SERIOUS CONSTRUCTION GAME IN VIRTUAL REALITY: EMBEDDING HIGH-RESOLUTION TELEMETRY FOR LEAN PERFORMANCE ASSESSMENT

Kilian Speiser and Jochen Teizer
Technical University of Denmark, Denmark

Abstract

Existing Lean construction simulation games rarely provide detailed personalized feedback for participants but rely on coarse metrics like completion time or flow visualization. This paper investigates how high-resolution telemetry in active multi-role Virtual Learning Environment (VLE) supports lean assessment on teams in a staged introduction of process and automation improvements. We developed a VLE for 11 building trades using role-specific input devices and a telemetry pipeline that captures interactions to compute Lean indicators (flow discontinuity, production rate, waste). We found high potential of embedding high-resolution telemetry into VLE of data-driven evaluation of Lean principles, offering value to educators, trainers, and practitioners.

Introduction

Lean construction builds on concepts from the Toyota Production System, later described as the Lean Production System (Ohno, 1988). It aims to increase value while reducing waste, thereby improving productivity (Koskela, 1992). Lean construction emphasizes several principles: respect for people, value, flow, waste reduction, and continuous improvement. A central school within Lean is pull planning, in which work is released by downstream demand rather than pushed by a central schedule, most prominently operationalized through the Last Planner System (Ballard, 2000). To teach Lean principles, serious games have emerged as an active method, in both analog and virtual forms (Bhatnagar et al., 2023). Serious games enhance learning through structured challenges and feedback (Clark, 1970; Muntean, 2011) (Domínguez et al., 2013).

An early implementation of such lean construction games included the assembly of a building using Lego bricks, with and without pull planning (Warcup and Reeve, 2014). Such games introduce Lean principles over several rounds, and improvements between rounds highlight how users can improve through the adoption of Lean. However, quantifying these improvements requires clear performance indicators. In analog games, this is difficult to achieve based on objective data. For instance, players must record time and manually assess how many tasks were completed correctly. Virtual Environments (VEs) overcome this by automatically capturing task duration or errors at high resolution (Speiser and Teizer, 2024a; Wolf et al., 2022; Wolf and Teizer, 2022), and by visualizing progress or flow lines (Jacobsen et al., 2021; Sacks et al., 2007). However, while serious games in Lean construction enable automated data collection, a crucial gap remains: sub-second logs of user inputs, location updates, tool and material interactions, zone entries/exits, and task events are seldom used to compute Lean predictive Key Performance Indicators (KPIs). The remainder of this paper uses high-resolution telemetry to refer to such logs.

The idea investigated in this paper is the embedding of high-resolution, cross-role telemetry into a multi-user VR game to compute KPIs, thereby enabling actionable feedback at individual and team levels to enable cross-role and cross-round comparison. This work sits within Human–Data Interaction (HDI). The telemetry pipeline operationalizes three HDI principles for construction training: *legibility* (raw behavioral traces are rendered as indicators non-experts can read), *agency* (workers see indicators about their own work and can act on them within the round), and *negotiability* (cross-role indicators such as EWPT make coordination losses visible to the team that caused them rather than logged against the trade that absorbed them).

This paper addresses the following research questions based on the gaps identified before.

RQ1: How can role-specific lean performance be quantified and assessed in real time using in-game telemetry data?

RQ2: How can cross-role telemetry data be used to analyze collaboration patterns and detect coordination breakdowns in VR-based construction training?

A design science research (DSR) methodology iteratively develops and evaluates a networked VR artifact and its telemetry pipeline. The artifact derives a conceptual indicator framework to assess lean performance. In a study combining hoisting and apartment finishing in a high-rise building with 11 roles, role-specific interactions, and staged interventions across rounds, the research results in the following contributions:

C1: A theoretically grounded telemetry-based indicator framework with standardized lean performance indicators suitable for VR telemetry.

C2: An instantiated VR prototype and modular architecture demonstrating how realistic tasks, roles, and indicators can be adapted across multi-round scenarios to operationalize Lean principles.

