Situational Awareness in Construction Using a Serious Game

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Abstract: Production planners in construction face several problems related to the lack of information regarding construction project status, changes to resource availability, instability in production rates, design changes, and limited situational awareness (SA). Poor SA leads to uninformed and suboptimal resource allocation decisions. As a result, the construction workflow is negatively affected, degrading project performance. This study focuses specifically on possible relationships between production planners' SA and the resulting workflow quality. Such understanding can lead to the development of measures to improve production management in construction. Interviews with diverse production planners highlighted the nature of the information needed, issues related to the lack of SA, and the effect on workflow. A serious roleplaying game was devised to measure the correlation between production planners' SA and workflow, and 14 live simulation experiments were conducted with two teams of nine players each. Finally, a qualitative analysis of the information flow configurations applied in the experiments evaluated the expected effects of information flows in the live experiment. The study found a positive correlation between the quality of information flow and workflow in construction, indicating causation in line with theoretical expectations. Specifically, free communication among planners together with management tools such as formal weekly work planning and a digital planning tool reduced the assembly time, working time, and non-value-added time of the subcontractors in the experiments. Good information flows among production planners and an up-to-date jobsite status diminish uncertainty and increase SA, which lead to improved workflow and productivity. **DOI: 10.1061/JCEMD4.COENG-12521.** *© 2022 American Society of Civil Engineers.*

Author keywords: Building construction; Information flow; Lean construction; Situational awareness (SA); Serious game.

Introduction

Construction projects often suffer quality issues, delays, and budget overruns (Vaardini et al. 2016). Projects are performed by large teams of diverse and independent stakeholders with conflicts of interest who must coordinate their decisions and actions. Production planners (individuals or groups) work to coordinate the stakeholders during the construction stage, deciding what physical and specific work will be done in sequential medium- and short-term planning windows (Winch and Kelsey 2005). However, production planners face several obstacles, including lack of information regarding construction project status, frequent changes to resource availability, instability in production rates, design changes, and limitations on their scope of action (Martinez et al. 2022). Difficulties in coordination generally lead to waste of resources, labor, and building materials (Serpell and Alarcón 1998).

Inaccuracy or lack of information on a project's current status during the construction stage constrain stakeholders' ability to coordinate (Alizadehsalehi and Yitmen 2016). In general, coordination must cover seven requirements: availability of workplace, materials, equipment, labor and information (product and process information), completion of preceding work, and external conditions (Koskela and Koskela 1992). In the absence of these conditions, the work cannot be carried out as planned, leading to material waste, flow interruptions, crew inactivity, and ineffective forward planning. Accurate process information is essential for effective planning (Doloi et al. 2012). Furthermore, by locating and defining barriers to the flow of status information, it may be possible to improve the reliability of the workflow itself and to reduce uncertainty during the decision-making process (Sacks et al. 2017). Indeed, a smooth workflow is a primary key to achieving benefits such as lower costs and shorter project durations (Ballard 2000).

The barriers to good flow (i.e., the ability to implement construction tasks in full at the time scheduled and with optimum productivity) are directly related not only to the status of the preconditions required to perform a task but also to production planners' perception of their status (Sacks 2016). Therefore, the availability of accurate, transparent, structured, and reliable information is expected to enhance production planners' understanding of jobsite progress, and ultimately boost productivity onsite (Lappalainen et al. 2021).

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In this study, we aimed to establish the relationship between production planners' situational awareness and the quality of the flow of work. As a first step, an exploratory field study was carried out with diverse production planners to outline current problems in construction sites related to their situational awareness and how those affect the workflow. A serious game, called iKan was developed to explore possible correlations between the quality of information flow and workflow in construction. A set of live roleplaying experiments was carried out using iKan to measure the impact of the information flow on the workflow. A range of prescribed information flow models was implemented in the experiments to compare the contribution of information flow to the players' performance in coordinating and carrying out their assigned tasks. The outcomes of this study aid construction practitioners and researchers in better understanding the barriers and the facilitators affecting information flow in construction and in selecting methods to minimize production planners' uncertainty. Moreover, by understanding the factors that affect production planners' SA, it will be possible to develop new strategies and methods for improving construction production management.

Background

Situational Awareness in the Construction Industry

Situational awareness (SA) is a term commonly used in the aviation industry (Melzer 2012; Stanton et al. 2001). It refers to the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and a projection of their status in the near future perfection (Endsley 1988). Other authors defined SA as the invariance in the agent–environment system that produces a momentary knowledge required to achieve the specific goals (Smith and Hancock 1995). According to Endsley (1995), SA is divided into three hierarchical phases: perception of the elements in the current situation (Level 1: data stage), comprehension of the current situation (Level 2: information stage), and projection of the future status (Level 3: knowledge state). The SA concept has been applied in different industries during the last decade, ranging from aeronautics (Craig 2012) to safety (Stanton et al. 2001). In construction, the SA concept has been employed in fields such as construction safety (Wang et al. 2021), planning and control (Görsch et al. 2020), and logistics (Tetik et al. 2021), among others.

During project planning and control, production planners need SA about the as-built and as-performed conditions when making daily decisions and developing short- and medium-term plans. However, production planners' SA is often compromised by inaccurate, incomplete, or latent information, leading to uncertainty. In the last decade, researchers in academia and industry have proposed and developed many hardware and software technologies to support construction managers' decision-making processes (Sawhney et al. 2020). Building information modeling (BIM), wearable sensors (WS), virtual and augmented reality (VR and AR), Internet of the Things (IoT) equipment, simulations, digital twin (DT) concepts, artificial intelligence (AI), and remote sensing technologies (RST) are some of the technologies that production planners may apply to obtain the information needed to make better decisions (Forcael et al. 2020). According to Osunsanmi et al. (2018), the use of such technologies might increase the amount and quality of field information while enhancing SA among production planners and field personnel.

Various tools and methods that may improve production planners' SA in construction have been decried in the literature. The Last Planner System (LPS) (Ballard 2000) and ANDON boards (Morgan and Liker 2006) are just two of the tools that provide planners with a comprehensive picture of a project's status and progress. The LPS plays a pivotal role in the short-term decision-making process (Salazar et al. 2020). LPS has been shown to boost knowledge sharing, enhancing planners' perception of the situation onsite, and therefore improve their SA (Görsch et al. 2020). ANDON boards are visual tools intended to support management practices in construction, specifically at the operational level. According to Reinbold et al. (2020), the use of such a tool can increase information flow among construction workers and crews, improving their SA throughout the construction project.

A relatively small body of literature on SA in construction is available, especially for production planning and control. Oloufa et al. (2003) developed and implemented a vehicle tracking and collision detection system to increase SA among the equipment operators. The research demonstrated that an effective collision detection system would allow operators to reduce the chance of collision while increasing their productivity. Later, Reinbold et al. (2019) investigated the potential of BIM and positioning sensors for SA in construction. The study results showed that an improved SA would allow managers to perceive the real-time status of the situation in an ongoing project concerning resource location and availability, value-adding time spent in the production processes, and adherence to planning targets and production flow signals. Görsch et al. (2020) studied how to capture SA of workers to improve assessment of the status of the preconditions of a task to improve the disciplinary and interdisciplinary coordination of individuals and crews and their overall decision making. The study concluded that better understanding and availability of the project and progress information could reduce workers' cognitive load and thus focus their capacity on task delivery. They assumed that the latter boosts the productivity onsite.

Recently, Lappalainen et al. (2021) identified the key requirements of SA system development in the construction industry and provided recommendations for the future development of SA systems. Their study revealed that the conceptual framework used in other industries is insufficiently employed in developing SA systems in the construction industry. Furthermore, currently available SA systems mainly focus on the first level of SA (data stage), which is limited to collecting the data and presenting it visually.

