Liu, C., González, V. A., Lee, G. & Davies, R. (2023). Development of an immersive virtual reality prototype to explore the social mechanisms of the Last Planner® System. *Proceedings of the 31st Annual Conference of the International. Group for Lean Construction (IGLC31),* 152–162. doi.org/10.24928/2023/0221

DEVELOPMENT OF AN IMMERSIVE VIRTUAL REALITY PROTOTYPE TO EXPLORE THE SOCIAL MECHANISMS OF THE LAST PLANNER® SYSTEM

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ABSTRACT

A successful implementation of the Last Planner® System (LPS) requires not only education on its principles, but also managing social mechanisms it brings up to reach outstanding outcomes. Simulation games have been widely applied to teach LPS principles, but they do not seem to appropriately capture the social mechanisms due to lack of socio-technical realism and inadequate gaming controls (i.e., control external factors other than one of interest). Immersive Virtual Reality (IVR) technology has the potential to reveal the LPS's social mechanisms by providing a highly-controlled and realistic simulation environment. However, how to effectively leverage IVR for LPS simulation is not well understood. In order to bridge this gap, we identified the essential elements that an IVR simulation should have to study the LPS social mechanisms. We then developed and tested a multi-user IVR prototype with the identified elements to simulate the LPS use in a "hypothetical" construction scenario. The results show that the prototype is feasible for studying LPS's social mechanisms. This study lays a foundation for future research in using IVR simulation games to study LPS social mechanisms.

KEYWORDS

Simulations, immersive virtual reality, Last Planner® System, social mechanism, collaboration

INTRODUCTION

Managing traditional construction projects is perceived as challenging due to the complexity of the construction environment, the interdependency of production processes, unreliable production pace, communication and coordination problems, antagonist organizational environments in projects, among others, resulting in uncertainty that negatively affects workflow reliability and project performance. Ballard (2000) pointed out that these problems in construction projects are exacerbated due to the traditional approach of viewing their production nature as a process of converting inputs into outputs, neglecting value generation and flow management. To address these issues, the Last Planner® System (LPS) has been introduced as a Lean based production planning and control tool. It intrinsically deals with the dual and symbiotic socio-technical nature of construction projects (Liu et al., 2020, 2022; Priven

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& Sacks, 2015). Technically speaking, the LPS deploys a robust methodological framework for production planning and control, which reduces workflow variability and uncertainty (Ballard, 2000). From another perspective, LPS can be seen as a social system comprised of project participants who work together to make plans and control project production (Ghosh et al., 2019). Therefore, social interactions among the project participants play a critical role in LPS implementation, improving project coordination and, thus, workflow (Ghosh et al., 2019; Priven & Sacks, 2015).

In spite of the increasing efforts to implement the LPS in the construction industry over the last 30 years, the comprehensive application of LPS principles on projects is still fragmented, and lagging behind (Ebbs et al., 2017; Priven & Sacks, 2015). Some studies have realized that this problem originates from the social-driven barriers: (1) Resistance to change; (2) Lack of cooperation, and technical-driven barriers: (3) Lack of understanding of LPS principles (Liu et al., 2020; Perez & Ghosh, 2018). Some researchers argue that the social and technical aspects associated with these barriers were not managed adequately in the past decades, impeding more effective dissemination and implementation of the team dynamics, LPS practices, knowledge in the construction industry (Gonzalez et al, 2015; Hamzeh 2011; Liu et al., 2020).

To achieve excellent implementation results, LPS requires not only effective implementation of tools and processes (Ballard, 2000; Ebbs et al., 2017) but also individuals to be motivated and empowered to complete teamwork in a highly collaborative environment (Kim & Rhee, 2020). Thus, studying and analyzing the project participant's social interactions, emergent psychological states, and their influence on enhancing positive teamwork, as well as how those behaviors seamlessly match the technical components of LPS, can bring valuable insight into realizing the full potential of LPS (Asadian & Leicht, 2022; Liu et al., 2022).

LPS Simulation Games

Simulation games are a hybrid of games and simulations that aim to train, educate, and entertain players while simulating the context of social system (Klabbers, 2009). Simulation games are often regarded as valuable in the Lean Construction industry because they offer a clear, realistic, and straightforward way of imparting knowledge about various Lean concepts. (Bhatnagar et al., 2022).

