# Experiencing Supply Chain Optimizations: A Serious Gaming Approach

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**Abstract:** To provide new opportunities for acquiring experience in coordinating construction supply chain activities, this paper describes a serious gaming approach. Serious games offer their users an experience that is designed to be meaningful. Following the triadic game design approach, the authors designed a board game that challenges a player to design and construct a skyscraper called Tower of Infinity. The research aim was to explore how serious games (like this one) can contribute to the experiential acquisition of construction supply chain management knowledge. Game sessions were organized in which 64 construction management students played the board game and reflected on it in a written report. A content analysis of these reports was then conducted to assess three hypotheses. Based on that analysis, it is concluded that serious games can enable students to experientially learn how to improve the performance of a construction supply chain through (1) co-ordinating design and construction tasks in a coherent manner; (2) taking constructability aspects into account when designing; and (3) continuously balancing scope, time, and cost throughout a project. Experiencing supply chain optimizations in such a playful way promotes better understanding of how and why waste occurs and may, ultimately, contribute to more efficient construction supply chain management practices. **DOI: 10.1061/(ASCE)CO.1943-7862.0001388.** 

**Author keywords:** Project planning and design; Experiential learning; Serious game; Supply chain management; Waste.



## Introduction

To provide new opportunities for acquiring experience in coordinating construction supply chain activities, this paper describes a serious gaming approach. Supply chain management (SCM) in construction has been defined as "the network of facilities and activities that provide customer and economic value to the functions of design development, contract management, service and material procurement, materials manufacture and delivery, and facilities management" (Love et al. 2004, p. 44). Numerous researchers have claimed that the construction industry is lagging behind in terms of supply chain practices and efficiency (Bankvall et al. 2010; Segerstedt and Olofsson 2010). Even in normal situations, construction supply chains have a large quantity of waste (Vrijhoef and Koskela 2000). That waste may manifest itself in waiting time for crews, rework, unnecessary movement and handling of materials, unused inventories of workspaces and of materials, and so forth (Sacks et al. 2010). Explanations are sought in the lack of coordination and communication between parties, adversarial contractual relationships, lack of customer-supplier focus, price-based selection, and ineffective use of technology (Love et al. 2004). Most scholars have, however, ignored one factor: it is hard for construction professionals to gain hands-on experience in coordinating supply chain activities.

Practically applicable knowledge about how to improve the performance of a construction supply chain is difficult to acquire. Bak and Boulocher-Passet (2013) argue that delivering supply chain education that is important and relevant for the industry is a major challenge. Besides introducing theoretical models and concepts, university educators typically rely on practical assignments and/or stories of best practices to enable students to gain such knowledge. Both of these approaches are problematic. Educational assignments usually ignore many of the peculiarities found in real-world construction projects, such as uncertainty, urgency, ambiguity, and uniqueness (Winch 2010). Similarly, stories of best practices cannot provide the thick context that is necessary to understand how practitioners in the past successfully applied a certain tool or method. Peterson et al. (2011) argue that these two common approaches often fall short because they neglect the complexity of the multiple intertwined factors found in practice. Rojas and Mukherjee (2005) also maintain that traditional teaching methods are not fully capable of conveying how theoretical concepts can be applied to construction practice. Likewise, studies in the area of safety and hazard recognition have illustrated that poorly designed, ineffective, and unengaging methods significantly impede teaching/training efforts (Albert et al. 2014; Namian et al. 2016). The consequence of these problems is that graduate students are poorly prepared for dealing with real-world supply chain management problems and need to learn on the job.

One promising way for dealing with this problem is to deploy serious games that enable learning about construction supply chain management. A game is defined as "a problem-solving activity, approached with a playful attitude" (Schell 2008, p. 47). The adjective "serious" is generally used to refer to a subset of "(digital) games that contribute to the achievement of a defined purpose other than mere entertainment" (Susi et al. 2007). These types of games

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playfully visualize and simulate real-world events or processes in an environment that resembles realistic work situations. They can bring important theoretical topics to life, providing ways to understand and practice essential educational issues (Battini et al. 2009). Serious games therefore integrate elements like rules, goals, challenges, and performance indicators in interactive environments. Players learn from making meaning of the experience that the game provides them, which is referred to as experiential learning (Kolb 1984). The aim of the presented research was to explore how serious games can contribute to experiential learning about construction supply chain management.

This paper is structured as follows. The next section provides the argument that it is unclear how players may learn from experiences that serious games for construction supply chain management offer them. The authors then illustrate how they designed such a game themselves, with the primary focus on exploring how it contributes to experiential learning. To that end, it is described how data were collected and analyzed in the context of a master's-level (M.Sc.) course. The results reveal how the game enabled graduate students to optimize construction supply chains. This is followed by a discussion of how these results should be interpreted and then a conclusion arguing that experiencing supply chain optimizations in a playful way promotes better understanding of how and why waste occurs.

## Theoretical Framework

The theoretical foundation for serious games can be found in experiential learning theory. This theory emphasizes the central role that experience plays in the learning process (Hussein 2015). Experiential learning theory defines learning as "the process whereby knowledge is created through the transformation of experience" (Kolb 1984, p. 38). Knowledge results from the combination of grasping and transforming experience. This process is commonly represented as a four-stage cycle that continues endlessly. It starts with a concrete experience, after which learners have observations that they need to reflect on (reflective observation). In this way, abstract concepts are grasped and generalizations are made (abstract concepts). These can be used as input for experimentation to test whether the newly formed ideas hold true (abstractive experimentation). That leads to a new concrete experience, with which a new cycle starts (Harteveld 2011). The term *experiential* is therefore used to differentiate experiential learning theory from cognitive learning theories, which emphasize cognition over affect, and behavioral learning theories, which deny any role for subjective experience in the learning process (Kolb et al. 2001).

Serious games allow people to experience situations that are impractical or impossible in the real world for reasons of cost, time, or safety. These types of games offer experimental environments in which learning can occur and be observed (Hussein 2015). Serious games are experiential by nature: they are about doing and, as such, offer an experience to the user. That experience is designed to be meaningful (Susi et al. 2007). Several studies have reported that serious games have positive effects on knowledge acquisition, motivation, and engagement (Bellotti et al. 2013; Connolly et al. 2012). Other benefits are that they may increase the verisimilitude of the teaching material and allow students to work at their own pace (Al-Jibouri and Mawdesley 2001). Serious games may augment traditional teaching methods (Hegazy et al. 2013) or be the only means of practicing with real-world problems such as for military operations or surgical techniques. They do this by mimicking and simplifying the real world in a risk-free environment that encourages exploration and trial-and-error actions and with the possibility of instant feedback (Mawdesley et al. 2011). In that regard, a serious game differs from a simulation model, defined as just a "representation of reality [of] some known process/phenomenon" (Deshpande and Huang 2009, p. 400), in that the latter is typically more accurate but lacks playful, motivational, and/or goal-oriented activities. Such closely related simulation models have been developed for (among others) interorganizational decision making (Xue et al. 2005), real-time information sharing (Min and Bjornsson 2008), inventory-production-transportation systems (Long and Zhang 2014), workforce management (Watkins et al. 2009), and the evolution of collaboration (Son and Rojas 2011).