Uncertainty in Construction Management

Uncertainty can be defined as a state that varies from thorough knowledge to a near-complete lack of knowledge about an outcome (Gosling et al. 2013). In the construction domain, uncertainty can be described as the gap between the amount of information required to perform a task and the amount of information already in possession of the project team (Howell et al. 1993). There are several ways to characterize the different types of uncertainty in the literature. Laufer (2009) stated that uncertainty can be divided into "ends uncertainty" and "means uncertainty." Ends uncertainty refers to the uncertainty of purpose or product. It is resolved when the project's objectives and technical requirements are stable and well-defined. On the other hand, means uncertainty indicates the uncertainty of the way. This aspect is determined when the program and the implementation methods are stable and well-defined.

In construction management, uncertainty manifests in several ways: (1) activities that take more or less time than was required or expected, (2) resources that may not be available, (3) materials that arrive later than needed, and (4) schedule and deadline changes due to the addition/removal of activities required as a result of changes in the scope of the project. As a result, significant amounts of work in the process (WIP) are generated, and production systems lose effectiveness due to schedule instability, increasing project costs and durations (Herroelen and Leus 2004). Addressing uncertainty about the construction project status is relevant to managing the process as it is executed. During the construction stage, process information helps reduce process uncertainty by creating an up-to-date snapshot of the seven prerequisites required to perform the task (Javanmardi et al. 2018). Under this scenario, a good information flow about production status is essential for production planners because it reduces the degree of uncertainty and thus allows them to make wiser decisions about the next steps (Gosling et al. 2013).

Lean construction (LC) is an approach employed to reduce uncertainty and improve the workflow in construction projects (Howell and Ballard 1998). LC can be defined as the continuous process of reducing waste, accomplishing customer requirements, centering on the entire value stream, and pursuing perfection during the construction stage (Salem and Zimmer 2005). LC practitioners use various tools to enhance project values, such as 5S, concurrent engineering, Last Planner System (LPS), Kaizen, Kanban, Pareto analysis, Poka-yoke, and Six Sigma. At the production planning level, LPS plays a vital role in the short-term decision-making process (AlSehaimi et al. 2014). The LPS was created to make production planning and workflow more steadfast and to create trust within a collaborative team by requiring teams to review their plan near its execution and verify that the promises made are tied to milestones and that these commitments are firm, timely, and unambiguous (Salazar et al. 2020).

Serious Games in Construction

A serious game is a game intended for purposes beyond entertainment, such as education, training, simulation, or advertising (Karshenas and Haber 2012). More specifically, serious games integrate game tools with pedagogy in a game environment to train, teach, and educate people in different life situations to increase their knowledge and enhance their situational awareness (Taleb et al. 2021). Several benefits of serious games have been demonstrated, such as (1) supporting knowledge acquisition, (2) experiencing situations that could be difficult to recreate in reality, and (3) improving players' technical capabilities (García-Mundo et al. 2015). According to Ravinder and Kollikkathara (2017), standard management training techniques are insufficient to prepare managers for project management roles due to the absence of practice perspectives; serious games can provide some sense of experience. Serious games are widespread in different areas, such as healthcare, military, education, and social skills, proving their effectiveness in replicating actual situations (Calderón and Ruiz 2015). In the construction domain, serious games allow players to experience the consequences of applying different management decisions, solving complex project management problems, and implementing diverse solutions (Marcelino and Domingues 2022).

Serious games for construction production planning can be separated into physical multiplayer roleplaying games and single-player digital simulators. Physical multiplayer roleplaying games, the category to which this study's experiments belong, typically involve players fulfilling the roles of various trades in a construction project who work together to construct a simplified, purpose-designed small-scale structure using Lego construction blocks. LEAPCON (Sacks et al. 2007), Villego (Warcup and Reeve 2014), and LEBSCO (González et al. 2015) are all examples of this type. They immerse players in fictional construction projects and offer them concise live simulations of construction under different communication and organizational structures. These games all aim to demonstrate to the players the principles of lean production and the differences between them and traditional production methods.

Recent serious game applications have focused on improving fidelity and realism by integrating emerging technologies such as the Internet of Things, BIM, and mixed reality (Dallasega et al. 2020; Sepasgozar 2020). Although such integrations can no doubt enhance players' situational awareness of the project status and intent, discussions on the matter of production control and situational awareness from these studies have been limited. To the best of the authors' knowledge, serious games in construction production planning have predominantly been developed for educational and demonstration purposes, falling short of devising experiments to investigate advanced topics in production planning.

Objectives and Method

This study aimed to explore and explain the relationship between production planners' SA, their consequent production planning and control decisions, and the resulting impact on the quality of construction flow. The study's hypothesis holds that improving the process information flow, reducing the uncertainty, and increasing information reliability onsite will boost production planners' ability to make better decisions and increase the workflow. The objective was to afford construction practitioners and researchers a better understanding of the effects of information flow on construction planning and to identify ways to minimize uncertainty during production planning.

To start with, a field study was conducted with different production planners to define current problems in construction sites related to the lack of SA and how this affects the workflow. Later, a serious game was tailored to quantify the relationship between production planners' SA and workflow. Then, a set of live simulation experiments was carried out using the game to measure the relationships between the information flows and the workflow. Finally, a quality analysis of the information flow models employed in the live experiments was applied to assess the influence of information flow in the live experiment.

The research method consisted of four steps, as illustrated in Fig. 1.

Specifically, the main steps are as follows:

1. Field study: a semistructured interview was designed and implemented to obtain a preliminary view of the information flow in typical construction sites and of the relationships between production planners' SA and its effect on the workflow quality.
2. Game development: a serious game called iKan was designed with the aim to represent distinct types of information flows in construction and quantify how these could affect workflow.
3. Live experiments: seven experimental runs were held to measure the impact of the information flow types on workflow.
4. Qualitative analysis of information flow models: the information flow models implemented in the live experiments were assessed to evaluate the contribution of information flow to players' performance in each experiment run.

Construction Field Study

Fourteen construction field personnel were interviewed to obtain a snapshot of the information flows in different construction sites. The aim was to understand the nature of the interviewees' SA and its impact on the workflows in their projects. The interview subjects were production planners with various formal roles, including project managers, site engineers, and superintendents.