Lean Performance Indicators

In construction projects, Lean performance is often assessed through outcome-focused indicators such as cost, schedule adherence, or percent complete, which serve as lagging indicators rather than true Lean metrics (Koskela, 1992; Ballard, 2000). Recent reviews highlight inconsistencies in their use that hinder comparison across projects and countries (Asmone et al., 2025). Process-oriented measures that capture flow, waste, and value have long been proposed in Lean research but are rarely applied systematically in practice, partly because collecting the fine-grained data required is difficult on active sites (Jacobsen et al., 2023). At its core, this is a HDI problem: data is fragmented across humans, devices, and trades, and translating it into legible indicators for workers and managers remains unresolved. The barriers are human-related (workers' attention demands), data-related (sparse, noisy site sensing), process-related (variable task definitions), and organizational-related (limited incentives to record). VLEs remove all four by capturing them automatically, offering an opportunity to measure Lean principles in new ways.

Flow is central to Lean thinking. Four indicators are particularly relevant (Rathnayake et al., 2023): (1) Level of Work Discontinuity (LWD), which quantifies crew downtime relative to work progress; (2) Mean Trade Production Rate (MTPR), which reflects the average completion rate of a trade; (3) Excess Work-in-Progress time (EWPT), which highlights inefficiencies between trades in the same location; and (4) Mean Location Production Rate (MLPR), which aggregates progress across trades at a given location (Rathnayake et al., 2023). Together, these provide diagnostic insights than higher-level indicators such as Percent Plan Complete (PPC), which is widely used but heavily dependent on the quality of the baseline construction schedule (baseline plan) against which progress is measured (Asmone et al., 2025).

Waste is another essential dimension of Lean, representing non-value-adding activities. The eight wastes are waiting, motion, inventory, extra processing, defects, overproduction, underutilised talent, and transport (Ohno, 1988; Liker, 2004). While it is difficult to measure waste on-site (Jacobsen et al., 2023), VR environments can automatically capture waste, linking low-level inefficiencies to overall productivity.

Value in Lean was originally defined as what the client is willing to pay for (Koskela, 1992). This concept has since broadened to include stakeholder benefit, end-user wellbeing, and quality-in-use (Salvatierra-Garrido and Pasquire, 2011). In VEs without client in the loop, quality and reliability serve as measurable proxies for the value the client would otherwise judge.

Research methods

The research presented in this paper follows a DSR methodology (Hevner et al., 2004; Kirk, 2013). DSR is appropriate here because the research question is not whether telemetry-derived Lean indicators correlate with productivity in the abstract, but whether such indicators can be constructed at all in a multi-role VR setting and made useful to learners and trainers. This is a design problem in the sense of Hevner et al.: it requires building an artefact, exercising it, observing where it breaks, and iterating. Pure observational or experimental designs cannot produce the artefact itself. The paper aims to produce a conceptually viable artifact as an instantiation of a serious Lean game in VR. The artifact is based on a relevant problem: Existing Lean games do not provide performance indicators across the different Lean principles from low-level data collection.

Recreation of the VR environment

The scene generation follows a mixed approach based on previous research. Two Building Information Modelling (BIM) models were obtained from contractors. The first project is a construction site in Munich, and the BIM model has been included using the IFC Importer (Speiser and Teizer, 2024a). The second BIM model represents a completed student dorm project in Denmark. The BIM model was included using the Unity Export plugin available in the Autodesk store. Using real projects rather than fabricated scenarios reduces authoring effort and avoids questions about ecological validity (Speiser and Teizer, 2024b).

The BIM models miss the construction site layout and machinery. Hence, these elements are added in Unity using Assets. Site equipment, including cranes, forklifts, guardrails, barriers, and materials, is manually added. On top of that, the elements that the users interact with are added manually, and scripts are assigned, like previously published research (Jacobsen et al., 2022). Generally, however, the materials that each trade needs are added. To further strengthen the real-world relevance, trajectory information for a forklift is included using an algorithm developed in previous work (Speiser et al., 2023).

Figure 1. Scene overview of the virtual construction site in Unity with zones highlighted.

The construction sequence integrated in this training environment is based on a handbook shared by a Finnish contractor. It outlines the construction of bathroom pods in residential housing in detail. The handbook was selected because it documents the bathroom-pod sequence at task-level granularity, which the German and Danish project documents lacked; pod-assembly logic is essentially country-agnostic, so the sequence transfers. This sequence was used to recreate the sequence. This sequence was also the baseline in identifying the trades required for the serious game. For simplicity, each trade represents one role, and each role is implemented as one user. Technically, there could be more users for each trade, and it would enhance the freedom during gameplay, but it has been chosen to stick with one per trade to enable smoother gameplay and implementation.