Serious games have a long-standing history in supply chain management education. To introduce management participants to economic dynamics, Sterman (1989) used a participative simulation model of a beer distribution system, which later became known as the MIT Beer Game. This game is particularly powerful in demonstrating the so-called bullwhip effect that causes high variability in order and inventory levels when several participants in the same supply chain attempt to anticipate the future demand of their immediate client. However, the game is criticized for its limited functionalities and for being based on an unrealistic supply chain model (Deshpande and Huang 2009; Holweg and Bicheno 2002). In the aftermath of this game many other supply chain management games have been developed. Examples include the Lean Leap Logistics Game, which deals with production and ordering in a steel-manufacturing environment (Holweg and Bicheno 2002); the Supply Chain Management Trading Agent Competition, which revolves around a PC assembly supply chain consisting of a number of competing manufacturers, component suppliers, and customers (Arunachalam and Sadeh 2005); the Distributor Game, which simulates the complexities of a global supply chain with physically separated distributors (Corsi et al. 2006); the Poker Chip Game, which illustrates the impacts of push versus pull inventory policies (Cox and Walker 2006); and the Supply Chain Puzzle Game, which addresses various design and behavioral issues in supply chain collaboration (Fawcett and McCarter 2008). Despite their educational value, none of these serious games deals with the peculiarities of the construction industry, like site production, one-of-a-kind products, temporary organizations, and the relationship between design and production.

Numerous serious games deal with such construction peculiarities. The Parade Game, for example, illustrates the impact that variability has on workflow in a single-line production system (Tommelein et al. 1999). The Technion Lean Apartment Construction Simulation Game (LEAPCON) simulates the execution of interior finishing activities required for construction of a high-rise building (Sacks et al. 2007). The Virtual Coach represents a multiyear project of a situational simulation environment for construction management education (Dossick et al. 2010; Rojas and Mukherjee 2005). It challenges players to respond to events like material shortages, low productivity, or incomplete designs by making decisions that affect the project outcome. Other games for construction management are Muck and Canal, which focus on project planning and control (Al-Jibouri and Mawdesley 2001; Mawdesley et al. 2011); Construction Contracts in a Competitive Market ($C^3M$), which introduces the principles of competitive bidding (Nassar 2003); the C-Negotiation Game for construction procurement and negotiation (Dzeng and Wang 2017), and The Expansive Hospital, which lets players learn the value of boundary crossing in design projects (Van Amstel et al. 2016). Furthermore, Tsai and Chi (2015) reported on three games for conflict management. Although these serious games cover aspects that are unique to the construction industry, they do not deal with coordinating supply chains in a holistic fashion.

There are two additional problems with the experiences that most of these serious games provide. An important assumption of serious games is that players can transfer the game experience to the real world. This raises the first question of whether these experiences are designed in a manner that is systematic (i.e., using established principles, procedures, and theories of designing games) and well-balanced (i.e., aiming to be valid, meaningful, and entertaining at the same time). Most of the aforementioned studies describe in detail a game design *as an object*, but they share little about game design *as a process*. This makes it unclear how and why certain game design choices were made. One exception is the study of Rüppel and Schatz (2011), which was based on the triadic game design (TGD) approach of Harteveld (2011) and carefully elaborated the design considerations for a serious game for fire safety evacuation simulations. A second question is whether players indeed acquire the experience that was planned when designing a serious game. To that end, multiple literature reviews concluded that many studies lack a rigorous assessment (Bellotti et al. 2013; Chin et al. 2009; Mikropoulos and Natsis 2011). Generally, data can be used to demonstrate that stated learning goals are actually being met either at the end of the learning process (summative assessment) or throughout the learning process (formative assessment). The most common postassessment method is a simple survey, which has the disadvantage of relying on the opinions of the players and not on all the information that can be collected regarding what happened in the game (Bellotti et al. 2013). In-game assessment that examines how and why a player applied certain strategies is scarcely used, even though digital games in particular have the advantage of keeping track of every move and decision a player makes. Bcause of these problems, the potential of those serious games to contribute to experiential learning remains unclear.

In summary, most previous studies on serious games did not deal with the peculiarities of the construction industry for supply chain management, did not methodically design a game, and/or lacked rigorous reflections. It thus remains unclear how players may learn from experiences provided by a serious game for construction supply chain management.

## Design of a Serious Game

The authors studied the use of a low-tech serious game called Tower of Infinity that was methodically designed by the first author. Tower of Infinity is a one-player board game that uses LEGO bricks to simulate an integrated (design and construct) project (Fig. 1).

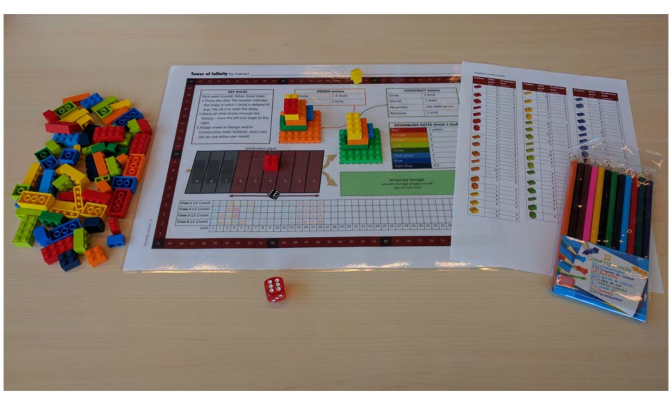

**Fig. 1.** Overview of the serious game Tower of Infinity with LEGO bricks, play board, die, product guide, and pencils

It puts players in the role of main contractor and, as such, lets them assign their available crews to modeling, ordering, and assembling tasks in order to satisfy client requirements and make a profit. This game came about by following Harteveld's (2011) triadic game design approach, which provides an overall way of thinking for designing a serious game. The core idea is that a good serious game balances the three interdependent so-called worlds of Reality, Meaning, and Play. These three worlds shed light on a game in different ways. Each of the worlds is inhabited by different people, disciplines, aspects, and criteria (which is why they are called worlds). They are all equally important and thus need to be balanced to create a single whole: a game capable of achieving its serious purpose. To reach an optimum balance, the three worlds should be considered at the same time in critical parts of the game design process (concurrent design) and in a repeated cycle of (1) prototyping, (2) testing and evaluating, and (3) continual redesign until the requirements of the three worlds are met (iterative design). Notwithstanding this iterative nature, the authors elaborate on these three main steps of the design process here.

### *Step 1: Prototyping: Integrating Worlds of Reality, Meaning, and Play*

The authors started the serious game's design process by considering the inhabitants of the three worlds of Reality, Meaning, and Play and by attempting to integrate them in a fully working prototype. Fig. 2 adopts the triadic game design theory of Harteveld (2011) to represent the inhabitants graphically.

#### World of Reality

The world of Reality considers the game's connection to the physical world. It includes domain-specific knowledge to make a game experience intuitive and understandable. The type of game and its purpose determine how elaborate, realistic, and valid the game's representations of (parts of) reality are. It should thus be noted that reality is interpreted, constructed, and translated into a game model. This game model describes the content, boundaries, and interrelationships of a game (Harteveld 2011). Others may well achieve a different model bcause of differences in scope, information sources, design choices, and the like.

Construction projects constitute steps to design, manufacture, and assemble a product for a customer. The principal construction company that manages a project typically relies heavily on subcontractors and suppliers of building materials to execute that project. The greater part, approximately 75%, of the product's value is built with materials and services purchased from subcontractors and suppliers (Dubois and Gadde 2000). This is incorporated in the serious game with a setting in which the player (as main contractor) needs to purchase building materials from suppliers by performing the following steps: choosing a product from a supplier's product guide (containing options with different costs and lead times for the same product), taking the raw material from a market/pool of raw materials (that is shared with other players), and placing it in the relevant production stage of a supplier's plant (conforming to the lead time as promised in the product guide).