On the other hand, simulation games can be used to explore the social psychological phenomenon (McFarlane, 1971; Yiannakoulias, 2022). For instance, some simulation games are designed as digitalized environments, making data collection easier and allowing researchers to manipulate and control the experimental environment where hypotheses can be validated by manipulating specific variables (Lukosch et al., 2018). Simulation games can also create a situation or context through their sequence-specific rules or game controls, making it easy to elicit the participant's response to that situation (e.g., project teams may need to decide on adjusting plans when facing construction constraints). Also, it allows researchers to easily develop a coding or measuring approach based on these sequential rules that determine the specific behavior of game users (Lukosch et al., 2018; McFarlane, 1971). In addition, they allow researchers to replicate the same experiment multiple times without having to change the experimental design or set-ups (Lukosch et al., 2018). Therefore, simulation games have the potential to analyze the social mechanisms of LPS by evaluating individuals' behavior and psychological responses to controllable stimuli or scenarios.

There has been a growing interest in adopting Lean simulations and games in Lean academia and community (Bhatnagar et al., 2022). Several Lean simulation games teach different LPS principles through hands-on activities, such as building a schematic house with Lego™ bricks, to show the benefits of LPS compared to traditional management. The most popular training method is the commercial product LPS-based Villego game, which teaches LPS through two round games in a day (Warcup & Reeve, 2014). Another example is LEBSCO (González et al., 2015), which provides quick LPS training in a classroom setting, and COLLAPSE, a digital simulation game that requires users to complete LPS-related activities on spreadsheets (Raghavan et al., 2018). These engaging games, particularly Villego, make LPS knowledge more accessible to participants.

However, these games are not suitable for uncovering social mechanisms and generalizing findings to real-world settings, which is essential to devise practical intervention strategies for changing their social cooperation accordingly. There are four reasons. Firstly, the sense of presence in the tasks and contexts is too weak for users to perceive and act as a social self (for instance, COLPLASSE uses spreadsheet templates to simulate the operation of the project with an abstract environment) or over-complicated to play (for instance, Villego, which is a highly intricate simulation game requiring an in-depth understanding of LPS concepts and following rules, leading some people to lose their interest in participation). Secondly, they have inadequate gaming controls associated with the LPS principles and procedures. The successful running of the existing simulation games relies on the facilitator's intervention and the participants' accurate understanding of the rules. For instance, analyzing behavior responses from inconsistent experimental controls among groups is difficult when players break the rules and deviate from the LPS workflow. In other words, researchers are less likely to isolate extraneous effects that are irrelevant to social mechanisms, hindering the reproducibility and validity of results. Thirdly, they normally need physical models and additional set-up times, which hinders large-scale experiments. Fourthly, these games are designed for collecting the technical indicators of LPS implementation, such as PPC, time, cost, and knowledge uptake, but not for social indicators emergent during LPS-based teamwork.

IMMERSIVE VIRTUAL REALITY

Immersive Virtual Reality (IVR) involves computer-generated virtual environments with high visual impact and immersion levels, leading to increased engagement and perception (Feng et al., 2018). Thus, IVR can elicit targeted behavior using artificial sensory stimulation, even when the user is unaware (Lavalle, 2017). This virtual environment allows participants to feel as if they were physically present, and the high level of realism can make it difficult to distinguish between the virtual and real worlds. Thus, users' behaviors and responses in IVR are likely to match their real work context (Lavalle, 2017). The ability to conduct behavioral research using IVR offers numerous opportunities (Feng et al., 2018). In particular, a multi-user IVR has gained attention among researchers due to its capability to simulate social interactions in a realistic manner, for instance, where individuals can engage with either a virtual agent or another real person. Therefore, multi-user IVR environments are rapidly becoming popular in the fields of social behavioral and psychology studies. This is due to the flexibility of these environments in investigating and analyzing social cognition and social stress in psychological experiments (Bernard et al., 2018).

In this regard, we argue that there are several reasons supporting the use of IVR to address the limitations of existing LPS simulation games in conducting social experiments. First, its ability to edit the storyline (a collection of scenarios or events in which individuals can make decisions and act to advance the story's progression) and gaming controls have the potential to create the situation that researchers desire, which means the people are more likely to follow the game rules and procedure, making researchers obtain reliable results. Second, with the advent of cost-effective, portable, and networked-supported IVR head-mounted displays such as the Meta Quest 2, researchers can conduct large-scale experiments online to study the social mechanism of LPS.