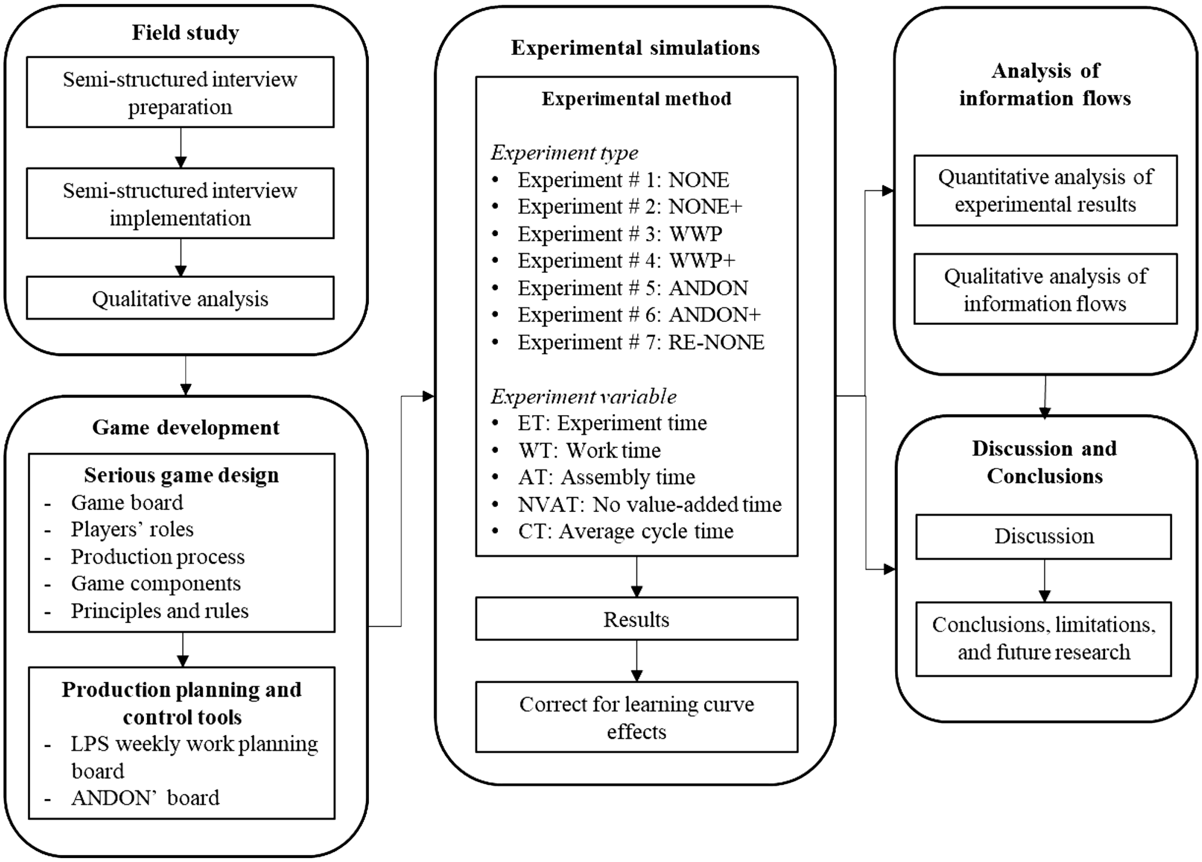

Fig. 1. Research method.

The instrument contained relevant questions regarding the following elements:

- Information flow for each of the seven constraint types that are prerequisites for construction activities, as defined by Koskela (2000). These are the availability of the workplace, flows of materials, equipment, labor, and information, completion of preceding work, and external conditions. Failures in any of these are likely to result in waste, such as poor productivity, rework, inadequate quality, and long cycle times.
- How and when information is transmitted.
- Uncertainty levels in information exchanges.

Open questions were added to elaborate on how uncertainty affects decision making and how it could be assessed. The instrument contained relevant questions regarding the information flow for each of the seven constraint types, how and when information is transmitted, and uncertainty levels in information exchanges.

Flowcharts were used to represent the information flow for each construction project. The charts detailed the communication channels commonly used [phone call (PC), face to face (F2F), email (EM), scheduled meeting (ME), and site tour (ST)] and how information is transmitted among production planners involved in the decision-making process (Supplemental Materials). Table 1 presents the number of interviews conducted, the interviewers' roles, and the construction project where the field study was held.

The interviews were transcribed and analyzed to determine the common threads of communication between the three roles of project manager, site engineer, and superintendent (also called works manager). Keywords for professional roles, communication modes, communication topics/contents, and timing of communication were identified and tracked.

According to the interview records, project managers, who were in charge of overseeing the planning and delivery of the construction projects, received information mainly from customer representatives and site engineers. Customer representatives informed project managers of design changes by email, phone, and face-to-face meetings. For minor design changes, they employed phone calls to notify of variations in the original design. For significant changes, they typically used emails and face-to-face meetings. Nevertheless, in some cases, design changes were reported directly to subcontractors rather than to project managers. These events caused interruptions to the construction workflow and consequently negatively impacted project durations because project managers could not update their work plans quickly enough, delaying the assignment of resources.

Most of the information that site engineers shared with project managers concerned problems in the supply chain and the project's

Table 1. Interviewees' details

Project ID	Project type	Number of interviewees	Interviewees' roles
1	Residential	4	Project manager, site engineer, and two superintendents
2	Residential	4	Project manager, site engineer, and two superintendents
3	Residential	3	Project manager, site engineer, and superintendent
4	Infrastructure	3	Project manager, site engineer, and superintendent

progress status. More specifically, they reported discrepancies between as-planned and as-performance progress by phone calls, daily meetings, and visits to the workplace. The latency and the transmission frequency of the information depend principally on its complexity and on the relative effort required to collect and process the required data.

Production planners indicated that the level of uncertainty during information exchange was a function of their previous experiences with the people who shared information with them in the past, i.e., of their degree of trust in the source (Loch and Terwiesch 1998). The level of uncertainty decreased when the information was provided by a reliable person who previously shared unfailing and timely information and increased when the parties have mistrust due to failures in previous information exchanges, causing delays in the decision-making process and affecting the workflow of several construction projects.

In general, the main factors that affected the information flows and production planners' SA were (1) the number of decision makers, (2) the company's procedures and practices, (3) the scope of the decision, the type of project, the number of stakeholders involved in the project, and (4) the cooperation level among stakeholders and the information flow reliability. Wambeke et al. (2011) found similar results regarding the factors influencing the information flow. Aspects such as difficulty in the information exchange among stakeholders, lack of confidence in the people who handle the information, and complex hierarchical structure that makes the exchange of information challenge were some of the barriers that could affect production planners' SA. Reliable and transparent information exchange between the parties involved significantly enhanced the workflow in construction projects (Olugboyega and Windapo 2019). This was reported at the construction sites on which project managers frequently held regular meetings with site engineers and superintendents to consolidate and revise the project status information. This practice reduced the levels of uncertainty during the information exchanges while improving the workflow.

iKan Game Development

The iKan game was developed as part of the research to explore the possible correlations between the information flow and workflow quality in construction. iKan is a roleplay board game that simulates the interior finishing work processes in high-rise residential buildings. Five wooden panels represent a 5-story residential building with 20 apartments. The game focuses on the interior finishing phase because the work packages are more complex than the structural phase in terms of information exchange, design change uncertainty, and work sequence variability, where work sequences are technologically constrained. In contrast to previous LC serious games, the design of iKan simulates the physical separation of space. As in real buildings, the status of work in any space is unknown unless one visits that space. Replicating this barrier to information is essential to recreating the need for reliable information flows between actors in construction projects. Table 2 compares the iKan game with other readily available LC serious games.

Serious Game Design

The game board depicts a residential building floor divided into four apartments [Fig. 2(a)]. The game boards are laser cut from 8-mm-thick wooden panels to create slots for work that requires the installation of Lego bricks [Fig. 2(b)].

Participants in the game fulfill five roles that embody the key jobs in the interior finishing stage of construction:

1. Project manager: responsible for the course of work while providing performance guidelines, building the work plan, and coordinating between the other players.
2. Customer representative: delivers the apartment finishing design drawings in a predetermined sequence according to the rules defined for each experimental scenario.
3. Quality controller: ensures that models are built according to the design drawings by checking the quality and monitoring production errors.
4. Materials supplier: supplies materials at controlled intervals according to the game's rules.
5. Subcontractors: build the models following the designs provided. There are five types of subcontractors: sound insulation installer, plumber, electrical, drywall partition installer, and floor tiler.

Table 3 explains the players' roles and their assigned tasks in the game.