Supply chain management in these project delivery settings generally consists of short-lived supply chains that must be established rapidly and remain flexible to match demands that vary over the course of project execution (Tommelein et al. 2008). Supply chains feature dynamics, uncertainty, and partial information sharing (Long and Zhang 2014). Construction projects differ from manufacturing supply chains in that the construction supply chain is typically converging (materials are clustered and transported to a single construction site rather than going through a factory), temporary (one-off projects are produced through duplicated

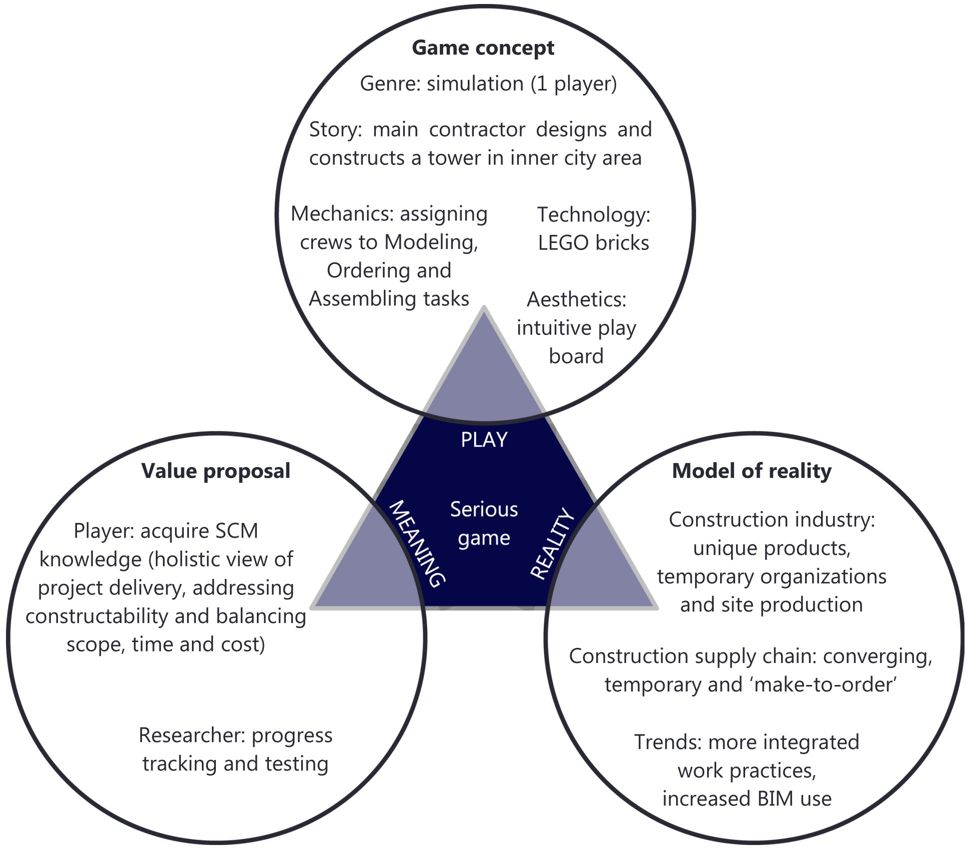


**Fig. 2.** Design of a serious game for construction supply chain management, based on the triadic game design approach of Harteveld (2011) (BIM = building information modeling)

reconfigurations of project organizations), and representative of a make-to-order process (production starts only after an order is received) (Vrijhoef and Koskela 2000). The game represents this with an empty construction site of limited size to which purchased materials are transported after their manufacturing is completed. Materials are only manufactured after the player places an order (see previous paragraph).

In recent years, several major trends in the construction industry have been reported that are also represented in the serious game. The industry has been moving toward more integrated work practices, with clients shifting responsibilities to main contractors (Bemelmans et al. 2012). Integrated contracts such as design and construct contracts, in which the main contractor is also responsible for the design (along with the construction), are becoming increasingly common. Multiskilled crews, which can perform a variety of construction-related tasks, are being recognized as a key factor in achieving stable, predictable production (Sacks and Goldin 2007). Construction companies are making more and more use of building information modeling (BIM) tools, which enable the creation of a virtual prototype of a complete building before it is actually built (Eastman et al. 2011; Hartmann et al. 2012). Finally, environmental awareness is increasing, with the construction industry starting to realize that virgin resources are limited (Kourmpanis et al. 2008). The serious game addresses these aspects by putting the player in control of both design and construction project stages and by offering four crews, all of which can perform several kinds of actions. The availability of (raw) materials used for manufacturing is limited. A three-dimensional (3D) prototype needs to be modeled before any materials can be ordered, manufactured, and eventually assembled.

## World of Meaning

The world of Meaning involves the types of value to be achieved by a game. This considers the meaningful effect beyond the game experience itself. This value proposal is an extensive description of how a game will affect the real world (Harteveld 2011). The values to be achieved can be subdivided into values for the player and values for the researchers/observers.

The player should be able to acquire an intuitive understanding about optimizing project activities regardless of functional or corporate boundaries. Supply chain management theories adopt a holistic and systematic view of project delivery. Traditionally, construction supply chains have much waste and many problems, which are mostly caused in a phase other than the one in which they are detected (Vrijhoef and Koskela 2000). Examples are errors in design that are discovered when the actual building is being assembled at the site. In supply chain management, project processes and activities are controlled in an integrated fashion (Tommelein et al. 2008). This is embodied in the philosophy of lean construction, which refers to a production system that aims to minimize waste of materials, time, and effort in order to generate the maximum possible value (Koskela 1992; Koskela et al. 2002). Being aware of the importance of production flow, or the sequence of supply chain activities, has a great impact on the effect of variations and is suggested as one approach to reduce waste (Lindhard 2014). Furthermore, waste can be reduced by explicitly addressing constructability: the capability of a design to be constructed. Projects where construction constraints and possibilities have been specifically addressed can achieve significant cost savings (Koskela 1992). To achieve systemwide advantages of production, it is, finally, necessary to understand how scope, time, and cost relate to each other (Peterson et al. 2011; Tommelein et al. 2008; Xue et al. 2005). Overall, the authors determined (as learning objectives) that players need to be able to understand how supply chain optimizations can be achieved through (1) co-ordinating design and construction tasks coherently; (2) taking constructability aspects into account when designing; and (3) continuously balancing scope, time, and cost.

Other values are more valuable for the researchers/observers. Serious games can provide possibilities for assessment, data collection, exploration, and theory testing (Harteveld 2011). Assessment focuses on learning from the perspective of the player and aims to demonstrate that stated goals and objectives are actually being met (Chin et al. 2009). Games must therefore "provide some means of testing and progress tracking and the testing must be recognizable within the context of education or training they are attempting to impart" (Bellotti et al. 2013, p. 8). When games allow for any changes in some aspects or when researchers can adjust variables, it is possible to conduct explorations or to test theories. Here, the game includes a set of pencils with different colors that players use to write down all their actions in a project schedule (so that their progress can be tracked).

### World of Play

The world of Play deals with the goals and rules of a game. Games are highly interactive and engaging tools that immerse people in a fictive situation. Clear goals and rules differentiate games from simulations and other types of playful activities. To develop a game, designers need to come up with a game concept—that is, a detailed idea of what the game will be like (Harteveld 2011). Seven game genres are conceived: action, adventure, puzzle, role playing, simulation, strategy, and virtual world.