As the user study, which will be described later, includes three different rounds, the scene is also adapted for each of the rounds. The changes include moving the position of equipment, adding or removing safety equipment, or changing tools and interaction possibilities. These changes were chosen based on role-practicability. The objective was that each role had technological enhancements in each round and that Lean principles were included in each role. Hence, each trade receives information on how to reduce waste within their task, how to improve flow (for all trades), and how to improve quality as a proxy for value.

The virtual training environment combines observations from two real projects into one synthetic site encompassing four interdependent activities with eleven

Table 1. Role overview with tasks, required tools, and interaction setup.

Trade	Task description	Required tools and materials	Changes over rounds	Input devices and immersive displays
Crane Operator	Hoist bathroom pods to target units; coordinate with Riggers via signals	Tower crane, rig, bolts/rigging hardware, bathroom pods	R2: Crane repositioned; overhead-load proximity notifications; reminders to clear under load	HMD (optional desktop); Farmstick
Rigger Ground	Attach pod to rig; signal crane; prep/load boxes for forklift	Rigging points; two bolts/connectors; material boxes/pallets; ladder/ platform	R1: Ladder next to bathroom assembly R2: Safe platform replaces ladder; reminder to exit under-load zone	HMD (optional desktop); XR controllers (optional data gloves)
Rigger Top	Prepare the bathroom location with heel tabs and drainage; signal the final position; and disconnect the pod.	Heel tabs for placement; hand tools for disconnect (two bolts); ladder	R1: Manual material collection, no Lean board; R2: Overhead-load notifications; Lean board progress reporting	HMD (opt. desktop); XR controllers (opt. data gloves)
Plumber	Install four pipe runs (hot, cold, wastewater, ventilation); close opening with plasterboard.	Pipes; wrench for connecting pipes; plasterboard	R1: Manual material collection, no Lean board; R2: Materials pre-positioned; Lean board enabled	HMD (opt. desktop); XR controllers (opt. keyboard/mouse)
Screed Layer	Place self-leveling screed; level to finish	Screed; screed pump; levelling tool	R1: Manual material collection, no Lean board; R2: Materials pre-positioned; Lean board enabled	HMD (opt. desktop); XR controllers (opt. keyboard, mouse)
Glazier	Remove guardrail; install window; tidy debris	Window unit; guardrail components; self-retracting lifeline	R1: Manual material collection, no Lean board; R2: Materials pre-positioned; Lean board enabled	HMD (opt. desktop); XR controllers (opt. keyboard, mouse)
Carpenter	Cut and install floor elements; tidy waste	Pre-cut floor elements (by round); miter saw	R1: Cutting & fitting; R2: Pre-cut elements on pallets; Lean board	HMD (opt. desktop); XR controllers (opt. keyboard, mouse)
Painter	Paint two walls; dispose of trash	Paint buckets; brush/paint roller	R1: Bring/return bucket; R2: Bucket pre-staged; Lean board	HMD (opt. desktop); XR controllers (opt. keyboard, mouse)
Electrician	Verify power is off; Install two outlets, two switches, and one wall lamp;	Sockets; switches; lamp; drill	R2: Materials pre-positioned; Lean board	HMD (opt. desktop); XR controllers (opt. keyboard, mouse); 3d-printed drill
LEAN and safety manager	Inspect site; report defects/hazards; support coordination	N/A	R2: Progress visible on Lean board; dashboards between rounds	HMD (opt. desktop); XR controllers (opt. keyboard, mouse)
Autonomous forklift	Transport material boxes along predefined trajectories	Forklift; fork; material boxes; storage area	Trajectory constant; interacts with Rigger Ground workflow	N/A (autonomous)

roles. Table 1 summarizes each trade's tasks, tools, input devices, and round-specific changes. Together, these define the game structure and performance assessment.

Flow indicators as a proxy for productivity

Trade flow is measured through LWD and MTPR. LWD is defined as the ratio of total time spent in between locations to the floor area of the building (12 m² per apartment). It captures discontinuity in a trade's workflow as time per unit area. Since this indicator rewards consistency, even at a slow pace, MTPR is added to represent the average completion time of a trade across all locations. Together, LWD and MTPR provide a trade-level assessment of flow performance as an evidence-based proxy for productivity.

