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ENHANCING LEAN CONSTRUCTION THROUGH INNOVATIVE TECHNOLOGY: A FOCUS ON VIRTUAL REALITY IN CONSTRUCTION

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ABSTRACT

This study delineates the integration of Virtual Reality (VR) within Lean Construction, emphasising its application across the philosophy, principles, methods, and tools of Lean Construction. By conducting a systematic literature review, this research considers the utilisation of VR to enhance construction processes, specifically focusing on its role in mitigating waste, maximising value, continuous improvement, and respect for people. The investigation reveals VR's capacity to bridge the theoretical and practical aspects of Lean Construction, offering a novel perspective on its implementation. The results demonstrate VR's potential in advancing Lean Construction practices through its philosophy, principles, methods, and tools. Also, the utilisation of VR, particularly in SCRUM, Set Based Design and Visual Management, underlines a transformative potential for enhancing construction project efficiency and value. The paper concludes by highlighting the contributions of VR to Lean Construction, proposing actionable insights for practitioners and suggesting avenues for future research. This approach provides a comprehensive review for integrating VR in construction projects, aligning with Lean Construction for enhanced project outcomes.

KEYWORDS

Lean Construction, Set Based Design (SBD), VDC, Virtual Reality (VR), Smart Construction.

INTRODUCTION

Numerous essential technologies support intelligent building practices, including big data analysis, robotics, laser scanning, 3D printing, and virtual reality (VR) (Wang et al., 2023). Among these, VR emerges as a notable advancement in the field of smart construction. Smart construction is closely associated with the concept of "Lean Construction," which was

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introduced by Koskela, (1992) as a novel production philosophy emphasising principles, concepts, and methodologies within the construction industry. that no longer regard construction as a mere process of converting materials into buildings but rather as a sequence of activities that add value (flow process). This perspective entails identifying problems within the flow and implementing solutions and improvements to address these issues (Wang et al., 2023). VR is one of the promising technologies that can improve the process of design, construction, application, and maintenance in many AEC projects (Safikhani et al., 2022). VR has garnered recognition for its ability to enhance customer satisfaction (Noghabaei et al., 2020), reduce project duration by minimising conflicts, serve as a cost-effective alternative to physical mock-up installations and savings of 15% of capital delivery (Haahr et al., 2019). Moreover, Building Information Modelling (BIM) is one of the VR tools that refers to the creation and utilisation of a computer-based information model that encompasses multiple dimensions. This model is not limited to structural documentation but also includes simulations of the construction and operation of capital facilities (Bidhendi et al., 2023). Increased penetration of BIM, as a manifestation of modern technology in construction, specifically VR, positively impacts resilience and waste reduction in construction (Saeedi et al., 2022). These outcomes stem from VR's ability to mitigate a major factor contributing to waste: deficiencies in communication, collaboration, clarification, and understanding, thereby enhancing the confidence required to accomplish the designated tasks (Getuli et al., 2020; Safikhani et al., 2022; Seyman Guray & Kismet, 2023; Zhang, 2021).

Jacobsen et al. (2021) emphasised the use of a VR-based serious gaming environment to teach Lean Construction concepts, underscoring the potential for collaborative and interactive learning. Liu et al. (2022) explored the socio-technical aspects of Lean Construction, particularly examining the Last Planner System (LPS) and its implementation challenges within an Immersive Virtual-Reality (IVR) setting. Trivedi et al. (2022) discussed the integration of VR simulations with Lean Construction principles to enhance project delivery and achieve high-performance in infrastructure projects. In a slightly different approach, Spisakova et al., (2020) focused on the use of virtual reality in designing safe construction sites, without specifically incorporating Lean Construction principles. Also, Brioso et al. (2019) presented a preliminary methodology for integrating Lean Construction and VR in the planning phase of structural interventions in heritage structures. Lastly, Rischmoller et al. (2018) discussed the use of Virtual Design and Construction (VDC) as a lean strategy for integration in construction projects, without mentioning VR in the context of Lean Construction. While several studies have investigated various aspects of VR applications in Lean Construction, including enhancing learning and training (Jacobsen et al., 2021; Liu et al., 2022), project planning and design (Brioso et al., 2019, Spisakova et al. 2020), and project integration and delivery (Rischmoller et al., 2018; Trivedi et al., 2022), there appears to be a lack of comprehensive research that holistically links the use of VR to the overarching philosophy, principles, and methods of Lean Construction. This indicates a research gap where a structured study could provide a more integrated perspective on how VR can be systematically aligned with and support the broader objectives of Lean Construction.