The supply chain management game here belongs to the simulation genre because the authors were interested in modeling actual processes and situations. According to Harteveld (2011), such games are characterized by a closer connection to reality, the lack of an extensive story that evolves as the player progresses, and many degrees of freedom and openness. As a guiding principle for designing the game, the authors gave emphasis to the "peculiar relation between design and production" (Segerstedt and Olofsson 2010, p. 348) found in the construction industry. This general game idea was elaborated by defining the four basic elements that are, according to Schell (2008), part of every game: mechanics, story, aesthetics, and technology. The game simulates a design and construct project in which a player takes the role of main contractor and performs a limited number of actions per week/round (mechanics). Actions include modeling, ordering, and assembling and are performed by crews that are multiskilled and thus capable of carrying them out. Creativity is needed to come up with a design proposal that meets the requirements and can actually be built. The game takes place after the player is awarded a contract of designing and constructing a high-rise building in an inner-city area (story). The player starts with a list of client requirements and is then challenged to complete the project for a fixed price and within a certain time. These requirements provide much freedom to experiment with different problem-solving strategies. The layout of the serious game aims to support the player's game play by indicating important rules, variables, and parameters (aesthetics). A board game that makes use of low-tech materials was considered most appropriate for this type of play (technology). LEGO bricks were selected as the main materials in the game because their standardized interfaces allow for rapid prototyping, simulations, and visualizations (Kristiansen and Rasmussen 2014). The in-game actions/tasks and objectives were then related to these bricks by their sizes and colors.

## *Step 2: Testing and Evaluating: Play-Testing Prototypical Serious Game in Workshop*

The next step in the design of the serious game was to test and evaluate a prototype that attempted to integrate the worlds of Reality, Meaning, and Play. The prototype can be described as a board game in which the player takes on the role of main contractor responsible for designing and constructing the Tower of Infinity, a multifunctional skyscraper located in an inner-city area. Each player is given a set of LEGO bricks meant for designing (modeling), and a group of players shares a (larger) set of bricks meant for constructing (ordering and assembling). Players use these bricks to create two towers, one representing the building information model and one representing the actual tower. Playing cards showing construction-related risks, in combination with a die, simulate project uncertainties (in a later version, the cards were eliminated). Four multiskilled crews that can perform one action/task in a round/week are available to a player. As conceptualized in Fig. 3, these crews can be assigned to any of the following design or construction tasks:

- Model: placing a design brick on the plane that represents the BIM software; a brick can be modeled only after the modeling of any underlying bricks is completed;
- Order: choosing a construct brick from a number of available options (displayed in a product guide) and placing it on the conveyor belt of the supplier for manufacturing; a brick can be ordered only when that part of the design is finished; and
- Assemble: placing a construct brick on the plane that represents the construction site; bricks can be assembled only after they

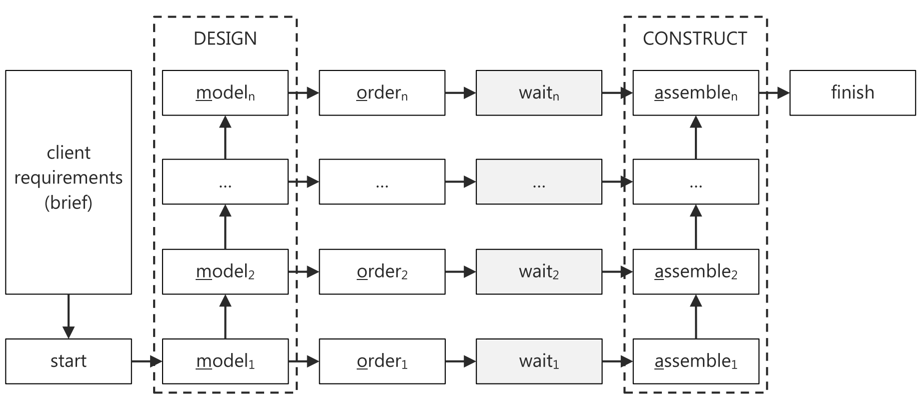


**Fig. 3.** Conceptual model of the serious game for construction supply chain management, Tower of Infinity, with in-game actions and their interdependent relationships

have been transported from the supplier to the construction site and after any underlying bricks have been assembled (thus, storage on-site is possible only if there is enough space).

To assign a crew to any task, a player writes down the action in a schedule using pencils in different colors. For example, for modeling (part of) a red brick, the player needs to write down a red *M*, whereas for assembling (part of) a yellow brick, the player writes down a yellow *A*. The schedule remains empty if no actions are possible in a certain round, such as when the player needs to wait for a brick to arrive at the construction site. The schedule can thus be used to keep track of a player's actions, which is useful for the player (to decide what to do next) and for the researchers (to analyze the player's in-game strategy).

An extensive play-testing workshop was conducted to verify whether the triadic game design worlds were well balanced in the prototype of the game. This workshop was attended by an international group of 22 construction management educators from Egypt, Sweden, the United Kingdom, and the Netherlands. After a short briefing, the educators all played the prototypical game simultaneously. They were then asked for their individual feedback on the game, organized by the three worlds: Reality ["What do you think of the way in which the game represents real-world construction management problems?"], Meaning ["What do you think of the value (meaningfulness) of the game for construction education?"], and Play ["What do you think of the game concept (goals and rules)?"]. The workshop concluded with a structured group discussion on the game design. Table 1 summarizes the educators' feedback: the initial game concept was found interesting and valuable because it offered an understanding of coordination issues in construction supply chains. However, the playing cards with construction-related risks were considered somewhat unrealistic, as was the absence of specific, detailed client requirements. The educators also criticized the game rules as being rather hard to understand.

### *Step 3: Redesigning: Incorporating Feedback into Final Serious Game Version*

The last step in the design process of the serious game was to adapt the game based on the educators' feedback on the prototype. To establish an optimum balance between the three worlds of Reality, Meaning, and Play, the authors made a number of changes to the version that had been played by the international group of construction management educators.

Fig. 4 represents the final layout of the play board. These are the most important game design changes:

- Removed the risk event playing cards (to make the game more realistic and to increase comparability of multiple game plays);
- Implemented a rule that would pose a risk of late deliveries to the player (to reintroduce an element of uncertainty);
- Increased the number and detail level of client requirements (to make the game more realistic and to increase comparability of multiple game plays);
- Changed the layout of the play board and simplified the game instructions (to increase understandability of the rules); and
- Created two variants of the game (to enable players to experiment with different problem-solving strategies and to track their progress).

All in all, the design changes resulted in the final version of a serious game for construction supply chain management called Tower of Infinity. The game is shown in Fig. 5, and its rules and objectives are described in the Appendix. This one-player board game challenges players, in their game role of main contractor, to design and construct a tower with LEGO bricks. It starts with displaying the client requirements on a screen, such as "Build as high as possible" (hence the name of the game). Each player can then assign her or his (four) multiskilled crews to modeling, ordering, and/or assembling actions/tasks. A crew can be assigned to a task by writing down the action in a project schedule and executing the task [e.g., for assembly the player writes down *A* and stacks a (manufactured) brick on the LEGO plane representing the site]. One crew can be assigned to one task in a round/week, which means that a player can conduct four actions per round. A die is thrown at the start of each round to determine in which of the supplier's production stages (represented by a conveyor belt) an ordered brick is delayed by one week (unless the player decides to invest a bit and undo the delay). Bricks that have been manufactured are stored for free on-site until assembly starts (but a fee needs to be paid for external, temporary storage if there is