Team performance at the location level is measured through EWPT and the MLPR. EWPT quantifies the time lost due to unnecessary accumulation between crews, with lower values indicating smoother flow. However, as with LWD, steady but slow work is rewarded. To address this limitation, the mean location production rate is added, capturing the aggregated completion time of all trades working in the same location.

Waste indicators as a proxy for productivity

The VE tracks five waste types: motion, extra processing, inventory, defects, and waiting. Underutilized talent, overproduction, and transport are excluded due to their limited relevance in the developed game. For each user role and task, different aspects of waste are monitored. As with the flow indicators, waste is assessed both at the trade (individual) and location (team) level. To maintain consistency with flow terminology, these are referred to as trade waste and location waste.

In this paper, waiting is defined as time spent outside the apartments, which is treated as non-productive time. More advanced tracking methods could include continuous monitoring of worker movement, but here, waiting is only considered when users are not inside the apartments. Waiting is also a key input for the discontinuity indicator. For the tower crane operator, waiting is measured as the time between the Rigger's signal to hold and the subsequent signal to move the load after connection or disconnection. Motion waste captures unnecessary movement that results in lost time. Inventory waste is defined as carrying too many or too few elements. Too few elements result in additional trips, which are already classified as motion waste. Hence, only surplus inventory is considered, and a 10-second penalty is assigned for each excess item. Extra processing waste is defined as repeating activities without added value. In this game, it is only assessed for the Painter and screed layer. The Painter may repaint the same area multiple times, while the screed layer may repeatedly level the surface without improvement. The time spent on such redundant actions is aggregated as extra processing waste.

By combining these low-level contributors into higher-level indicators, the framework enables a new perspective on Lean performance in VR training.

Data collection and analysis

Unity provides robust data collection features. Specialized scripts are created and added to game objects, and for each role, the collected events are stored in the *UserDataCollector* component. Each script was tested individually during early tests of the training scene (Speiser and Teizer, 2024b).

Zones are modelled as colliders so that each avatar's entering and exiting can be detected. These events are sent to the *UserDataCollector*. The content of the virtual toolbox is also sent to analyze whether users brought the correct amount of materials to the rooms. Task completion is recorded based on the installation of the objects. Each trade has a certain number of elements to install. Elements snap into place once the user holds the correct item near its final position.

User studies

The study validates the technical and operational feasibility of the developed artifact to collect high-resolution telemetry data and convert it into performance indicators that enable comparison across roles. Based on previous experiences (Teizer et al. 2017, Teizer et al. 2019, Tagliabue, et al. 2020, and Teizer et al. 2020) the evaluation is structured in three parts. First, each role was tested individually with researchers through think-aloud sessions supported by expert feedback. Two evaluation sessions were then conducted with researchers as participants: Study 1 (n = 3, roles: Painter, Glazier, Plumber) and Study 2 (n = 3, roles: Rigger Top, Plumber, Crane Operator). The aim of this stage was to verify the data collection mechanisms and to confirm that the captured telemetry can be operationalized into indicator-based feedback using established Lean metrics. At this stage, verification and validation are limited to the Riggers, Crane Operator, Plumber, Electrician, Glazier, and Painter, while the Screed Layer and Carpenter roles are still under development.

Computed Role-level indicators

Figure 2 compares the trade-specific results for all indicators. LWD is an indicator of trade flow. At the trade level, the Glazier, Rigger, and Plumber in Study 1 showed much higher discontinuity compared to the Painter and Plumber in the Study 2. However, the Painter had a much lower MTPR. This highlights two findings: the Painter worked at a consistent pace, but at the lowest rate. The choice of combining indicators is therefore essential, since a pure flow metric cannot capture productivity.

Figure 2 illustrates this issue. The flow charts alone do not make the differences immediately clear. It shows the flow over time, and it's also visible that the trade spent most time in unit C3. Nevertheless, quantifiable units are more usable at first sight. While the graphs help, high-level KPIs provide quantification and decision support. Only with the numerical value discontinuity of 66 is an objective flow performance comparison possible.