Our discussions are structured to explore the influence of VR on Lean Construction within projects of varying scales and environments, involving a variety of stakeholders. Accordingly, the research questions are set as follows:

1. How can VR support the Lean Construction Philosophy?
2. How can VR support the Lean Construction principles?
3. How can VR support Lean Construction methods?
4. What tools are offered to implement VR in Lean Construction?

In this paper, a systematic review and integration of literature across various sections are conducted to identify the intersection of VR and Lean Construction. Following this introduction, the paper is structured as follows: first, the research method section details our systematic literature review process and the criteria for selecting relevant studies. This is followed by the results section, where we present findings from the reviewed literature, categorising them into Lean Construction philosophy, principles, and methods enhanced by VR. In our analysis, we provide commentary on all four pillars of Lean Construction: value generation, waste minimisation, continuous improvement, and respect for people (Abdelhamid et al., 2008). Furthermore, we explore value identification, value stream mapping, workflow optimisation, demand-driven execution, and continuous improvement, as guiding Lean Construction principles (Karmaoui et al., 2023). We also have selected SCRUM, Set Based Design, and visual Management as our preferred methods to examine. In our analysis, we specifically examine how VR as an innovative technology can be integrated within the pillars, principles, and methods of Lean Construction to enhance construction project outcomes. The Discussion section then synthesises these findings, examining the implications for current and future Lean Construction practices. Finally, the Conclusions section summarises the key insights, discusses the limitations of our study, and suggests directions for future research.

RESEARCH METHOD

This study utilises a bibliometric approach via a universal library portal that incorporates EBSCO, a prominent supplier of research databases, e-journal and e-package subscription services, book collection planning and procurement management, as well as a significant provider of library technology solutions. This strategy was preferred over direct engagement with databases like Scopus for its broad access to diverse materials, including academic journals, books, and other varied databases. This allows for a more extensive review and analysis of literature across different fields and subjects.

The literature search aimed to systematically identify and select publications that contribute to the understanding of integrating VR into the Lean Construction methodologies. The search strategy was carefully designed to encompass a broad spectrum of databases and sources, leveraging keywords such as "Lean Construction", "Lean Construction Philosophy", "Lean Construction Principles", "Lean Construction methods and tools", "Virtual Reality (VR)", "Smart Construction", "SCRUM", " Set Based Design", and "Visual Management". These keywords were used in various combinations to ensure a comprehensive retrieval of relevant literature. In identification process, 18 books and 13,662 articles were founded.

The selection process commenced with an initial screening based on the relevance of titles, abstracts, and keywords to the research topic. This preliminary filter aimed to capture studies that directly address the use of VR in enhancing construction processes, aligning with Lean Construction methodologies which 13 books and 152 articles were chosen. Following this, a more detailed assessment was conducted, examining the conclusions, discussions, and methodological approaches of the papers to ensure they provided substantive insights into the research questions where we could select 3 books and 42 articles.

Given the innovative nature of VR applications in construction and the evolving landscape of Lean Construction practices, the study extended its inclusion criteria beyond peer-reviewed journals to encompass conference papers, industry reports, and unpublished studies. This was predicated on the condition that these additional sources were recent, maintained academic validity, and offered substantial contributions to the field.

The selection process culminated in the identification and detailed examination of 23 articles and 3 books that provide a comprehensive overview of the current state and potential of VR in the Lean Construction. The process can be seen in Figure 1. Notably, the selection favoured qualitative insights due to the exploratory nature of the topic, although quantitative studies were also considered to ensure a balanced view. However, it was observed that quantitative research in this specific area remains limited.