On the other hand, by using IVR, researchers can obtain additional benefits for studying LPS social mechanisms that cannot be obtained from non-IVR simulation games. First, IVR enables individuals to behave as close to reality as possible (Feng et al., 2018), which has the potential to make the transferal of the simulation results to the real world more feasible. Second, with its high compatibility with biometric sensors and wearable instruments that participants can use during experiments, it has become easier to observe social behaviors and collect physiological data, such as galvanic skin response (GSR) and Heart Rate Variability (HRV). These features can provide a more robust result and help the researcher to gain a deeper understanding of social mechanisms of LPS.

Despite the potential of IVR technology to study the social mechanisms of LPS, there are still limitations to effectively integrating IVR functionalities and LPS principles into a simulation game to deepen the understanding of LPS. Specifically, at the preliminary stage, we do not know how to enable users to follow the LPS workflow using IVR-powered gaming controls. Additionally, we do not know how to design tasks and rules to create scenarios where social mechanisms can be captured. We also do not know what suitable technical solutions enable users to conduct teamwork, communicate, and finish tasks in the IVR environment. More importantly, we do not know how to enable researchers to collect behavior and physiological data in such an environment.

RESEARCH OBJECTIVES AND METHOD

As a preliminary step in filling the aforementioned knowledge gaps, this study aims to explore the viability of using IVR to create LPS simulation games, focusing on technical development. The purpose of developing the IVR simulation game is not for training but for experimentation, which opens doors to the broader use of IVR technology to conduct "controlled" Lean-driven social experiments. Specifically, the study aims (1) to explore the simplified LPS simulation workflow and rules, as well as related IVR prototype designs, and (2) to demonstrate the effectiveness of using IVR technology for LPS simulation games to explore the social mechanisms of LPS.

To achieve the objectives, bearing in mind the nature of the intended simulation game aimed to develop in this research, we first identify and determine the essential elements and rules that the VR-based LPS simulation should have. Then we developed the IVR prototype based on these findings. To test whether the developed IVR simulation game is feasible to study LPS's social mechanisms, we did "actually what" with a typical pavement task scenario. Specifically, it contains two testing rounds of the simulation case: traditional and LPS. We checked: (1) whether every user can complete their task and follow the procedure and rules using the proposed gaming controls; (2) whether our design in task dependencies and variations trigger social interaction among users; (3) whether the researcher can use this IVR prototype to conduct large-scale experiments and collect behavior and physiological data.

DEVELOPMENT OF THE IVR PROTOTYPE

CONCEPTUAL DESIGN AND GAMING CONTROLS OF THE IVR SIMULATION GAMES

The simulation games should have the ability to create a realistic and engaging setting allowing users to feel things like "it was a very meaningful experience" and respond to what they perceive as a realistic situation (Bhatnagar et al., 2022; Lukosch et al., 2018; McFarlane, 1971). We argue that IVR simulation games should offer users realistic construction scenarios and scenes to complete construction tasks. In this regard, the IVR environment should mimic real construction scenarios with 3D models, meeting areas, and construction sites. Second, The simulation game should find suitable navigation (moving around and exploring the virtual environment) solutions and interaction (communicating with people and interacting with virtual surroundings) solutions, allowing users to complete the tasks intuitively and realistically, as inappropriate navigation solutions may cause the motion sickness (Lackner, 2014). Third, cooperation and goal are important motivations that drive the users to complete tasks in the simulation games (Koivisto et al., 2018), so the IVR simulation games should allow users to make plans and complete construction tasks collaboratively, but limit their completion time. Fourth, the IVR prototype should simulate real-world construction and production systems. This requires users to perform key last planners, order materials in meetings and carry out tasks. In turn, the systems should respond to users' behavior like the real world (Lukosch et al., 2018). Sixth, the IVR simulation should have simplified rules and procedures, given that long duration and complex simulation rules are the major reasons for users' reluctance to participate in LPS simulation games (González et al., 2015). Lastly, to obtain better user experience and engagement, the IVR system should have a tutorial session to ensure every user can understand the game mechanism and goals.