MTPR for the Glazier and Plumber was comparable, while the Painter and Rigger lagged. Read alongside their LWD, this distinguishes two failure modes that flow charts cannot: the Painter is consistent but slow (low LWD, low MTPR), whereas the Rigger is fast but discontinuous (high LWD, moderate MTPR). The two cases require different interventions, namely pacing support for the Painter and dependency smoothing for the Rigger. Because the Painter was scheduled last in the work sequence, downstream trades were not affected any more.

Waste indicators provide insights into non-value-adding activities across trades. In Study 1, extra processing dominated the Painter's waste profile (678 s of 848 s). Without task-level guidance, learners optimized for visible coverage rather than first-pass quality, identifying this as the primary lever for round-2 improvement. The Glazier's waste (466 s) was driven by motion (320 s), indicating that material staging rather than execution was the bottleneck. The Plumber's profile (367 s) combined inventory (190 s) and defects (100 s), pointing to logistics and standardization as separate addressable issues.

Study 2 totals were lower across all trades (Crane Operator 255 s; Rigger Top 318 s; Plumber 458 s), but the composition matters more than the total. The Rigger Top's profile is dominated by waiting (218 s), which reflects coordination loss propagated from the Crane Operator rather than Rigger performance. Trades downstream of slow signalers absorb their inefficiency, and only telemetry surfacing this dependency makes the loss attributable to its source. The Plumber's recurring inventory (210 s) and defect (100 s) waste across both studies indicates the issue lies in the task rather than the participant, with material logistics and installation standardization as the relevant levers. Figure 3 illustrates these differences. Charts help to show the spread of waiting, motion, inventory, defects, and extra processing, but numerical KPIs allow for easier comparison. Listing the waste types is important for identifying potential improvements in the next round. The Glazier mainly suffered from motion waste caused by repeated trips to storage. If they did not need to carry the window, they could transport more inventory in one trip and reduce this waste. The Painter's waste was driven mostly by extra processing, which is hard to see in flow graphs. The Rigger experienced the longest waiting time due to slow crane operations. The crane operator also showed high extra processing waste, which points to possible improvements through automated trajectory planning instead of manual operation, since they often deviated from the shortest path.

Computed Team-level indicators

Study 1 shows lower waste and shorter completion time, resulting in a higher production rate. The main waste contributor is extra processing, which is caused exclusively by the Painter (see Figure 4). The second-largest waste category is motion, driven mainly by the Glazier. In contrast, Study 2 eliminates motion waste but shows a higher waiting waste. This waiting time could be reduced if the crane operator worked faster. Inventory and defect waste are comparably high in both groups. The higher waste observed in Study 2 also results in longer completion time per unit.

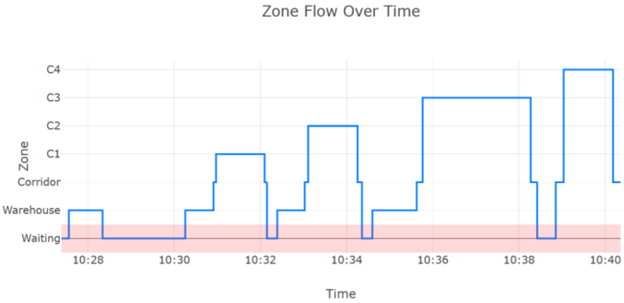

Figure 2. Plumber trade flow over four units.

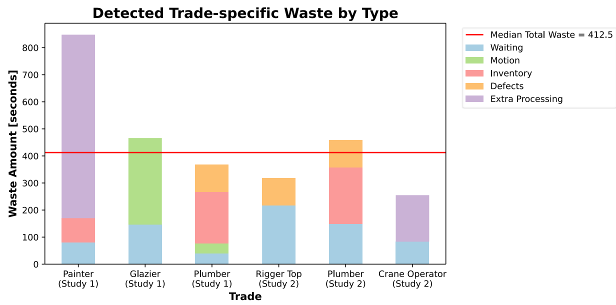

Figure 3. The detected waste for all trades by waste type.

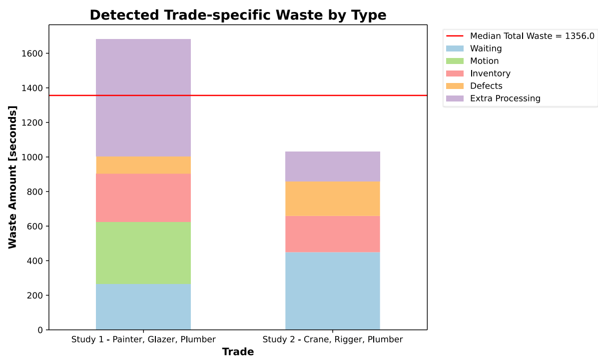

Figure 4. Aggregated team waste by waste type comparing Study 1 with Study 2.