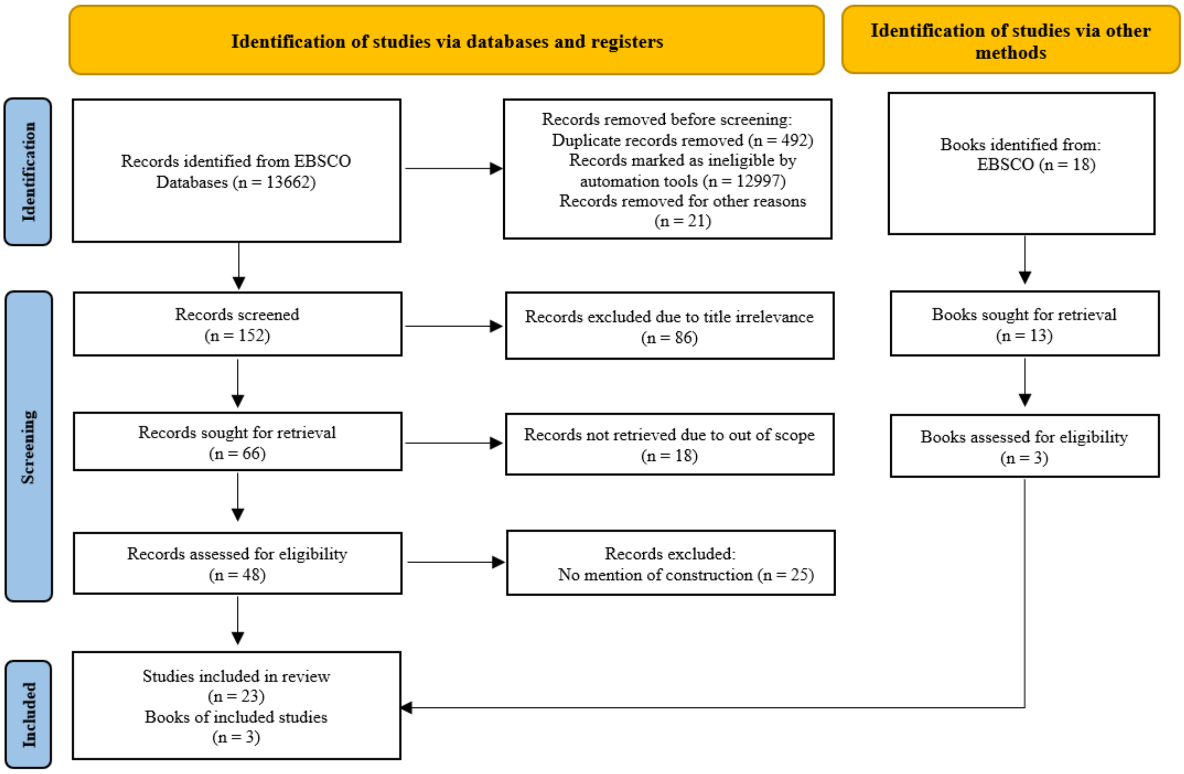

Figure 1. Identification, Screening and Selection process of the systematic literature review

LEAN CONSTRUCTION PHILOSOPHY AND VR

Lean Construction philosophy is based on the principles of lean manufacturing, which originated from the Toyota Production System. This approach focuses on eliminating waste, improving efficiency, and delivering value to customers. Glenn Ballard and Lauri Koskela have conducted extensive research on Lean Construction philosophy. They argue that lean construction is not limited to standardised products or high-volume construction projects. Instead, they believe that Lean Construction can be applied to dynamic projects, promoting innovation and value generation (Ballard & Koskela, 1998). According to Ballard and Howell, Lean Construction philosophy is not about cost-cutting or cheapness. It is about focusing on producing value for customers and eliminating everything else (Ballard & Howell, 2003).

The four pillars of Lean Construction are: Waste Minimisation which focuses on reducing non-value-adding activities and materials in construction processes; Value Maximisation that Emphasises creating maximum value for clients through efficient and effective construction practices; Continuous Improvement which Involves the constant evaluation and enhancement of construction processes to achieve better outcomes; and Respect for People Prioritising the welfare and development of all individuals involved in the construction process (Abdelhamid et al., 2008).

To establish a linkage between the Lean philosophy and VR predicated upon its four pillars, the following connections can be drawn:

WASTE MINIMISATION

VR has a transformative impact on minimising waste in construction, addressing the eight types of waste identified in Lean Construction. Defects are reduced through detailed simulations, allowing for early identification of design flaws (Trivedi et al., 2022). VR aids in accurate demand assessment, which helps prevent overproduction (Jacobsen et al., 2021), and streamlines project timelines to reduce waiting times (Rischmoller et al., 2018). It also promotes the utilisation of talent by visualising every team member's contribution, and assists in reducing unnecessary transportation and motion by enabling precise planning (Noghabaei et al., 2020). Furthermore, VR contributes to maintaining optimal inventory levels and prevents over-processing by allowing teams to finalise designs virtually (Zhao, 2022).

