indicating the placement trajectory for static objects (such as conveyor belts) and specifying the movement path for dynamic entities (such as trucks). The designated object is subsequently linked to the corresponding spline to visualize its operational pathway. Figure 6 provides illustrative examples of these advanced visualization features.

The visualization of the final solution is depicted in Figure 7, where it is observable that material flows within the factory are primarily represented through dynamic blue arrows. Additionally, a conveyor belt is also featured, illustrating another method of depicting flow. These visualizations are accessible during navigation within the Virtual Reality (VR) environment and can be comprehensively viewed from a top-down perspective.

The Instructional Guide

The instructional guide is composed of 11 tutorial videos, alongside a promotional trailer designed to showcase the framework's capabilities. Each tutorial video is dedicated to explicating a distinct functionality of the framework, with the duration of each video varying in accordance with the complexity of the content. Furthermore, every video is accompanied by a descriptive title and an illustrative thumbnail that succinctly conveys its subject matter.

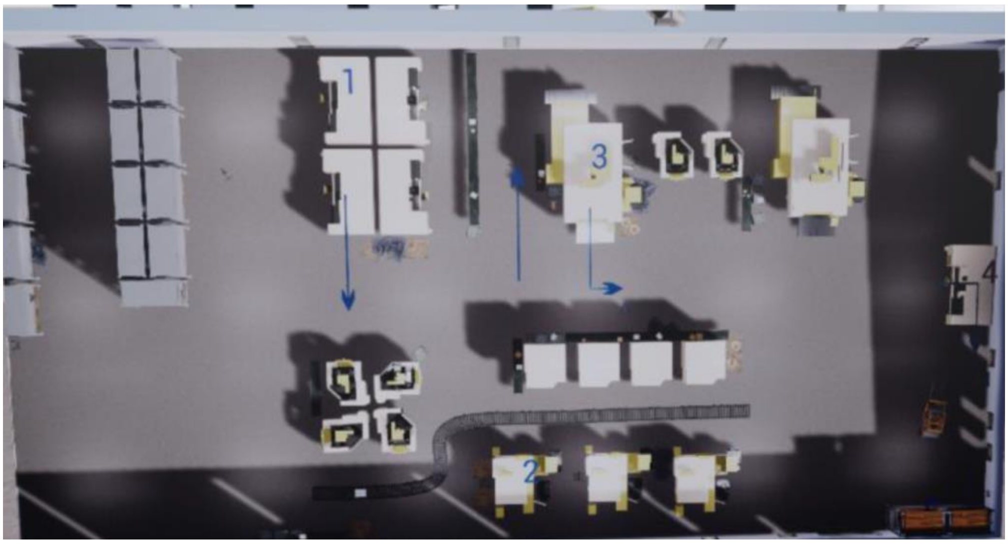

Figure 7. A top view of the final solution to visualize flows in the factory. Blue numbers for the order in which the machines should be accessed, pulsating and moving blue arrows between. A

The efficacy of the guide was assessed through evaluations conducted with five individuals, all of whom possessed prior exposure to VR technologies and basic operational knowledge of Unreal Engine. The evaluative focus was on verifying the testers' ability to independently complete tasks as outlined in the tutorial videos, without necessitating additional inquiries. This assessment encompassed the sequential organization of the video content, the clarity provided by the video thumbnails, and the comprehension of the equipment prerequisites required for following the guide. Fortuitously, all participants successfully met these criteria, obviating the need for any modifications to the instructional content.

5 Discussion

The user testing sessions and subsequent interviews were instrumental in identifying both deficiencies and constructive recommendations for the system's enhancement. Notably, the interface and the overarching framework benefitted significantly from these evaluations, as evidenced by the tangible progression from preliminary designs to their finalized forms.

The system automatically updates the flows when machinery is repositioned, facilitating the identification of inefficient flows and potential collision risks. While intersecting flows pose safety concerns, it is recognized that certain flows may experience minimal traffic, thereby diminishing collision risks.

An envisaged enhancement for the framework involves the integration of performance metrics within the flows. Such metrics could illuminate efficiency variations consequent to relocating machinery or other objects, in addition to pinpointing potential bottlenecks. Ideally, the framework would interface with a Product Lifecycle Management (PLM) system, enabling real-time factory simulations. This functionality could predict the necessity for relocating objects within the factory in response to new manufacturing orders.

The project's primary objective was to develop an open-source, user-friendly framework for Virtual Layout Planning (VLP). Although the final framework and guide were evaluated by only five testers, the goals were considered achieved, as all testers were able to utilize the framework solely with the guide as a reference. However, a sampling size of five testers is statistically insignificant to justify that no further modifications need to be made. Additionally, several testers were involved repeatedly during the iterative development of the framework. They had a large influence throughout the development of the framework since only three to five testers were consulted each time a new iteration was tested and evaluated. Consequently, they might have approved of the functionalities and interface of the final framework partly since they guided the project in their preferred direction.

6 Conclusions

This paper introduces a Virtual Reality (VR)-based methodology for the visualization and modification of factory layouts. Our platform enables users to engage with a virtual representation of the factory, reposition machines and workstations, and assess the movement of components and products. This approach harbors the potential to markedly enhance production efficiency and diminish operational costs within the manufacturing sector. A significant advantage of the framework is its ability to facilitate layout editing within the VR environment, obviating the need for users to exit VR for layout modifications. The development of the framework was iterative, incorporating user feedback and interviews to augment its functionality and ease of use. However, the small number of testers throughout the development reduces the statistical significance regarding the overall usability of the final framework.

Future directions for this research are twofold: refining the framework and its instructional guide and innovating new methodologies for VLP. Enhancements could include the introduction of multiplayer capabilities, permitting collaborative layout discussions within the virtual environment from disparate locations. A prospective challenge is the development of methods for integrating the virtual environment with logistics management systems, thereby enabling the presentation of efficiency metrics for individual machines and the factory at large. Such integration would assist in identifying bottlenecks and potential collision points within high-traffic flows. Additionally, a rating system for different layouts could be developed to rank layouts according to different performance measures, enabling users to select the most appropriate layout based on different scenarios. Moreover, it could enable the application of mathematical models to VLP to facilitate the optimization of factory layouts.

The framework and guide have been made publicly accessible, allowing any interested party to employ the framework for importing 3D models and planning facilities directly in VR.

Acknowledgements and Supplementary Materials

The language in this paper has been improved by using chat GPT 4.0. It has not been used to generate new content.

The guide and link to the framework can be found on YouTube by following the link below.

Factory Visualization - YouTube

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