The iKan game requires players to build two types of construction elements: walls and floors. Five trade subcontractors perform nine tasks during the construction of the apartments' walls and floors. Moreover, each trade has five possible designs representing five housing variations or customer changes that simulate real-world situations in which owners may request customization of their apartments. Delivery of the design information replicates the need for interaction, communication, and information flow between production managers and planners, trade subcontractors, quality inspectors, and material suppliers as required in construction projects to fulfill the product design specifications.

Table 2. Comparison of features of LC serious games and construction projects

Features	Real project	LEAPCON	Villego	LEBSCO	iKan
Space structure	Complex	Simple	Simple	Simple	Simple
Technological dependence of the craft	Complex	Simple	Simple	Simple	Simple
Uncertainties (process delays, design changes, and so on)	Y	Y	N	Y	Y
Expert crews	Y	Y	Y	Y	Y
Work in stages	Y	Y	Y	Y	Y
Re-entrant flow	Y	Y	Y	Y	Y
Space limitations	Y	Y	N	Y	Y
Physical space separation	Y	N	N	N	Y
Quality control	Y	Y	N	Y	Y
Material supply	Y	N	N	Y	Y
Workforce supply	Dynamic	Fixed	Fixed	Dynamic	Fixed
Cash flow	Y	Y	Y	N	N
Long-term planning	Y	Y	Y	Y	Y

Note: Y= yes; and N = no.

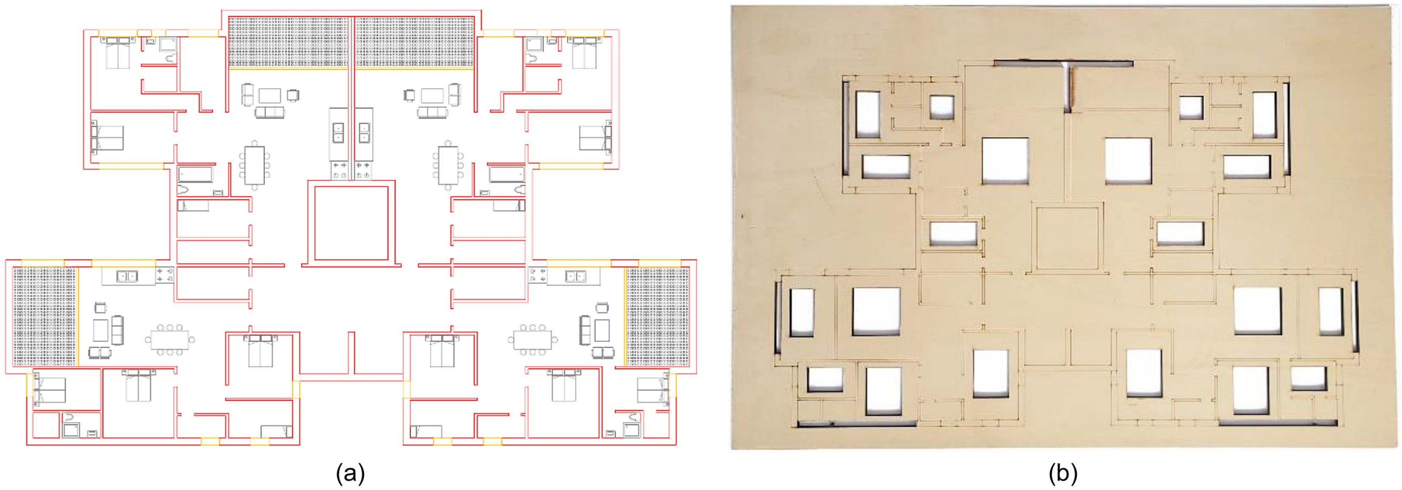

Fig. 2. Game board: (a) apartment floor plan used for the game development; and (b) iKan game board panel.

Construction of drywall partitions requires four trade subcontractors to complete five tasks: (1) first side of drywall partition, (2) pipes, (3) electrical conduits, (4) second side of drywall partition, and (5) tiles. Installation of a floor requires four tasks: (1) sound insulation, (2) pipes, (3) electrical conduits, and (4) floor tiles. In both activities, only one subcontractor may occupy any floor at any given time. Floors and walls are installed in specific slots on the game board according to the various design drawings provided. Fig. 3 shows examples of a typical wall and floor. The materials are Lego plastic bricks, color-coded according to the subcontractor trades. The quantity of work and the material requirements varied between models.

At the start of play, the project manager provides the subcontractors with standard designs for all the apartments and work begins. The subcontractors enter the floors in sequence, perform work, and move on once done. The quality inspector must approve the correct completion of each trade's completed work on a floor before authorizing the next trade to commence its work in the floor (the set of rules is provided in the Supplemental Materials). Play continues until all the work is completed.

Table 3. Tasks in the iKan game

Role	Tasks
Project manager	• Direct subcontractors to next work location upon task completion • Instruct Quality Control to check locations with finished products • Inform subcontractors of production errors and schedule rework
Customer representative	• Deliver design changes to apartments at fixed time intervals
Quality inspector	• Perform quality checks on completed products • Report production errors
Material supplier	• Receive orders and prepare material batches for delivery • Deliver material to specified locations at 5-min intervals
Subcontractors	• Complete the trade-specific construction work at the assigned locations • Perform rework on products when production errors are identified • Report on material shortages at a location • Order materials • Report any subcontractor space conflicts • Coordinate material deliveries

Production Planning and Control Tools

Two construction management tools were implemented to improve participants' information flow and leverage their SA. According to the literature, these tools provide a more concrete and comprehensive situational picture of the status of the project. In other words, the use of such tools improves production planners' SA in construction. The first was a LPS weekly work planning. This tool enables production planners to organize and plan the schedule and tasks for the upcoming week. The top row of the board indicates the expected timing of the task, and the others the task location (per floor). Color-coded notes were affixed to the cells in the board to depict the work planned for each player.

The second tool, called the ANDON board, was tailor-made for the experiment. The Japanese term ANDON describes a system that reports failures in quality or project deviations in real-time to production planners, workers, and the quality control area (Wojakowski 2015). The goal of the board was to communicate the status of the production tasks, with four status aspects per task: (1) delivery of materials, (2) provision of design drawings, (3) production process issues, such as quality failures or errors, and (4) completion status. Fig. 4 illustrates a section of a stand-alone ANDON board used to track tasks' status for the construction of the partitions on a single building floor. A similar section was used for the flooring work, and the full board contained five rows of two sections, one for each floor of the building.

The ANDON board was then implemented as a software service comprising a large-format screen display in the project manager's control room and a smartphone app used by the other players (Fig. 5). The mobile application tests the feasibility of managing processes and operations on construction sites by visualizing the information flow and democratizing the information access to all production planners involved. The application offers players real-time production process information by presenting the current progress status and capturing players' locations in real-time to avoid location conflicts during the game. The application matched players with their assigned tasks and presented the status of the