VALUE MAXIMIZATION

As highlighted by Nasirzadeh & Nojedehi, (2013), VR enhances value in construction projects through improved visualisation, aiding in better decision-making and client satisfaction, which are core aspects of value maximisation in Lean Construction. It enables clients to experience and interact with the project before construction, ensuring their needs are accurately met (Trivedi et al., 2022). Furthermore, enhanced communication facilitated by VR leads to a clearer understanding among stakeholders, while also allowing for detailed inspection and quality control (William & Jose, 2023).

CONTINUOUS IMPROVEMENT

VR's ability to simulate various construction scenarios supports the Lean principle of continuous improvement. It allows for iterative testing and refinement of project designs before actual construction, aligning with the ideas presented by Muya et al., (2013). This approach allows for the rapid incorporation of feedback into project plans and aids in performance tracking and analysis for ongoing improvement (Hatoum & Nassereddine, 2023).

RESPECT FOR PEOPLE

Incorporating VR in construction respects and enhances the workforce's capabilities. It offers safer, more efficient, and ergonomically beneficial ways for workers to engage with construction projects, thus respecting and enhancing the workforce's capabilities (McHugh et al., 2023).

Moreover, accidents on construction sites often result from a deficiency in proactive safety measures (Bidhendi et al., 2022). Proactivity, in this context, involves training for safety awareness and the identification of potential risks. To address this, many organisations are increasingly emphasising 'cultural intervention, enacted policies, communication, and induction' (Li et al., 2018). Figure 2 illustrates the efficacy of VR in on-site risk mitigation, as tested and demonstrated.

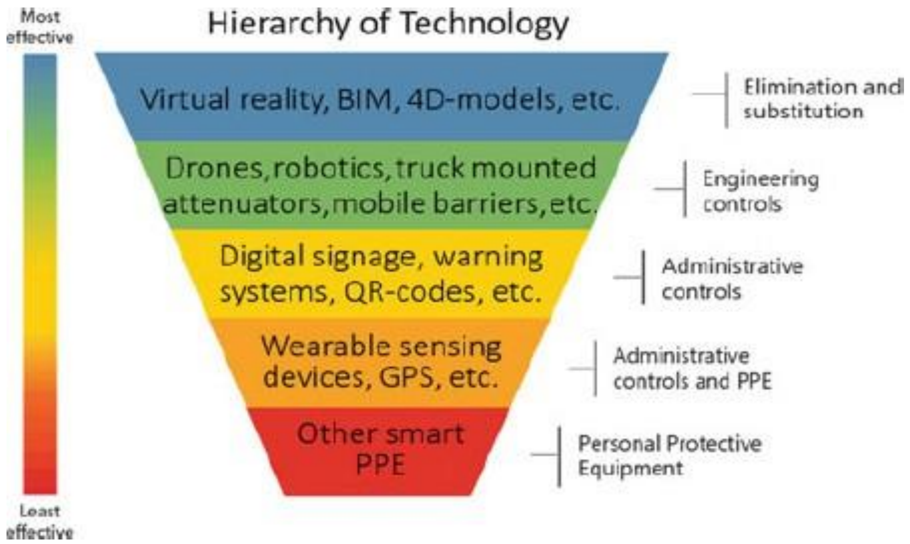

Figure 2: "Technology alternative organised in a hierarchy based on level of risk mitigation effectiveness" (Karakhan et al., 2019)

In the context of Lean Construction, VR aids in the identification and elimination of potential on-site hazards such as spatial collisions. Through VR-enacted site walkthroughs, construction personnel can practice emergency response protocols, bolstering their instinctive reactions to critical incidents (González et al., 2022). Moreover, VR enables the safe visualisation of demolition processes, highlighting potential risks without actual exposure (Seyman Guray & Kismet, 2023).