EWPT quantifies what Figure 5 shows visually. Idle times between trades grow as the sequence progresses, most sharply between the Glazier and the Painter, totaling 389 s across locations (Figure 6). Three implications follow. First, EWPT exposes a lagging-trade penalty that PPC and completion time cannot, since locations sit unused even when each individual trade appears on track. Second, the metric is round-comparable: learners can be tasked with reducing EWPT and measure their own improvement quantitatively, which turns the dashboard into a learning instrument rather than a report. Third, the C1 value functions only as a relative baseline; calibrated thresholds remain a field-validation task (see Limitations). EWPT and LWD are interdependent, since a discontinuous trade upstream creates EWPT downstream.

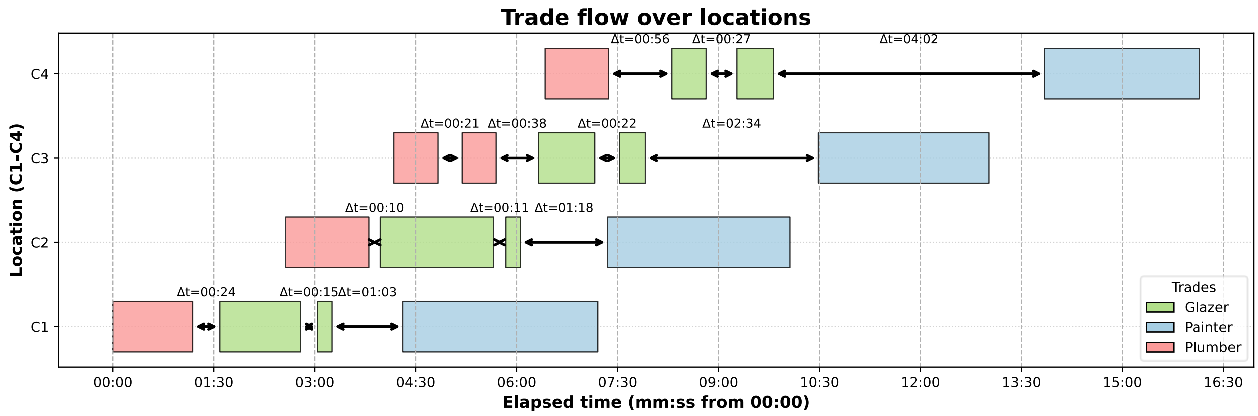

Figure 5. Location flow for group 1, where both motion waste and EWPT per location are included.

Bottlenecks and identified improvements

The Painter consistently worked at a much slower pace than the other trades. Unless their performance improves, subsequent activities will be delayed. A possible solution would be to either add a second Painter or redistribute the workload to balance the overall schedule. The Crane Operator's slower response times also created waiting waste for the Rigger. Improving crane operation speed, for example, through additional training or automation of trajectory planning, could reduce idle times and increase throughput. In addition, workers who arrived on site but could not start immediately contributed to unnecessary waiting and overcrowding. Adjusting arrival times or sequencing work differently would minimize idle presence and improve location utilization.

The Glazier experienced high motion waste due to frequent trips to storage. Improved material staging or delivery batching would reduce unnecessary movement. The Plumber repeatedly generated inventory and defect waste, suggesting systematic issues in material quality or installation practices. Standardizing installation procedures and improving material logistics could help mitigate these recurring inefficiencies. The Painter's extra processing waste points to inefficiencies in task execution. Clearer task planning or defined performance benchmarks could help prevent overworking the same areas.

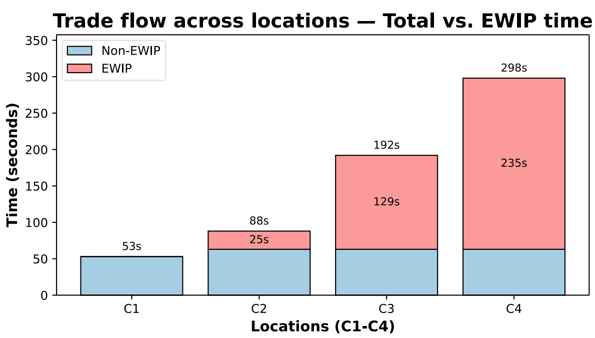

Figure 6. EWPT time by location.