On the other hand, simulation games should allow researchers to study social mechanisms by observing behavior and measuring psychological states. However, some social mechanisms are not easily found if users deviate from the rules. This requires the IVR system not only to allow the researcher to capture the social mechanisms but also to have gaming controls to create situations that induce these social nuances. Communication and decision-making are induced by dealing with uncertainty and task dependencies in construction management activities (Priven & Sacks, 2015). Thus, If a simulation game creates such a situation, the researcher can easily identify the emergent social mechanism. In order to identify these mechanisms, the IVR system must have a robust method to collect and analyze behaviors and psychological responses during the simulation. Therefore, the IVR simulation game should give users a level of freedom to finish tasks while also imposing dependency restrictions and uncertainty.

In order to study the social mechanism behind LPS, the prototype should provide two rounds of experiences (i.e., traditional and LPS) so that researchers can clearly see the social nuance when comparing the result of these two rounds. In that respect, it is necessary to determine the key principles and tools among traditional and LPS-based project teams, and design corresponding simulation rules and principles. Table 2 presents the LPS elements and devised rules in IVR simulation. It selected eight elements of the LPS based on Ballard's research (Ballard, 2000). The framework links the LPS elements and rules of simulation games to articulate the IVR design environment. In the traditional round, the LPS elements consider master scheduling, push planning, centralized decision-making, as well as the Planned Percent Complete (PPC) measure. In turn, the LPS-based round considers master scheduling, pull planning, constraint management, lookahead planning, commitment planning, distributed decision-making, continuous flow, and continuous improvement (discuss and analyze PPC). The implementation of these rules will be described in the next section.

Table 1: The LPS elements and devised rules in IVR simulation

LPS elements	**IVR simulation rules**	
	Traditional round rules	**LPS-based round rules**
Master scheduling	The manager released the plan	All users discuss the plan
Decision-making authority	Only manger	The manager along the other users develop the plan
Constraint management	Not applied	Users should discuss the constraints and remove them
Pull planning	The manager pushes the plan on others	The last planner can request resources when needed verbally and directly to the supplier
Lookahead planning	Not applied	Applied
Commitment planning	Tasks released by manager's requests	Tasks released by users' commitments
Continues improvement	Only PPC measure	Users should review and analyze the PPC.
Continuous Flow	Batch size is limited	The batch size can change if needed

SYSTEM ARCHITECTURE

Figure 1 depicts the architecture for a multiplayer IVR prototype designed to run both traditional and LPS-based rounds. It consists of a host acting as the researcher and clients. The prototype utilizes cutting-edge standalone wireless IVR headsets, Meta Quest 2, which offers a high level of mobility and a seamless match between users' movements and gestures in the virtual and real worlds (Meta, 2023). The controllers utilized in the prototype are wireless and do not require any additional tracking devices (the headset has integrated tracking sensors), providing users with the freedom to use them in any location. Also, the headset provides a casting function allowing users to share their IVR screen to a computer or smartphone. Wearable biometrical sensor sets: Shimmer3 GSR+ were attached to users' palms and ear to capture physiological data such as GSR, and HRV. The IVR prototype was created using C# programming language and the Unity game engine. Unity, a commonly used platform for creating desktop and VR video games and applications (www.unity.com), is compatible with the Meta Quest 2. Unity program provides basic modules to support the execution of the game. The login module defines the user identity by configuring the user roles and names; the production module provides the basic game mechanism that simulates the project lifecycle. The navigation and interaction model gives users a great degree of freedom to move, turn, and interact with the environment. The event module use a timer to measures and records the amount of time taken in a game. The timer has several timestamps or milestones associated with the pre-defined events waiting to be triggered. If a timestamp is reached, specific users will be notified and the environment will be influenced by the corresponding event. For example, suppliers will receive the notification of increasing delivery time, while global environment variables (e.g., delivery time) will be modified for all users. The network module provides an interface that synchronizes the local datasets to the cloud. All headsets are connected to a cloud server with Wi-Fi. Pun 2 and Photon voice (Photon, www.photonengine.com) are chosen as online hosting platforms, providing multiplayer supports. In addition, a researcher will join the network as a host by using a laptop with an Intel Core i9-10980HK processor, NVIDIA GeForce RTX 3080 graphic card, 32 GB of RAM, and a Windows 10 operating system. The host uses the Unity desktop editor to control the game, including starting and stopping the game, observing behavior, and accessing data from iMotions. The iMotion platform (iMotions, www.imotions.com) also operates on the laptop along with the game. It can read data generated by biometrical sensors wirelessly and capture headsets' screen.