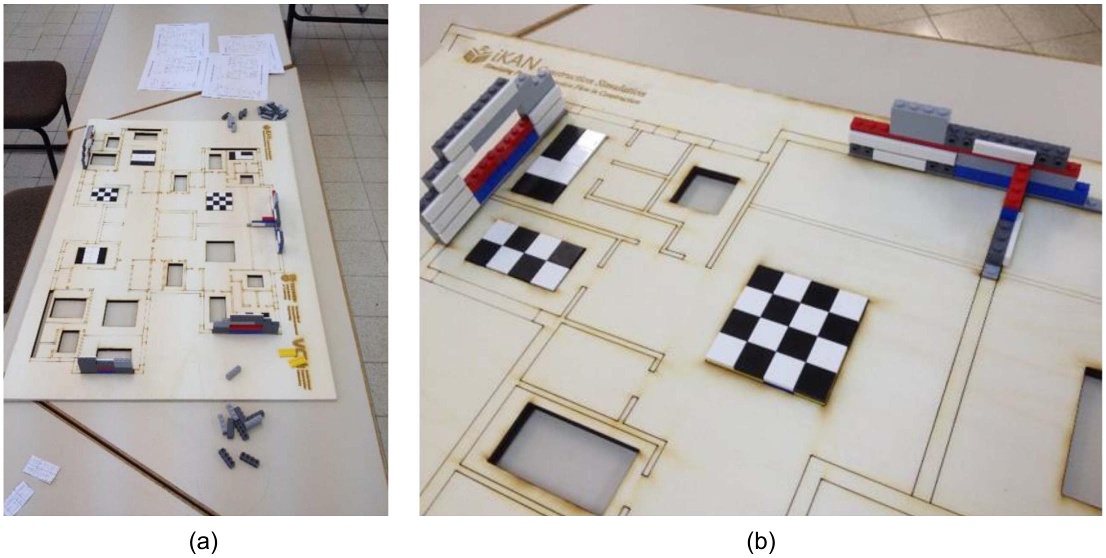
(a)
(b)

Fig. 3. Wall and floor models example: (a) drywalls, electrical conduits, water pipes, and wall tiles; and (b) floor model example.

prerequisites for those tasks. Players' locations were registered by the app as it automatically detected unique Bluetooth beacons placed with each game board so that the times of entry and exit of each subcontractor to each floor were reported live and recorded. Using the application, players could also report a lack of materials, delivery of design drawings, and quality issues. Icons presented the real-time status of each space and each task type.

Experiment Simulation Runs

Experimental Method

A set of seven experimental runs was designed to assess the impact of various configurations of information flow on the quality of workflow. The experiments took the form of live simulations of permutations of a model crafted to represent an archetypal production workflow found in construction sites where general contractors employ subcontracted work crews, such as those described in detail by Hinze and Tracey (1994) and others (Korb and Sacks 2021; Priven and Sacks 2016). Each permutation generated a distinct scenario in which information flows were different. More specifically, the quality and quantity of information, communication barriers between stakeholders, and tools used to depict the current status of the jobsite were varied. The runs were implemented with two separate teams, making a total of 14 simulation runs.

Each team consisted of nine undergraduate students from the Technion–Israel Institute of Technology, making a total of 18 participants. Each team performed the game once a week over 7 weeks. The composition of each team was unchanged throughout the 7 weeks. The students were randomly assigned roles (project manager, customer representative, quality inspector, material supplier, or subcontractor), which they played for the full duration of the experiments. At the end of each experimental run, participants answered a set of questions concerning the communication tools used and their level of uncertainty regarding the project's status at various points during the run. The game rules and the technical constraints of the physical setup ensured that the procedures followed resembled the behaviors observed in construction sites with similar characteristics and features.

Access to situational awareness information was controlled differently in each experimental run by incorporating different

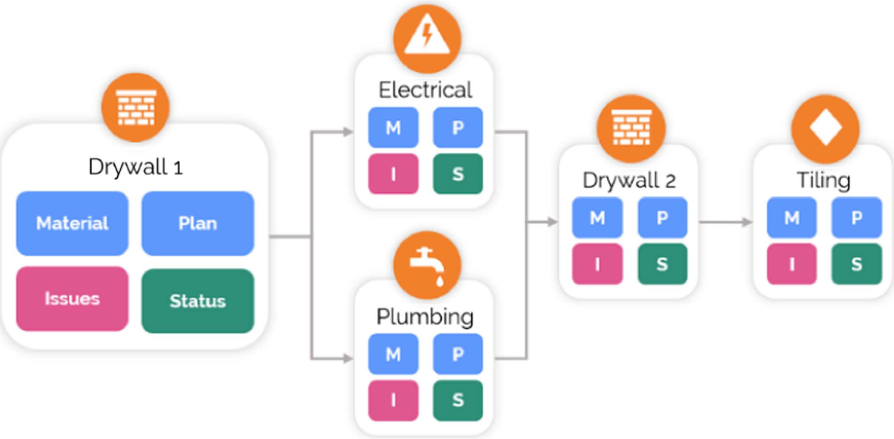

Fig. 4. ANDON board for drywall construction.

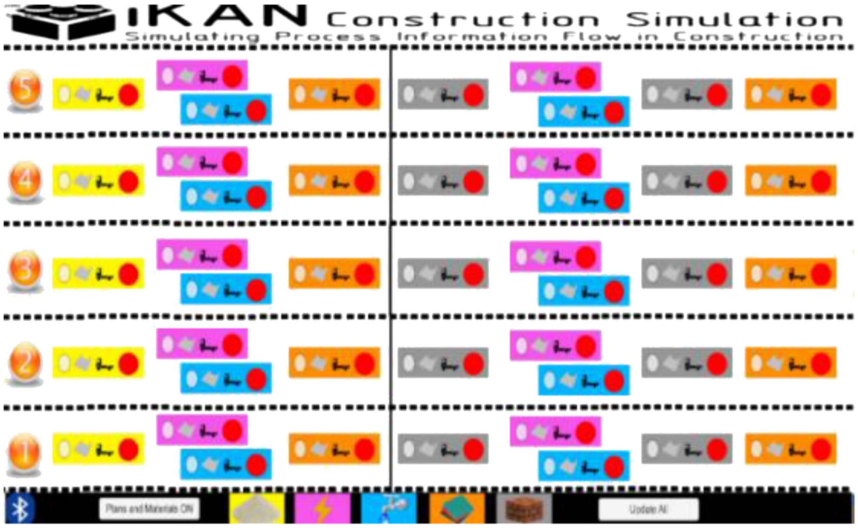

Fig. 5. iKan game app interface.

conditions for the players to communicate with one another and different tools to provide them with status information. Table 4 summarizes the information flow combinations and tools used for each round of experiments. The first column denotes the six experiment runs. Columns 2–5 present the information flow types ranging from centralized flow (players were not allowed to share information) to free flow (all players could communicate with each other) and the management tools used on each one [ANDON and weekly work meeting (WWP)].

Six parameters were computed to compare the outcomes of each experiment run:

1. Total elapsed time (ET): the time required for the team to complete all the work.
2. Working time (WT): the sum of the time for all subcontractors during which they were present in the work areas and performing tasks.
3. Assembly time (AT): the sum of the time all subcontractors spent assembling Lego bricks.
4. Non-value-added time (NVAT): for each subcontractor i, $\mathrm{NVAT}_i = \mathrm{WT}_i – \mathrm{AT}_i$. This is the time spent waiting between tasks due to ineffective management, lack of materials, and available space.
5. Average cycle time (CT): an average of the total times from the start of work in each floor to the completion of all the work required for the floor.
6. Standard deviation of the cycle time (SD).

Given that the composition of the two teams of players remained consistent throughout the series of experimental runs they performed, we expected that a learning effect accounts for some of the improvement observed in their performance. Similar to real construction environments, the learning curve plays a vital role in increasing labor productivity on the premise that workers become more efficient at doing a task when they accomplish the same task continually (Jarkas and Horner 2011; Lee et al. 2015). In the iKan game, there are two possible aspects of learning: players learn to assemble the Lego bricks with greater skill, and they also learn the overall production process, and the data must be corrected for these effects before drawing conclusions concerning the effects of the structural changes to information flows. The standard learning curve formula [Eq. (1)] proposed by Srour et al. (2016) was used to calculate the expected improvement factor for each run from Run 2 to Run 7 to provide a corrected baseline expected time for the WT, AT, and NVAT of each

$$y = A \cdot x^{-n} \tag{1}$$

where y = time expected for any given experimental run with index x; A = time measured in the first experimental run ($x = 1$); and n = learning curve fitting parameter.