**Table 1.** Summary of Construction Management Educators' Workshop

| Source | Reality | Meaning | Play |
|---|---|---|---|
| Group discussion | Represents practice to some extent | Provides proper understanding of coordination issues | Good concept: serves its purpose |
| | All risk probabilities the same, which is unrealistic | Helps understanding of many concepts in construction (supply chain) management, such as importance of long-term planning and allocation of resources | Interesting and lots of fun |
| | Client requirements not specific enough | — | Rather difficult: more instructions needed |
| | Most realistic are concepts of lean construction, supply chains, and time scheduling | — | — |
| Individual feedback | Simplified, but realistic and applicable to practice | Great introduction to dependencies between design, procurement, and construction | Very good concept: player (student) feels actual process complications and gets sense of how to sort them out |
| | Realistic construction constraints | Useful for understanding how hard coordination issues are in real world | Rules support learning outcomes |
| | Probabilities related to risk events unrealistic (all the same) | Fantastic way to make construction science easier to imagine | Game needs some time to understand: more instructions are needed |
| | Game ignores some problems difficult to implement in games | Very useful for education, particularly to introduce certain topics | Goals should be clearer (maximum time, cost, etc.) |
| | Uncertainty (die) very realistic | — | Holistic but not very simple game |
| | Makes cost-time trade-offs realistic and very interesting | — | — |

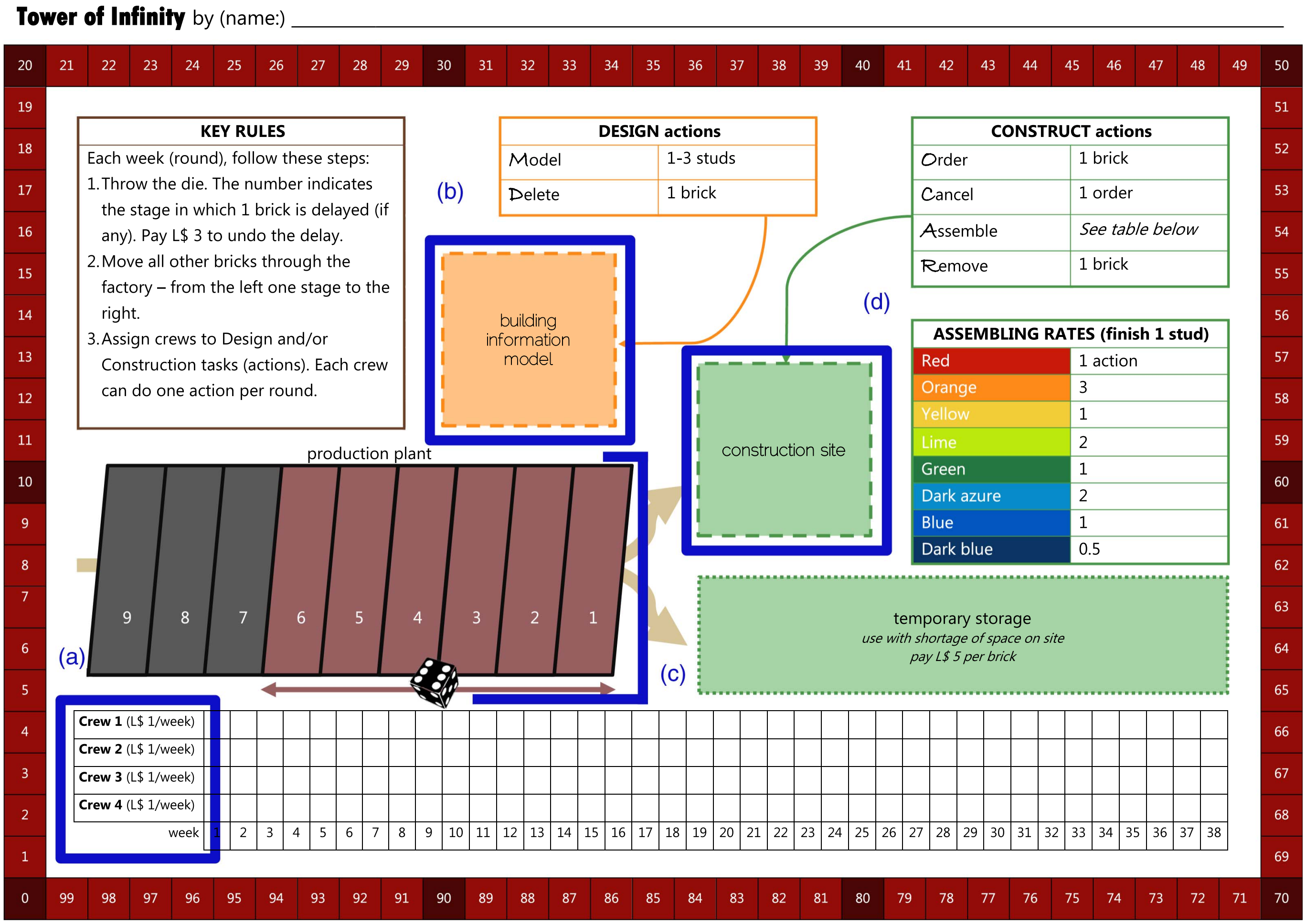


**Fig. 4.** Layout of Tower of Infinity: (a) multiskilled crews; (b) design actions using building information modeling; (c) construction materials ordered from suppliers; (d) construction of actual building based on design

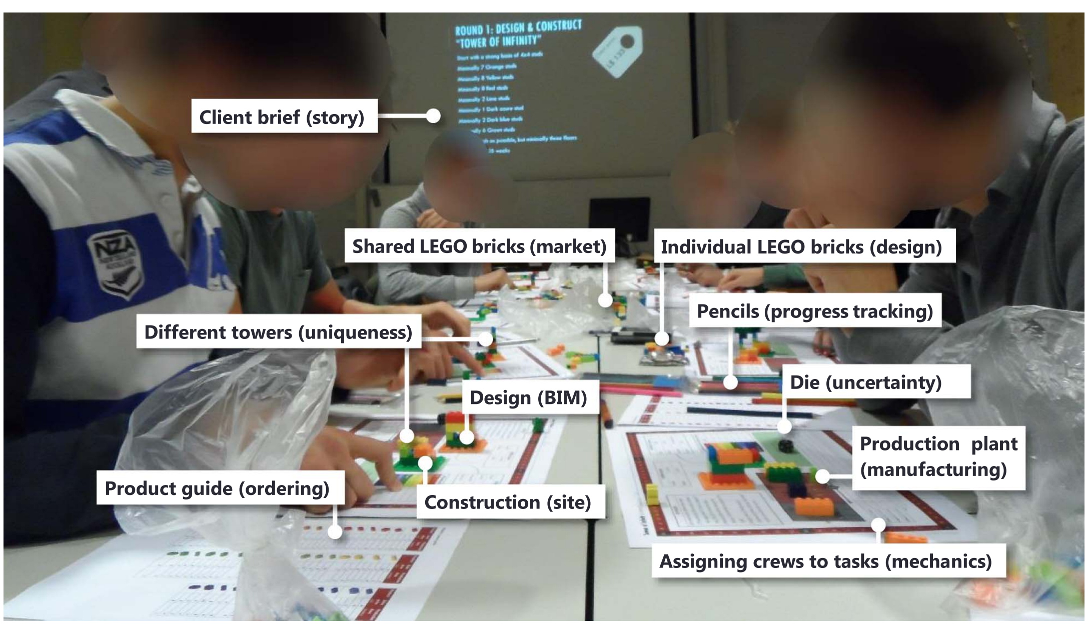


**Fig. 5.** Main triadic game design elements incorporated in Tower of Infinity

insufficient on-site space). The game is finished when the Tower of Infinity is fully designed and constructed. The objective is thus to maximize profit through efficient supply chain management.

## Research Methodology

The aim of the presented research was to explore how serious games can contribute to experiential learning about construction supply chain management. The research was carried out in the context of a M.Sc. course, the main research subjects being construction management students: the workforce of the future. With reference to the world of Meaning, the authors hypothesized that serious games for construction supply chain management can enable students to experientially learn how to improve the performance of a construction supply chain through

1. Co-ordinating design and construction tasks in a coherent manner;
2. Taking constructability aspects into account when designing; and
3. Continuously balancing scope, time, and cost throughout a project.