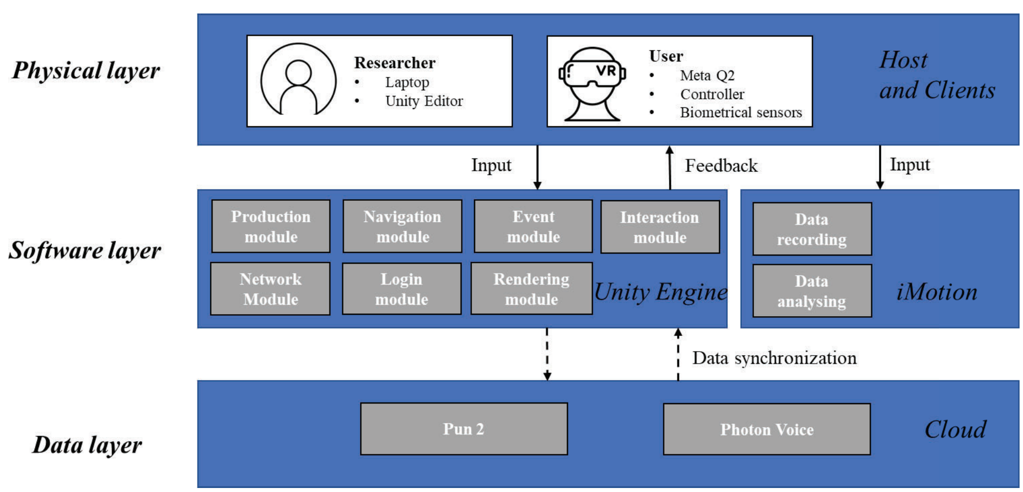

Figure 1: System architecture

IVR ENVIRONMENT

Four scenes and associated user interfaces have been devised in the IVR environment: (1) A Login scene enables users to use a virtual keyboard to enter a username, use a ray to select a role and different simulation scenes (see Figure 2a); (2) A Tutorial scene features an instruction board to provide game rules and guidance (see Figure 2b); (3) A Traditional Construction scene includes multiple sub-scenes: Construction, Production & Shipping, and Meeting & Planning sub-scenes (see Figure h). Figure (2c) shows that the users can control an embodied avatar. Figure (2d) shows that if the user presses the button, a ray will be cast from their hand to indicate the destination. Their embodied avatar will move the destination instantly after the user release the button. Figure (2e) shows the Meeting & Planning sub-scene is equipped with whiteboards, and users can use a virtual keyboard to make plans. The Production & Shipping sub-scene has a workstation for producing bricks and shipping them, allowing users to select the number of materials to be produced (see Figure 2f), while the Construction Site sub-scene has roadbeds where user can realistically use their hand to lay bricks and retrieve shipped bricks from pallets (see Figure 2g). (4) A LPS Construction scene is another scene that incorporates LPS procedures and tools into the production planning and control process of the project. It features similar sub-scenes and layout as the Traditional Construction scene, but with different rules and processes (e.g., the traditional Meeting & Planning sub-scene is replaced by a Lean-based Meeting sub-scene).