To provide a benchmark for calculating n, experimental Run 7 applied the same basic process used in the first round. As for the

Table 4. Experiments based on information flow combinations and tools

Experimental run	Information flow			
	Centralized process information flow (NONE)	Free data transfer (NONE+)	Weekly work planning (WWP)	Use of ANDON application (ANDON)
1	Y	—	—	—
2	—	Y	—	—
3	Y	—	Y	—
4	—	Y	Y	—
5	Y	—	—	Y
6	—	Y	—	Y

Note: Y = yes.

other runs, this was performed by both teams. This yielded a value of $n = 0.517$.

Results

Tables 5 and 6 provide the results of 14 live experiment runs. Tables list the times per type of experiment, including the ET, WT, AT, and NVAT for each type, and the CT and SD of the cycle times for each floor in each type. Furthermore, two additional rows are provided for each of WT, AT, and NVAT; these are the expected values after accounting for the learning curve effect and the net percentage improvement over the learning curve.

Experimental Run 1 had the largest total WT for both groups, and the minimum was obtained in Run 6, with a gross reduction in total subcontractor working time ranging from 10 h and 55 min to 13 h and 55 min to just 1 h and 45 min and 2 h and 40 min for Groups A and B, respectively (Tables 5 and 6 and Fig. 6). After accounting for the learning curve factor, the expected total WT for Run 6 for Groups A and B were 4 h and 49 min and 5 h and 20 min, respectively, which yielded an overall improvement of 64% and 50%. This can be attributed to the fact that players could transfer information among themselves without any restrictions and limitations. They had access to the ANDON boards using their smartphones, thus streamlining the information flows and consequently improving the workflow. The impact of open communication can be considered by comparing all experiments where information was transferred without barriers and impediments (Experiments 2, 4, and 6) with those where communication was constrained (Experiments 1, 3, and 5). In all of these, workflows improved measurably.

After initial improvement from Runs 1 to 2, AT remained as expected by the learning curve through most of the remaining experiment runs for both groups. This was expected because there was no change to the standardized assembly instructions across any of the run types. It appears that the management techniques implemented, such as ANDON and LPS board, did not have a significant effect on this variable.

NVAT was significantly affected by the application of different management tools, with measurable improvements for each intervention when compared with the standard case, with the singular outlier of Run 5 (Fig. 7). Open communication led to improvement across all groups. More specifically, Groups A and B reduced 41% and 40% the NVAT, respectively. The marginal improvements due to weekly work planning were from 36% to 38% for Groups A and B (comparing Run 4 with Run 2 and Run 3 with Run1, respectively. The impact of WWP was greater when communication was constrained and lower when it was open. Similarly, the marginal improvements due to the ANDON boards and app ranged from 49% to 51% for Groups A and B (comparing Run5 with Run 1 and Run 6 with Run 2). Here, the anomalous value for Run 5 makes it difficult to draw any conclusion.

Qualitative Analysis of Information Flow Models

The differences between the six alternative experimental run formats were evaluated qualitatively. The field study yielded eight

Table 5. Live experiment results before and after learning curve corrections

Variables	Experiment 1 (NONE)	Experiment 2 (NONE+)	Experiment 3 (WWP)	Experiment 4 (WWP+)	Experiment 5 (ANDON)	Experiment 6 (ANDON+)	Experiment 7 (RE-NONE)
Elapsed time (ET)	2:11:00	1:04:00	1:31:00	1:18:00	1:11:00	0:21:00	0:54:00
Total working time (WT)	10:55:00	5:20:00	5:15:00	4:50:00	5:55:00	1:45:00	4:30:00
Expected WT considering learning	10:55:00	7:57:00	6:37:00	5:48:00	5:14:00	4:49:00	4:30:00
Net WT improvement (%)	0	33	21	17	−13	64	0
Assembly time (AT)	3:47:00	1:49:00	2:03:00	1:36:00	1:45:00	0:52:00	1:47:00
Expected AT considering learning	3:47:00	2:53:00	2:28:00	2:12:00	2:01:00	1:53:00	1:46:00
Net AT improvement (%)	0	37	17	28	14	54	0
Non-value-adding time (NVAT)	7:08:00	5:12:00	3:12:00	3:34:00	4:10:00	0:53:00	2:43:00
Expected NVAT considering learning	7:08:00	5:03:00	4:08:00	3:35:00	3:12:00	2:55:00	2:43:00
Net NVAT improvement (%)	0	−3	23	1	−30	70	0
Average cycle time per floor (CT)	1:45:00	0:46	0:43	0:54	0:46	0:21	0:32
Cycle-time standard deviation (SD)	0:15:00	0:10	0:09	0:12	0:13	0:04	0:07

Note: Group A time given in hours:minutes:seconds.

Table 6. Live experiment results before and after learning curve corrections

Variables	Experiment 1 (NONE)	Experiment 2 (NONE+)	Experiment 3 (WWP)	Experiment 4 (WWP+)	Experiment 5 (ANDON)	Experiment 6 (ANDON+)	Experiment 7 (RE-NONE)
Elapsed time (ET)	2:47:00	1:29:00	1:29:00	0:59:00	1:04:00	0:32:00	0:59:00
Total working time (WT)	13:55:00	7:25:00	5:53:00	2:50:00	5:20:00	2:40:00	4:55:00
Expected WT considering learning	13:55:00	9:36:00	7:43:00	6:37:00	5:53:00	5:20:00	4:55:00
Net WT improvement (%)	0	23	24	57	9	50	0
Assembly time (AT)	4:28:00	2:13:00	1:33:00	1:39:00	1:32:00	1:54:00	1:34:00
Expected AT considering learning	4:28:00	3:04:00	2:28:00	2:07:00	1:52:00	1:42:00	1:34:00
Net AT improvement (%)	0	28	37	22	18	−12	0
Non-value-adding time (NVAT)	9:27:00	3:31:00	4:20:00	1:45:00	3:48:00	0:55:00	3:21:00
Expected NVAT considering learning	9:27:00	6:31:00	5:15:00	4:30:00	4:00:00	3:38:00	3:21:00
Net NVAT improvement (%)	0	46	18	61	5	75	0
Average cycle time per floor (CT)	2:07	1:07	0:50	0:50	0:41	0:22	0:45
Cycle-time standard deviation (SD)	0:18	0:09	0:02	0:16	0:12	0:04	0:10

Note: Group B time in hours:minutes:seconds.

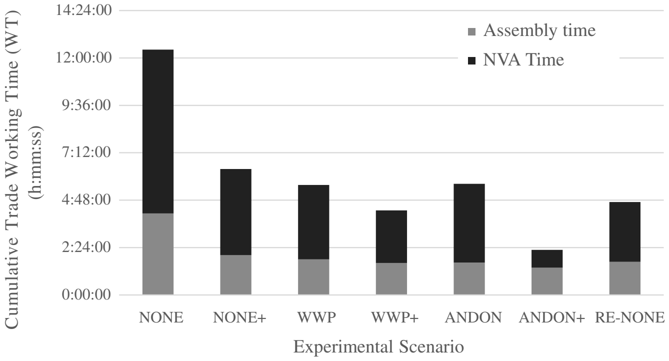

Fig. 6. Average AT and NVAT.