The EWPT analysis revealed significant idle times between the Glazier and the Painter. This indicates a misalignment in trade sequencing that could be improved by staggering tasks or adjusting work areas. Monitoring and reducing EWPT times in subsequent rounds would allow teams to better visualize and quantify improvements in location flow. Moreover, providing real-time feedback on discontinuity (LWD) could enable trades to adjust pacing immediately and reduce downtime.

Conclusions

This paper developed a multi-user VLE that integrates lean indicators through high-resolution telemetry. The system shows how telemetry can turn low-level interactions such as signals, movements, and errors into actionable indicators that quantify flow and waste on both an individual and a team level. Linking role-specific and team-level data, the framework revealed coordination bottlenecks such as crane–rigger timing gaps and excess work in progress that remain hidden in single-role analyses. These results show that the telemetry pipeline enables a more comprehensive evaluation of construction workflows compared to pure completion tracking.

The study makes two main contributions. First, it provides an indicator framework to track lean performance in serious games. Second, it provides methods to collect data in VEs and compute the determined indicators, which support the assessment of both individuals and teams.

Compared to prior VR Lean games (Jacobsen et al., 2021; Sacks et al., 2007), which report aggregate completion or flow visualizations, this paper expands the knowledge through nuanced performance evaluation and eases the identification of coordination breakdowns or weak performance.

The HDI contribution lies in *who* the indicators are computed for. Conventional construction analytics produces dashboards for managers from data workers cannot see; here the same telemetry stream feeds back to the workers themselves during play. This shifts the indicator's function: LWD becomes a signal the trade can act on, not a post-hoc score; EWPT becomes a coordination signal visible to the team that caused it, not a report on them. The Rigger's 218 s of waiting in Study 2 is the clearest example: under conventional reporting, the waste is logged against the Rigger; under telemetry-mediated feedback, it is attributable to the Crane Operator's trajectory and visible to both in real time. This is what makes pull planning measurable rather than aspirational: downstream readiness, the quantity the Last Planner System asks teams to commit to, becomes a continuous signal rather than a weekly self-report.

This paper is subject to several limitations. Interactions were simplified and limited to zone entries, tool pickups, install snaps, and signaling to ensure reliable measurement, which reduced ecological validity. The evaluation involved a small number of participants and only a subset of trades. The indicators do not yet have calibrated thresholds, so results can only be interpreted in relative terms. The framework has not yet been thoroughly tested in the field with construction workers, which restricts external validity. Telemetry collection from trades-people also raises privacy and ethical questions that this study does not yet address: data minimization, informed consent, and which indicators are appropriate to expose to whom remain open design questions for field deployment.

Practical implications arise for both education and industry. Trainers can use the framework to provide learners with immediate and data-driven feedback on lean performance. Cross-role visualizations, such as location-based flow charts and EWPT, also act as game mechanics that help players and trainers understand Lean principles in an active and engaging approach.

A priority future direction concerns HDI-aligned indicators for the respect-for-people principle. The current framework demonstrates that lean indicators can be computed from telemetry, but does not yet test whether they are meaningful to the people they describe. Future work will operationalize three HDI indicators: *trust calibration* (do users act on the indicator they see?), *perceived agency* over personal data, and *cognitive load* imposed by dashboards during play. These will be measured by pairing telemetry with short in-VR self-reports and post-session interviews. This direction also frames future integration of safety telemetry (Speiser et al., 2024, 2025; Speiser and Teizer, 2024c) and field validation as steps toward calibrated thresholds, benchmarks, and longitudinal evidence of behavioral change.

Declaration of AI in the writing process

During the preparation of this work, the authors used generative AI to proofread text and improve clarity. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Acknowledgments

The research presented in this paper was funded by the European Union Horizon 2020 research and innovation program under grant agreement no. 101058548 (BEEYONDERS) and Erhvervsfyrtårn Femern (FF6S). The Business Lighthouse Femern is co-financed by the European Union and the Danish Business Development Agency.

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