To provide evidence for these hypotheses, the authors qualitatively analyzed how the board game supported experiential learning in an M.Sc. course on construction supply chain management. This case study made it possible to investigate how playing serious games supports construction supply chain management education.

### *Collecting Data: Play Sessions during M.Sc. Course*

During two subsequent years, the authors facilitated (in total) four play sessions of the serious game Tower of Infinity as part of an M.Sc. course on construction supply chain management at a university in the Netherlands. The course aims to teach students how to apply supply chain and purchasing management concepts from other industries to construction. It consists of two parts: (1) an introduction to the scientific literature on supply chain management, purchasing, and the role of building information modeling in construction supply chains; and, subsequently, (2) a practical fieldwork assignment. The play sessions took place at the end of the first part, after the students were introduced to the aforementioned theoretical concepts.

The game was played by a total of 64 students: 40 in the first year and 24 in the second year. In both years, the students were split into two groups. The first author started all four play sessions by explaining the rules of the game (15 min). The students then played their first (trial) game round (30 min) while the game facilitators answered any questions regarding the rules. This round was followed by a break in which the facilitators took pictures of the final status of each game. After the break, the students started from scratch and played a second game round (30 min). This round ended with picture taking and the announcement of an obligatory assignment related to the serious game (15 min). In comparison with the first year, in the second year the authors cleared up some ambiguities in the explanation and simplified the trial game round (but kept the game setup, rules, and objectives the same). The assignment asked the students to reflect on their game play by answering the following questions in a one-page document:

- How do you see the theoretical ideas from the course used in the game?
- To what extent did you change your strategy in the second round of the game?
- To what extent do you think that the game represents real-world supply chain management problems?

In line with experiential learning theory, the questions were meant to stimulate students to critically reflect on their game play experiences and thereby connect theory with practice. Their reflection reports represent a tried-and-true (yet less common) postassessment method that has the advantage of enabling players to articulate their thoughts in ways that are most meaningful to them (Chin et al. 2009) and thus can reveal how and why they applied certain strategies. Together with the pictures, these reports provided an important data source for the authors (as researchers) to test the previously formulated hypotheses.

### *Analyzing Data: Content Analysis of Reports and Pictures*

The authors performed a content analysis of the data collected. Content analysis involves the tagging of data with codes derived from prior knowledge and then analyzing the distribution of the codes. The aim is to explore explicit and covert meanings in the data (Bernard and Ryan 2010). In this way, a set of codes based on the three hypotheses was created. The first author and an independent researcher individually pretested these codes on a few randomly selected student reports and pictures, discussed differences in coding, and then refined the coding scheme. They then applied the codes to the rest of the data: for each of the 64 game sessions both coders investigated whether or not the player was aware of specific learning goals/hypotheses (yes = 1; no = 0). This resulted in two case-by-variable matrices. The first author thereby added qualitative evidence supporting the inferences (excerpts of text, notes) to extra columns of his matrix. Intercoder reliability was assessed with Cohen's kappa ($\kappa$), a statistic that measures how much better than chance the agreement between a pair of coders is with regard to the presence or absence of binary (yes/no) themes in data (Bernard and Ryan 2010). Adequate agreement was found between the two coders ($\kappa = 0.76$). The coders then discussed and resolved the discrepancies in their coding (50 discrepancies out of 512 items). The authors finally used the final data matrix to compare and contrast similar game sessions to try to understand how and why certain game mechanisms contribute to individual experiential learning processes.

## Findings

The authors hypothesized that serious games can contribute to experiential learning regarding construction supply chain management. This section presents the study findings; descriptive statistics are provided in Table 2.

### *Hypothesis 1: Players Experientially Learn how to Improve the Performance of a Construction Supply Chain through Coordinating Design and Construction Tasks Coherently*

First, the authors hypothesized that serious games enable students to experientially learn how to improve the performance of a construction supply chain through coordinating design and construction tasks in a coherent manner.

It was found that students were able to view the entire supply chain from a systems perspective. The game enabled players to order construction materials from a supplier which were then produced (make-to-order) and transported to the site. These steps connect upstream (modeling) and downstream (assembly) processes. Players found that these design and construction processes are interrelated and need to be viewed as a whole. For example, Player 22 wrote: "The different elements in the supply chain are dependent

**Table 2.** Evidence from Content Analysis of Data Collected during M.Sc. Course on Construction Supply Chain Management

| Hypothesis—players experientially learn how to improve the performance of a construction supply chain through | Variable/theme | Instances of confirmation ($n = 64$) |
|---|---|---|
| 1. Coordinating design and construction tasks coherently | Uses systems perspective to focus on entire supply chain | 58 |
| | Tries to achieve a lean process and/or just-in-time deliveries | 47 |
| 2. Taking constructability aspects into account when designing | Recognizes construction sequences | 42 |
| | Adapts strategy based on product lead times and assembly rates | 47 |
| | Bases design on availability of materials and construction site characteristics | 28 |
| 3. Continuously balancing scope, time, and cost | Makes systematic trade-offs to fulfill client requirements | 53 |
| | Balances time and cost when ordering construction materials | 55 |
| | Makes trade-offs in response to manufacturing delays | 32 |



upon each other, and strategic decisions need to be made in order to have an efficient construction process." "All processes that have to be done to get to the end-product are interconnected," wrote Player 39. Players came to similar conclusions because they observed that "decisions made during the design phase have a great impact on the assembly phase" (Player 3). Particularly at the very start of the game, students regularly "overlooked, neglected or approached [the dependencies] in a wrong way" (Player 16), which resulted in "problems discussed during the lecture" (Player 24), such as budget and schedule overruns. For example, Player 44 was initially "just ordering some materials and then assembling them on the construction site without taking into account some important aspects of the supply chain" such as product lead times, which led to "significant losses in terms of idling construction crews." This illustrates Player 28's conclusion that there is "a need for coordination and planning" at the level of the complete supply chain. As summarized by Player 9, the "striking theoretical concept that is represented in the game, is the concept of the systems approach."

The game also enabled students to streamline work flows as in lean construction. Players had four crews available during the design and construction process. These crews needed to be paid when idle, and thus it was most efficient "to keep the crews occupied every week" (Player 25). The strategy to "maximize the efficiency of the labor" (Player 42) was identified by many as a lean approach to supply chain management and "the most obvious" (Player 58) theoretical idea of the game. Players who had many idle crews indeed concluded that their in-game process was "very inefficient and costly" (Player 12) or even "an economic failure" (Player 4). Player 25, for example, could not assign any tasks to some crews in Weeks 24 and 25 because they were waiting for delivery of a green and a yellow brick on the site (Fig. 6). The empty squares in a project schedule gave an indication of the waiting times. This could be significant, according to Player 33, because "most waste was caused by [a lack of productivity] after the design phase."

Another indicator of waste is the fee that needs to be paid if a brick that is being delivered cannot be stored on the construction site. After a brick is manufactured, it is transported to the construction site and stored there until assembly can commence. However, a fee for temporary, external storage needs to be paid if there is not enough on-site space available. This invoked the following reaction from Player 4: "By the implementation of costs for temporary storage, the application of the lean principle together with Just-In-Time delivery (JIT) became more and more understandable, as these costs do strongly increase the overall costs." Similarly, Player 3 said that a clearly noticeable game aspect "was the importance of Just-In-Time production to eliminate possible storage cost and ensure the full utilization of construction workers," concluding that "the most important theoretical lesson from the game is the importance of synchronizing the supply chain in such a way [that] the design, [manufacturing] and [assembling] phases perfectly fit together."