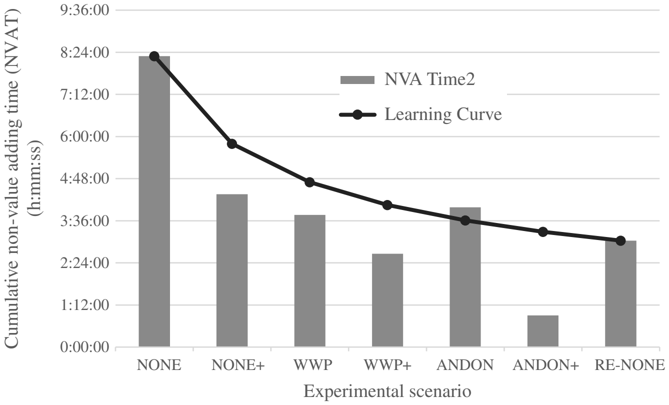

Fig. 7. NVAT and learning curve.

parameters that reflect the status of the production process in construction and that were consequently explicitly incorporated as monitored information items in the iKan game. They are (1) actual task start time, (2) actual task completion time, (3) design change information, (4) subcontractor production rate, (5) subcontractor location, (6) production error, (7) material arrival, and (8) material order.

The value of knowing any information item for an actor in the process depends on that person's role in the production system and on four aspects that characterize the information's flow. The relative value of each of these eight information items was classified distinctly for each of the five professional roles (project manager, client representative, quality inspector, materials supplier, and trade subcontractor) with a score of 2 (critical), 1 (valuable), or 0 (irrelevant). An information item was deemed critical to a role if the lack of such information inhibited or prohibited the player from fulfilling their work responsibilities. An information item valuable to a role was one that, although not critical to its operation, could improve the players' situational awareness and operational performance. An irrelevant information flow did not meaningfully impact the decisions or operations of a role.

The four aspects that characterize an information item and its flow are (1) frequency, (2) latency, (3) efficiency, and (4) uncertainty. Frequency refers to the time between discrete information exchange events. Latency refers to the duration from the appearance of an exchangeable information item's value to the delivery of the item to the intended receiver. Efficiency refers to the proportion of critical and valuable information items to the total number of information items in an information exchange. Uncertainty refers to the accuracy and precision of the information received when compared with the actual status of the subject of the information. In general, high frequency, low latency, high efficiency, and low uncertainty are desirable attributes for any information flow.

Each experiment setup was assigned a score from 1 to 5 for each characteristic based on their performance relative to other setups. Performances were evaluated based on a combination of experiment observations, postexperiment questionnaires, and theoretical interpretations as suggested by the information flow models in experiment design.

Contributions of information flow to each role in the iKan game were evaluated as reported in Table 7 according to the aforementioned criteria. The project manager (PM) is highly dependent on information flow. Namely, the input of task start time and completion status provided by subcontractors and occurrences of production errors discovered by the quality inspector are essential for the PM to coordinate work with the subcontractors. Although not essential for the PM's responsibility, all other information flows can no doubt enhance PM's situational awareness and enable more accurate ongoing planning.

Meanwhile, subcontractors (SCs) are responsible for providing information to the PM concerning their task status and any material shortages that may occur. Because the SCs are responsible for material ordering and instructing material delivery, they must be fully aware of the material demand per location and the arrival of materials. Another essential information SCs must receive is the detail of production errors relevant to them. For optimal forward-looking work planning, SCs would benefit from an awareness of the readiness for work in other locations. The arrivals of design changes and material delivery remove the information and material constraints, respectively, and productivity rates and locations of other SCs indicate when the labor and space constraints will be removed.

The material supplier's (MS) responsibility is to prepare material deliveries according to the orders from the SCs and transport them to locations as instructed by the SCs. Therefore, the inflow

Table 7. Value of information items for situational awareness according to professional role

Parameters	Project manager	Customer representative	Quality inspector	Materials supplier	Subcontractor
Task start	2	0	0	1	2
Task completion	2	0	2	1	2
Design change	1	2	2	1	2
Contractor productivity	1	0	0	1	1
Location of contractors	1	0	1	1	1
Production errors	2	0	2	1	2
Material arrival	1	0	0	2	2
Material order	1	0	0	2	2
Total	11	2	7	10	13

Table 8. Quality of flow characteristics per experiment scenario

Experiment	High frequency	Low latency	High efficiency	Low uncertainty	Total
NONE	1	1	1	1	4
NONE+	3	3	2	2	10
WWP	2	2	3	3	10
WWP+	4	3	4	4	15
ANDON	3	4	3	3	13
ANDON+	5	5	5	5	20

and outflow of the material order and arrival information are essential to the MS's role. In the ideal case, MS can proactively prepare for deliveries by predicting the needed material based on information on design changes, production errors, and activities status.

The quality inspector's (QC) task is to check the quality of finished products upon completion and inform the subcontractors of any identified production errors, either through the PM or directly, depending on the experiment setup. QC thus requires inflows of task completion and design change information and outflow of production error information. For more effective communication, the QC would benefit from information on the location of subcontractors.

Lastly, by game design, the customer representative's (CR) only responsibility is to deliver design changes at set intervals. Therefore, only the outflow of design change information is essential to the CR's function.

The quality of information flow per experiment scenario is evaluated in Table 8 on a relative scale from 1 to 5, with 5 being the high score. In the NONE scenario, the PM was situated in a separate room and acted as the conduit for all information flow. All other players were only allowed to exchange information with the PM, and no interactions were allowed with the others. This constraint encouraged players to prioritize their own work and avoid information exchange unless essential. This setup had the lowest frequency, highest latency, lowest efficiency, and highest uncertainty among all the scenarios considered.

The next scenario (NONE+) allowed all players to talk and transfer information between them. Moreover, the PM could walk around the work areas and observe the task progress. This setup greatly increased the frequency of information exchange between players and lowered the latency of information flow. Allowing information exchange between all players largely relieved the PM's responsibility as a relay point for information flow, resulting in a slight improvement in exchange efficiency and information uncertainty.

The weekly work meeting (WWP) setup applied the same restrictions on the players as in NONE, where the information flow was centralized on the PM. The difference in the WWP setup was that the whole production team could meet once every 10 min to coordinate their work. Apart from these weekly work meetings, the WWP setup had the same information flow model. Therefore, there was only a slight improvement in communication frequency and latency. What these meetings did offer was a systematic approach to communicate information efficiently and accurately. The project status was exposed to the whole team, increasing all players' awareness of what others need from them and what they need from others. Conscious of these meetings, players also became more selective concerning the information that can be communicated during the meetings and what should be communicated in between meetings through the PM, thus alleviating some pressure from the PM.

With a free exchange of information combined with weekly work meetings, the WWP+ setup replicated the same improvements from NONE to WWP in flow characteristics of frequency, efficiency, and uncertainty. However, WWP+ did not meaningfully decrease the latency of information exchanges. Although weekly work meetings are useful for creating a common situational awareness of the project, they did not contribute to earlier delivery of time-critical communications that take place between these meetings.

Although still prohibited from communicating with others, players in the ANDON setup had in their hands the digital ANDON management board for reporting and viewing activities, quality control, and material statuses for each location while retaining the option to communicate with the PM. Players could deliver this critical information in real-time efficiently and accurately using the ANDON board. However, the ANDON board was only designed to provide status information of a location (started, completed, or has problems). It could explain why issues have occurred or what material is needed for a task. This information still needed to be delivered face-to-face to the PM and relayed to another player.

The ANDON+ setup was designed to exhibit the highest quality of information flow relative to other setups. Acting as a real-time Kanban signaling platform, the ANDON board encouraged players to take a lean production approach that assigns work based on pulling and proactively identifies constraints and bottlenecks. With the freedom of information exchange, players could efficiently communicate the identified issues to the relevant parties at the earliest time possible. The combination of ANDON board and free flow encouraged a more systematic and standardized approach to communication, thus alleviating the cognitive load for all players.