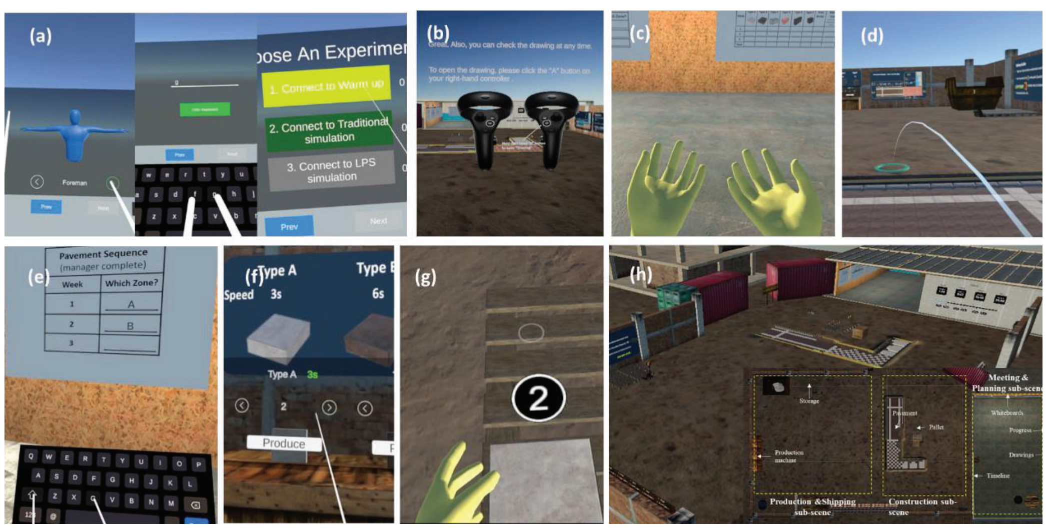

Figure 2: The user interfaces and scenes of the IVR environment: (a) A user selects roles, inserts usernames, and chooses simulation round; (b) A user read the tutorial boards; (c) A user has an embodied avatar; (d) A user moves to a position; (e) A user uses a virtual keyboard to make the plan (f) A user produce materials (g) a user grab materials (h) a construction simulation scene and a map.

PROTOTYPE TEST

TEST SCENARIOS AND STORYLINES

Hypothetical cases were created to test whether the architecture prototype presented in the "Development of the immersive virtual reality prototype for LPS simulation" section works as designed. In this hypothetical case, users must complete a pavement project (containing three different zones) within three weeks (simulated as 5 minutes per week in the IVR environment). This prototype should be played by three users maximum, including a manager, subcontractor, and supplier, which enables the exploration of the social interaction among key Last planners. Generally, the subcontractor is accountable for performing paving tasks at the construction site. The supplier is responsible for producing and delivering specific bricks to the subcontractors. The manager makes a plan and monitors the workflow. To achieve reliable gaming control, we use programming to restrict each role to only access its role-specific functions when performing tasks. Other than measuring and instruction before the game, the researcher does not provide cues or feedback to the users on the optimal way to complete the tasks. Before the game starts, all users will have a tutorial to learn how to interact with the VR environment and controls, as well as basic LPS procedures. Users must follow traditional (non-Lean) and LPS-based production planning and control approaches to complete the same tasks.

A simplified storyline was devised in this section, which presents a typical one-week simulation for all users. The IVR simulation has both the Traditional-based and the LPS-based construction rounds, which contain four main scenarios: Tutorial, Meeting & Planning, Construction, and Recap.

It is assumed that, in the beginning, users go through the Traditional round (see white blocks). Three users and a researcher meet for briefing goals and rules. In the Meeting & Planning scenario, the manager is responsible for compiling the plan (deciding on paving sequences, bricks production schedule, brick delivery schedule, and batch size). This simulates the Master scheduling and Weekly Work Plan (WWP) meetings. Once the meeting ends, the supplier and subcontractor are automatically taken to the production and delivery area and the construction area respectively to carry out the paving tasks. The supplier produces different types of bricks and delivers them in fixed batches, while the subcontractor executes the paving tasks. The manager is able to roam in all areas to monitor the project's progress and guide them to perform tasks. After the week ends, all players are immediately brought to the meeting area for a recap, where they discuss the previous week's outcomes, such as PPC, time, and quality. During this time, the supplier has notified the bad weather condition, and the supplier may report this issue to the manager. These processes will repeat three times (three weeks) to finish the project using the Traditional approach. After that, users will go through the LPS round. The workflow is similar to the Traditional round but has different planning and control rules and tasks (see the difference in Table 1). We envisaged that the researcher designates the traditional group as the control group and the LPS-based group as the experimental group, where the behavior and physiological data are to be collected.

TEST RESULTS

We illustrate the example screenshots of the demonstration case scenarios (see Figure 4a-e). Figure 4a shows that two users are controlling their embodied avatar and discussing the plan in the third user's view at the Meeting & Planning scenario. Users' positions and gestures have been synchronized with other users across the network. These features simulate a realistic social interaction environment, which could improve users' sense of presence during communication. Figure 4b shows the users' inputs on the commitment log, and the PPC register with automatically updated figures according to the planning status and the project progress. This information reveals the constraints among tasks, creating a situation where researchers can analyze social mechanisms by observing how users make decisions. In addition, their attendance in commitment analysis shows that users are able to complete the tasks following the procedure and rules (both traditional-based and LPS-based). Figure 4c shows an uncertain event is triggered and information (delivery time increase) pop-up on the supplier's screen, which provides a realistic situation in which the project team must address constraints. It also allows the researcher to compare the user's psychological responses to such situations in different experimental groups (e.g., compare each user's stress level between LPS and the traditional round in dealing with uncertainties). Figure 4d shows that the subcontractor has grabbed a brick and is placing it on the roadbed, while the manager is checking the time lapse on the timeline. The timeline shows that the second week is about to end, and all players will be brought to the meeting room to make a plan. The evidence suggests that the IVR system not only allows users to act on their own, but also has programmed gaming controls to ensure the simulation operates under the rules and procedures. Figure 4e shows that the researcher successfully uses the IVR system to observe behavior and collect GSR and HRV data during these situations. Notably, the behavioral and biometrical data can be aligned and streamed, which provides robust data collection methods for unpacking the social mechanisms.