In sum, the students' reflections were clear and consistent that the game enabled them to optimize the supply chain by using a systems perspective, trying to streamline workflows, and pursuing just-in-time deliveries.

### *Hypothesis 2: Players Experientially Learn How to Improve the Performance of a Construction Supply Chain through Taking Constructability Aspects into Account When Designing*

The authors hypothesized that serious games enable students to experientially learn how to improve the performance of a construction supply chain by accounting for constructability aspects when designing.

It was found that the game helped students to understand how desired construction sequences influence the design. The LEGO building that players make needs to be assembled from the ground floor up. The vertical, logical construction sequence that this implies encourages players to consider "the order in which the construction will be [built]" (Player 38) during the design stage. A number of students identified the challenge of "vertical assembly versus horizontal production" (Players 25, 38, and 43). Some of them explicitly confirmed that "more attention was [paid] to [a]

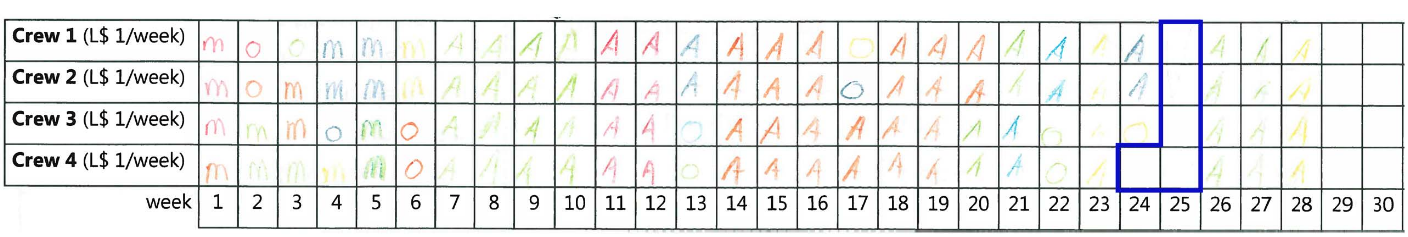


**Fig. 6.** Project schedule with empty squares (emphasis added) indicating idle crews in Weeks 24 and 25 because of late ordering and delivery of a green and a yellow brick

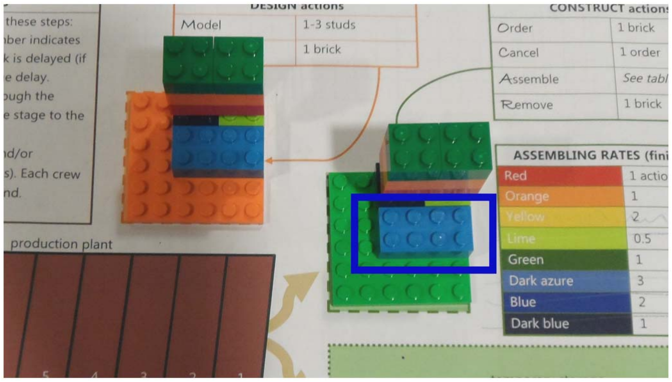


**Fig. 7.** Player 14's decision, based on assembling rates, not to design (and build) on top of the dark azure brick, ensured that it is no longer in the critical path and can be assembling whenever possible

logical sequence of building component location" in the second round of the game (Player 18). This is made possible, for example, by stacking a LEGO brick on top of only one other brick that has been assembled completely (whereas building on top of multiple bricks requires the finished assembly of multiple bricks). Thus "one [brick] should be stacked upon only one other [brick]. If this is not the case, you increase your chances for delay" (Player 63). Player 14, applying this idea, chose to design a brick with a long assembly time "on a place where the [brick] does not have relevance at all" and "then not build on top of that" (Fig. 7). This improved the performance of the supply chain because "every open spot in the schedule of the workers could [now] be filled with 'assembly' of that [brick]."

There is also ample evidence that students based their designs on information regarding product lead times and assembling rates. Depending on brick size and color, some suppliers promise a fast product delivery whereas others specify a longer lead time in their product guide. The effort needed to finish assembling a LEGO brick differs by color. A red brick of a certain size may require 4 in-game actions (for example, two crews working two weeks or four crews working one week), whereas an orange brick of the same size may require 12 assembly actions. "How much time does the production or assembling [take]?" and "Is it useful to use that brick first?" are therefore relevant questions, according to Player 16. Indeed, product lead times and assembling rates affected project outcomes: "In the first game, there was a problem because I had to wait two weeks because of the production of the orange brick [by the supplier] which also needed six weeks to assemble [on-site]. This was a lesson for me, so in the second game I based the choice of the bricks more on the assembling rates to save time" (Player 36). Player 17 also said that, to achieve an optimization in that way, "I started by [analyzing] the requirement[s], and analyzed the material cost and production time. [Then I started] modeling and … ordering based on the production time of the material. … The second round I did so much better than the first round." Along with the authors' observations, the pictures taken support the players' stories: in the second game round, these players had fewer idle crews waiting (empty squares in the schedule) than in the first round.

There is some evidence that students adapted their designs based on the availability of construction materials and construction site characteristics. When players ordered a brick, they chose it from a market of construction materials and then placed it on a supplier's conveyor belt. However, the number of available bricks in the market was limited, requiring a player to "be on time to get the materials you needed or you could choose to use only the materials with the sufficient supply stock" (Player 30). This "perfectly simulates the dependence on the market," according to Player 9, but not all players seemed to realize this. On a few occasions, the authors even observed that some players bent the rules of the game by taking two smaller green bricks when the larger one that they needed was no longer available (when they should have just ordered two smaller ones or changed the design). According to Player 34, it was a "real-world problem" that a "designer makes a design, but the constructor cannot acquire the right materials and has to work with other (and more expensive) materials." These players prevented "rework and delays" (Player 38) by timely consideration of the availability of materials.

Finally, it was found that the designs of some students were informed by construction site characteristics. The construction site is represented in the game by a $6 \times 6$-stud LEGO plane, and the client requires that "a strong basis of $4 \times 4$ studs" is used for the tower's ground floor. There is thus little space available to store any manufactured bricks on the site. Because external, temporary storage is relatively expensive and delays may occur, the game rules force players to think ahead about where to store any fully manufactured bricks. According to Player 32, "this means you can play the game strategic and build on the sides of the construction site" so that space remains available for on-site storage. Indeed, Player 54 chose to "design and build in the corner of the [site]," reflecting that she "did not have to pay for renting temporary storage in the second round of the game." A few players had similar reflections, and the pictures reveal that most actually did the opposite: building in the center of the site, thus leaving practically no space for storing any bricks.

In summary, the evidence shows that the game helped students to improve their construction supply chains by taking into account constructability aspects such as the desired construction sequence, product lead times and assembly rates, market availability of materials, and construction site characteristics.

### *Hypothesis 3: Players Experientially Learn How to Improve the Performance of a Construction Supply Chain through Supply Chain Improvement by Continuously Balancing Scope, Time, and Cost throughout a Project*

The authors hypothesized that serious games enable students to experientially learn how to improve the performance of a construction supply chain by continuously balancing scope, time, and cost throughout a project.