LEAN CONSTRUCTION PRINCIPLES AND VR

VR is increasingly recognised as a catalyst for enhancing the Lean Construction framework. This section aims to explore the integration of VR with the Lean principles of value identification, value stream mapping, workflow optimisation, and continuous improvement, as these are crucial for advancing construction practices. These principles were selected due to their direct impact on operational efficiency and their ability to be significantly enhanced through technological integration (Karmaoui et al., 2023).

IDENTIFYING VALUE

At the forefront of Lean Construction is the principle of delivering value as envisioned by the client. VR technology serves as a conduit for this vision, providing clients and stakeholders with a tangible representation of project outcomes. Through VR, clients can virtually walk through the construction project, offering feedback that can be incorporated instantly, ensuring that the end result aligns with their expectations (Trivedi et al., 2022). This interactive approach helps in defining the scope more accurately and avoiding costly changes during later stages of construction.

MAPPING THE VALUE STREAM

Value Stream Mapping in Lean Construction is integral to visualising the entire project from inception to completion, pinpointing inefficiencies, and minimising waste. VR can significantly enhance this process by creating a virtual model of the construction value stream, allowing for a comprehensive analysis and optimisation of each step. This digital twin approach not only helps in identifying current waste but also in predicting and preventing future inefficiencies (Sacks et al., 2009).

CREATING FLOW

Creating a consistent and uninterrupted flow of work is crucial to maintaining efficiency on construction sites. VR technology aids this Lean principle by simulating the construction process and identifying potential workflow interruptions. This preemptive analysis allows teams to reorganise tasks and resources to prevent bottlenecks and ensure a smoother flow of operations (Liu et al., 2022).

PURSUING PERFECTION

Pursuing perfection through continuous improvement is a key tenet of Lean Construction. VR allows for an iterative design process where construction scenarios can be tested and optimised in a virtual environment. This virtual prototyping not only enhances the quality and performance of the construction process but also fosters a culture of continuous learning and improvement within the team (Li et al., 2018).

The integration of VR with Lean Construction principles provides a robust framework for enhancing construction project outcomes. By leveraging the immersive and interactive capabilities of VR, stakeholders can achieve a deeper alignment with Lean Construction principles, leading to reduced waste, improved efficiency, and enhanced client satisfaction (Noghabaei et al., 2020).

LEAN CONSTRUCTION METHODS AND VR

This section aims to explore the integration of VR with Lean methodologies like SCRUM and Set-Based Design (SBD). These methods were selected for their potential to significantly benefit from VR's capabilities in enhancing collaborative and iterative processes. Given the scarcity of direct references connecting VR with SCRUM and SBD in existing literature, this document interprets supportive evidence and discusses its potential application to these frameworks.

SCRUM

Recent advancements in project management have seen the integration of SCRUM, an Agile method, into Lean Construction practices to address the dynamic and uncertain environments of construction projects. This integration, conceptualised as 'AgiLean PM', enhances Lean Construction by incorporating SCRUM's agility and iterative feedback processes, proving effective especially in the design phases of construction projects (Bryde et al., 2014).

SCRUM, akin to a relay race featuring brief pauses between each participant, is a highly collaborative method that emphasises continuous review, feedback, progress, and repetition for incremental advancements and superlative quality, all while striving to deliver the highest value swiftly (Arroyo, 2022).

VR facilitates a more profound and qualitative design review throughout the entire project lifecycle by inviting end-users to navigate freely in a virtual environment and provide candid opinions (Spisakova et al., 2020). This heightened engagement enhances productivity by securing each decision-making process, ultimately reducing the need for rework. Given SCRUM's rapid and confident approach, feedback from end-users becomes a crucial resource. For instance, clients evaluating alternative design options can virtually experience the scale of rooms affordably. In another context, researchers found that VR, without additional cost, significantly reduced lighting electricity consumption in commercial buildings by providing options for lighting conditions (Noghabaei et al., 2020). This underscores how VR-enabled design reviews not only add enduring value for end-users but also contribute to ongoing cost reductions.

Moreover, for projects requiring simulations, VR can realize real-time occupancy flow, making it less cognitively demanding for clients (Safikhani et al., 2022). However, if VR settings reveal excessive detail too early in the process, they can become distracting and create false expectations, potentially obscuring the overall project scope (Ventura et al., 2019). With these possibilities in mind, it becomes evident that in the context of VR and SCRUM, effective management necessitates a directive approach to adopting VR and avoiding incremental deviations from the principal task.