Discussion

Experiment Results

The experimental results were similar for both groups and exhibited little variation in the improvement ratios from scenario to scenario. The discrepancies that were encountered in the recorded performance times likely stemmed from the varying characteristics of the people in each group in terms of their cooperation skills, technical abilities, and group dynamics. Nevertheless, the progress patterns for both groups were similar and comparable. The AT results for both groups reduced over time where free information flow was allowed. In addition, when considering the learning curve, NVAT was significantly lower than the expected duration. The most significant improvement was seen in experiment Run 6, in which free information flow was allowed and the ANDON board was used.

In experiments in which free information flow was permitted, players improved their planning strategies, reduced unnecessary movement, and minimized uncertainty during the decision-making process. Indeed, in the WWP+ and ANDON+ experiments, the AT was reduced between 17% and 23% for Groups A and B compared with restricted information flow experiments. A similar effect had the free information flow in the NVAT. In this case, the NVAT was diminished by 22% and 23% for Groups A and B. Comparable to the construction field study, the experiment showed that information flow reliability and management practices improved players' SA. Indeed, in experiment runs in which the information flow was restricted or less reliable, the NVAT was higher.

Players have a global learning curve of the process flow, rules, and mechanisms of the iKan game: the functions of each role and its interaction with others. The local learning curve reflects their increasing skill in assembling the floor and wall works using Lego bricks. These were considered explicitly in the analysis presented in the section "Experiment Simulation Run." However, there is a third component of learning, which occurs when players are exposed to a new information exchange mechanism, such as the weekly work meetings or the ANDON management board. This aspect means that the progressive improvements from Run 3 to 4 and from Run 5 to 6 were in fact smaller than the data reflect. In particular, this component may explain to some degree why Run 5 was surprisingly worse than expected: the digital ANDON board requires significant cognitive effort to learn to use it. Players were not accustomed to delivering and receiving information through a digital interface of this kind, yet clearly used it more effectively on its second application (i.e., the large improvement from Run 5 to Run 6).

Qualitative Analysis

Qualitative analysis of the different information flow configurations revealed the differences in the expected quality of information flow (in terms of frequency, latency, efficiency, and uncertainty) across experiment configurations. The ANDON+ scenario, supported by a real-time digital information board and unrestricted communication between players, was predicted to provide the highest flow quality, whereas the control setup NONE with centralized information flow was predicted to exhibit the worst performance. Overall, the results of the 14 live experimental runs confirmed the trends predicted by the qualitative analysis. The only discrepancy occurred in the ANDON configuration, where the results showed little or no improvement.

According to the impact of the information flow, models such as WWP and ANDON allowed players to have a complete picture of the project status, raising all players' SA of what others need from them and what they need from others. Management meetings carried out during WWP runs led players to become more selective regarding the information to be shared to fulfill their assigned tasks. On the other hand, the ANDON model offered the highest quality of information flow compared with other models. Furthermore, the ANDON model proactively encouraged players to identify constraints and bottlenecks by providing a real-time signaling platform. With the free communication exchange, this model offered a more systematic and standardized communication approach, increasing the frequency and reliability of information exchanges.

Overall Discussion

The experiment analysis results are superimposed in Fig. 8 to illustrate possible correlation between information flow quality and project performance. For the qualitative results, the quality of flow for each experiment setup is presented as a percentage improvement over the baseline NONE setup (Table 8). For the experiments results, each setup's completion time is shown as a percentage improvement over the learning curve time (Tables 5 and 6). When comparing these two, with the sole exception of the ANDON experiments, we observed that the better the information flow, the shorter the completion duration.

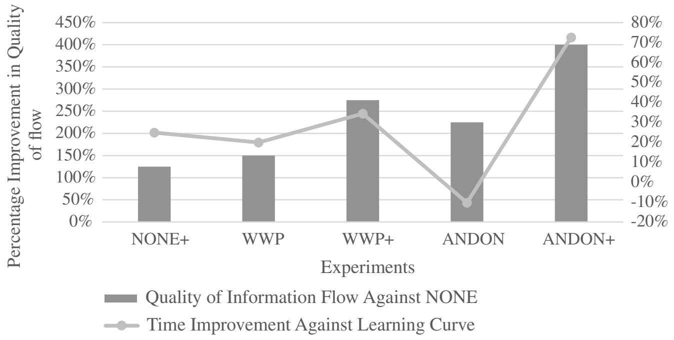

Fig. 8. Percentage improvement of the information flow quality and completion time.

Overall, this study showed that enhanced quality of information flow contributes to better situational awareness, resulting in better production flow and productivity. Planners and work crews in particular require good SA to perform effectively in the production system because their work is dependent on good coordination among trade crews. Digital tools such as the ANDON system appear to support the flow of information. However, the difference between the ANDON and ANDON+ results suggests that digital tools alone may not be enough to boost planners' SA; open communication is essential.

Conclusion

This study sought to explore the nature of the relationship between productions planners' situational awareness and the quality of the flow of work in an experimental simulation using a serious game, called iKan. Its field-study component documented some of the current problems in construction sites related to the SA of various actors onsite and highlighted the ways in which SA, or lack thereof, affects the workflow. Finally, the study compared qualitative analysis of information flow quality and the experimental results. The results provide construction practitioners and researchers with a better understanding of the barriers and the facilitators affecting information flows in construction and how to design and implement methods to minimize production planners' uncertainty.

The experiment results indicated a positive correlation between the information flow quality and construction workflow. In experiments where free communication was allowed and management tools such as ANDON were used, all the indicators—AT, WT, NVAT, and CT—showed improvement. Good information flow among production planners concerning up-to-date jobsite status may reduce the uncertainty during decision making and increase their SA. Good information flow may thus increase productivity because the non-value-adding time spent gathering information, which is waste, is diminished. We conclude that it would be valuable to test interventions that improve information flow and situational awareness, such as ANDON boards, the LPS system, and others, in construction production systems.

Naturally, given the complexity of construction sites and the multiple stakeholders participating in the decision-making process, other internal and external factors also affect the flow of work in construction. To test such interventions, full-scale field studies will be necessary. Randomly varying the sequence of interventions would be beneficial in enhancing the validity of such future experiments.

The research has limitations that need to be stated explicitly. First, the iKan game did not model monetary incentives, which could influence players' behaviors and motivations. Further research is warranted to incorporate the effect of cash flow and productivity concerns on the subcontractor trades. Second, the iKan game introduced variance only through design changes but not in the workforce supply and availability. Under the game's conditions, trade subcontractors were consistently available so that work commenced immediately after any period of waiting. This is generally not the case in construction projects. Indeed, situational awareness has been shown to play a significant role in subcontractors' labor allocation decisions, with subcontractors preferring to withhold labor when uncertainty erodes their confidence in future productivity (Sacks and Harel 2006). Extensions of the study might incorporate additional sources of variance.

Third, the live experiments were conducted with undergraduate construction management students. An experimental group made up of practitioners could introduce behaviors common in the industry, which may differ in some ways from those observed. Fourth, the quality of information flows was assessed using qualitative analysis. The study did not devise nor adopt a way to measure flow quality quantitatively. Additional studies are warranted to incorporate a robust approach to measuring flow quality. Fifth, the 14 rounds of experiments could be extended to include additional experiments incorporating new players with different abilities and roles.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request (photos, interviews, and raw data from experiments).

Supplemental Materials

Figs. S1–S4 and Table S1 are available online in the ASCE Library (www.ascelibrary.org).

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