Overall, the gaming control of the IVR prototype has the potential to enable robust experiment controls, thus ensuring the experiment's reproducibility, while time restrictions and few user requirements indicate its feasibility for conducting a large-scale experiment.

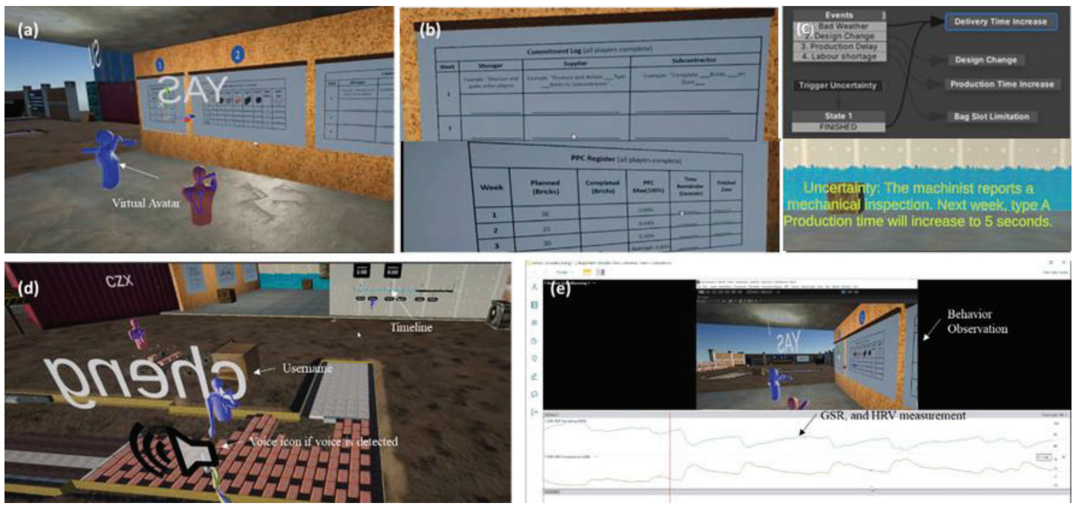

Figure 4: Screenshots of the demonstrative case and data collection platform: (a) During the Meeting & Planning scenario, a user interact with another user; (b) During Meeting & planning scenario, in the Meeting & planning sub-scene, users make the commitment plan, and analysis the PPC; (c) During Construction scenario, the system triggers uncertainties and impose the effect; (d) During Working scenario, in the Construction Site sub-scene, a user provide suggestions; (e) After the game, researcher code behaviors and analyses biometrical data.

DISCUSSION AND CONCLUSION

The purpose of this paper was to explore the viability and feasibility of using IVR to create LPS simulation games, with the goal of being able to develop methodologies to use these to better understand the social mechanisms of LPS. To do so, this paper determined the rules and essential elements of the IVR-based LPS simulation games. In this regard, this paper developed the IVR prototype, and illustrates a hypothetical case to demonstrate the realizations of these purposes.

The results show that the proposed IVR system is feasible for simulating the LPS and can improve our understanding of it by supporting the implementation of social experiments. This is due to its advantages in experimental control and support for large-scale experiments that involve the collection of behavioral or physiological data. The theoretical contribution lies in advancing Lean project management by providing a prototype design and data collection approach (containing technical requirements and design principles) that steps a stone for a new experimental avenue to study the social mechanisms of LPS. From a practical standpoint, using this IVR platform combined with gamification principles for purpose-training could improve the implementation of LPS in the construction industry. The use of IVR technology is not without limitations. (1) The IVR environment is a simplified representation of the LPS, only simulating a few technical and social dimensions of the LPS in real life. (2) ecological validity test of this prototype is needed before using it to conduct social experiments.

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