SET BASE DESIGN

The foundational design method, Set Base Design (SBD), is characterised by its open-minded approach, keeping design options open until the final stages to better address unpredictable elements through continuous inquiry, analysis, clarification, and selection. SBD relies on a competent and dependable team that can undergo training and eventually operate autonomously toward achieving the project's end goal (Oliveira et al., 2024). This section explores the role of Virtual Reality (VR) in enhancing SBD practices.

In an experiment involving riggers, signal person, and operators, it was found that VR enabled participants to visualise the impact of their decisions on project cost and schedule. It also provided a platform for practicing tasks, boosting confidence, and reducing human error (Safikhani et al., 2022). This led to a significant reduction in decision-making time and the elimination of timidity (Paes & Irizarry, 2018). Additionally, VR proved beneficial in identifying potential clashes in building services (Haahr et al., 2019). A proposed method for on-site training involved setting up a trailer with full equipment capable of hosting virtual meetings, which was found to enhance satisfaction and communication richness compared to non-VR alternatives (Getuli et al., 2020).

While the research acknowledges that the accuracy and appropriateness of meetings were better in a non-VR face-to-face setting, the overall effectiveness of VR in SBD lies in its ability to empower individuals in decision-making. This worker-centered approach, although not necessarily reducing project timelines, influences the occurrence of rework or defects, thus aiding in budget control.

VISUAL MANAGEMENT

Visual Management (VM), defined as 'visual and definitive verification' (Hatoum & Nassereddine, 2023), is a Lean principle adopted in methodologies such as Last Planner System (LPS), SCRUM, Kanban, and others. Research indicates that visual platforms like VM can forecast design conflicts and deficiencies, thereby minimising rework in construction projects (Noghabaei et al., 2020). VM enables the calculation of metrics such as Percent Plan Complete (PPC) by breaking down and making tasks measurable through visual representation.

In the research conducted by Liu et al., (2022), VR was utilised in an LPS setting, incorporating VM elements within their hypothetical project. While VM was not the primary focus of their study, it contained pertinent elements of VM. The Figures below illustrate key aspects of their research.

In Figures 3 and 4, one can observe tables listing tasks alongside adjacent images. The VM environment depicted is reminiscent of actual scenarios, albeit possibly more simplified. Consequently, the study indicates that participants engaged in more negotiations and achieved a higher Percent Plan Complete (PPC) compared to projects managed using conventional methods, even though negotiations in both instances took place within a VR context. The author further suggests that VR contributed to reducing mental stress, fostering clear communication, and enhancing commitment among participants (Liu et al., 2022). This effect may stem from the necessity for discussions to be straightforward or focused, as the visuals in VR are self-explanatory, eliminating the need for complex language usage by those negotiating.

Figure 3: " In the construction phase, the sub-scene manager on the construction site oversees the work and updates the progress." (Liu et al., 2022)

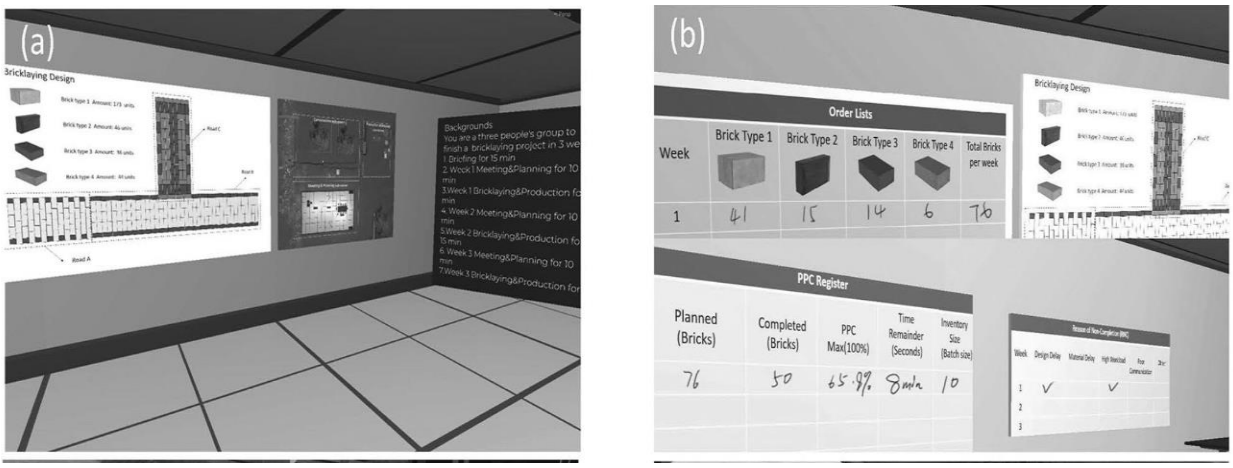

Figure 4: Presenting their VM (Virtual Model) within a VR (Virtual Reality) environment offers a level of detail far surpassing that of conventional methods used in meetings (Liu et al., 2022)

FINDINGS AND DISCUSSIONS

This research comprehensively examines how Virtual Reality (VR) can enhance Lean Construction practices. Our findings suggest that the utilisation of VR, particularly in SCRUM, Set Based Design, and Visual Management, underlines a transformative potential for enhancing construction project efficiency and value. Notably, VR's impact on reducing rework and defects while fostering an environment conducive to innovation and continuous improvement aligns with Lean Construction philosophy pillars. The study further emphasises VR's capacity to enhance Lean Construction's principles: value maximisation, waste minimisation, and continuous improvement. Studies by Jacobsen et al., (2021) and Trivedi et al., (2022) have similarly highlighted VR's role in improving project delivery and training effectiveness. The discussion points to VR as not just a technological tool, but a paradigm shift in construction management, fostering a more collaborative, efficient, and safety-conscious project environment. The integration of VR into Lean Construction not only streamlines project management and design processes but also enhances safety and worker engagement, aligning with the Lean principle of Respect for People. For practitioners, adopting VR could lead to more efficient project outcomes and improved stakeholder satisfaction.

The research identifies a crucial need for quantitative analysis to measure VR's impact, suggesting future studies focus on empirical data to solidify VR's role in Lean Construction. This exploration opens avenues for innovative project management strategies, advocating for VR's broader adoption in the industry.

Despite the qualitative nature of this research analysis, the evidence suggests VR as a pivotal tool in bridging communication gaps. However, the research underscores a critical gap in quantitative studies, pointing to an emergent need for empirical evidence to validate VR's operational benefits comprehensively.

One of the main limitations of our study is its reliance on secondary data, which might not capture the nuanced experiences of implementing VR on construction sites. Future research should focus on primary data collection, including case studies and experimental designs, to validate and extend our findings. Future explorations should aim at quantifying VR's effectiveness in Lean Construction, offering a clearer picture of its return on investment. This study serves as a steppingstone for deeper inquiries into VR's role in smart construction, encouraging stakeholders to consider its strategic implementation for Lean-aligned project outcomes.

Our discussion underscores the transformative potential of VR in Lean Construction but also acknowledges the complexity of its implementation in real-world settings. By addressing these challenges and focusing on empirical studies, future research can pave the way for more effective and widespread use of VR in Lean Construction.

CONCLUSIONS

In conclusion, this study has demonstrated the transformative potential of VR in enhancing Lean Construction practices. Our research systematically investigates how VR supports the four pillars of Lean Construction—value maximisation, waste minimisation, continuous improvement, and respect for people—as well as principles and methods, thereby contributing significantly to smarter construction practices.

Our findings illustrate that VR can act as a powerful enabler of Lean Construction by providing immersive and interactive environments that improve understanding and collaboration among project stakeholders. Through detailed VR simulations, construction projects can reduce waste and enhance efficiency, aligning closely with the principles of Lean Construction. Specifically, methods such as SCRUM, Set-Based Design and Visual Management have shown great potential for integration with VR, offering new ways to manage and execute construction projects that promote both efficiency and precision.

While our study primarily utilised secondary data, the potential for VR in qualitative research remains substantial. Future research could focus on case studies that examine the real-time application of VR in construction sites to provide deeper insights into its operational benefits and challenges. This will be particularly impactful in exploring how VR can further streamline Lean Construction in practice.

The ongoing development in VR technology promises further innovations that could be harnessed to support Lean Construction philosophy principles and methods more robustly. It is imperative for future research to continue exploring these technologies in diverse construction environments to solidify VR's role and optimise its benefits in Lean Construction.

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