There is abundant evidence showing that students recognized the need to make systematic trade-offs to fulfill requirements. The game starts with the "translation of the requirements to your design" (Player 38), and the main challenge is "matching the requirements of the client with the limited resources (time and money) available" (Player 1). Most requirements define a certain minimum quality level, such as "minimally 8 red studs." This suggests that more "value to the project" (Player 18) can be delivered by building higher and/or more. Because project time and lump-sum payment are fixed, "trade-offs … have to be made" (Player 47). Player 4 clearly described how he initially experienced the interrelationships of scope, time, and cost and how he then used that experience to achieve some supply chain optimizations: "In the first play I did manage to fully meet the design requirements both within time and budget, however I continued with building till the end of the weeks given for the project. This meant that I built more than demanded, which also resulted in a budget overrun … However, in the second play I only focused on the design requirements and decided to stop with building when these were met. This meant I stayed within budget this time and also within time." This illustrates how players were able to balance the project's scope against time and cost.

The game also enabled students to balance time and cost when ordering construction materials. For each kind of material, a product guide displays one or multiple options (with variations in lead time and cost) that the player can choose from. Thus, "continuously one should trade off the costs against the lead times" (Player 9). Players experienced how they could make these trade-offs throughout the game. For example: "The first time I didn't [have] a real strategy. I just modeled the building and decided to spend [as little] time as possible in the production plant, [the] consequence[s] of this decision were higher production costs" (Player 22). Player 22 changed this strategy because she found that "sometimes it isn't necessary to pay more for a faster production because you have to wait with construction [as] other parts … are not finished yet." Similarly, Player 53 reflected on an incorrect trade-off in the first game round: "The expensive/fast yellow [brick] was a mistake, because the brick was laying on the building site 5 weeks before it could be assembled." Player 25 wrote that "two bricks were not ordered in time … resulting in a budget and time overrun." However, the authors' pictures show that this player chose—at that particular moment—to pay more for these bricks so they would be delivered faster. Because a standstill in the project is more expensive than undoing the delay, this prevented an even higher budget and time overrun. As concluded by Player 30, choosing "the right combinations could lead to great profits in the end."

Players also made trade-offs to deal with manufacturing delays. In the game, players throw a die to identify the manufacturing stage in which one brick is delayed. This "can have a big impact to the whole project especially related to time and cost" (Player 17). Player 15 noted that delays "happen in every stage of the supply chain and for various reasons. The game illustrates this well because the delays can totally mess up the [assembly] process. As a result, a lot of the finished bricks will end up in the temporary storage, which costs extra money." However, the game rules allow players to speed up the process and undo a delay by paying a certain fee. With reference to such delays, Player 12 stated that "choices … should be made in order to stay on track and budget." Describing his two game rounds, Player 27 stated that a "difference between the first and last game [was] the penalties paid for [undoing a manufacturing] delay … In the first game I accepted the delay; in the second game this was not possible anymore because [at] a [certain] moment the complete design was in production leading [to] more penalties for delays and more penalties for storage [outside of] the construction site." Player 53 decided that it was not necessary to pay for undoing a delay. "This was because there was always an opportunity for the crews to assemble another brick instead." Players were thus balancing one-week delays against fees to speed up manufacturing with the aim to improve the overall result.

All in all, students were able to optimize the supply chain throughout the game by balancing the project's scope with time and cost, by balancing time and cost when ordering construction materials, and by balancing manufacturing delays against fees to mitigate those delays.

## Discussion

This paper aimed to explore how serious games can contribute to experiential learning about construction supply chain management knowledge. The authors therefore methodically developed a serious game (Tower of Infinity) that simulates an integrated (design and construct) project in which a player takes on the role of main contractor and assigns crews to modeling, ordering, and assembling tasks in order to meet client requirements within certain boundaries. The authors then investigated the use of this serious game in a graduate-level (M.Sc.) course to provide qualitative evidence for three hypotheses. By doing so, this study makes two primary contributions. First (and foremost), it contributes to the field of construction supply chain management by reflecting on the use of an innovative serious game that deals with the peculiarities of supply chain management for construction. Second, it contributes to serious gaming literature by illustrating the serious game design process with a case for construction supply chain management.

### Experiencing Supply Chain Optimizations: Evidence for Three Hypotheses

One reason for the great amount of waste and many problems in construction is that it is hard to acquire experience in coordinating supply chain activities. Graduate students are often poorly prepared to deal with real-world supply chain management problems bcause educational assignments, on one hand, usually ignore many of the peculiarities found in practice; stories of best practices, on the other hand, cannot provide them with the thick context that is necessary to understand those practices. With their theoretical foundation in experiential learning theory (Kolb 1984; Kolb et al. 2001), serious games have been found to be powerful in providing their users with a meaningful experience. Previous studies on serious games nevertheless did not deal with supply chain management practices specific to the construction industry, did not follow a methodical approach for designing a game, and/or lacked robust and transparent reflections. This study is an attempt to address those issues.

First, this study shows that serious games can enable students to experientially learn how coordinating design and construction tasks in a coherent manner helps to improve the performance of the construction supply chain. The construction management students who played the proposed serious game reflected that the game helped them to gain a systems perspective of the entire supply chain. Players recognized that the game's modeling, ordering, (manufacturing/waiting), and assembling activities are interrelated and therefore need to be seen as a whole. The players' attempts to streamline these activities and achieve just-in-time deliveries reduced or even prevented waiting times. This was further promoted by another game feature: a fee for temporary, external storage is charged if construction materials cannot be stored on site. The players' systems perspective and attempts to synchronize activities thus helped to minimize waste and thereby resulted in more efficient construction supply chains.

Second, this study shows that serious games can contribute to an understanding that taking constructability into account during the design stage can improve the performance of the construction supply chain. The authors provided evidence that players adapted their designs to a desired construction sequence. Players made strategic choices to efficiently cope with the game rule that upper bricks can only be assembled when lower bricks are finished. Similarly, players took construction information regarding product lead times and assembling rates into account when they worked on a design, which ultimately led to less waste (waiting times). It was also found that some players considered the availability of construction materials and construction site characteristics in their designs. Players thus dealt with constructability issues during the design, such as desired construction sequence, product lead times and assembly rates, market availability of construction materials, and construction site characteristics.

Third, the study shows that serious games can help students to learn how continuously balancing scope, time, and cost throughout a project helps to improve the performance of the construction supply chain. Players recognized how systematic time and cost trade-offs helped to fulfill client requirements. While ordering materials, players had to choose between various alternatives using a product guide. The authors showed how carefully selecting the right combinations throughout the game led to greater profits in the end. A game rule that allowed players to undo a certain manufacturing delay finally enabled them to balance an investment fee against a delay in delivery. Thus, players achieved overall optimizations by matching the project's scope with available time and cost and by balancing time and cost when ordering construction materials and manufacturing delays against fees to undo such delays.

It is apparent from this discussion that serious games can contribute to experiential learning about construction supply chain management in a number of ways. The authors found that the students were able to connect the game both with theories discussed during their (earlier) lectures and with construction practice. That is important if the serious game is to have a meaningful effect beyond the game itself. It was also observed that students seemed genuinely interested in the game and had fun while playing it: they were all very focused (completely silent), particularly during the second game round, they wanted to continue playing during the break, and sometimes they added positive comments about playing the game to their reflection reports. Educators may appreciate these insights about enriching construction supply chain management education with a serious game.

Finally, this work contributes to serious gaming literature with a case for construction supply chain management. The authors illustrated how a serious game was developed for this discipline by defining the inhabitants of the worlds of Reality, Meaning, and Play (Harteveld 2011). According to Triadic Game Design, these worlds need to be balanced for an effective game. An optimum balance was found after a game play workshop with international construction management educators. Their pertinent feedback helped to determine the right balance between the three worlds. From this, the authors suggest that the three worlds can also be used as a framework for systematic critique and redesign of a serious game.

### *Limitations of the Study and Directions for Future Research*

As with all studies, this study has a number of limitations based on which directions for further research are suggested.

This research did not assess whether serious games for construction supply chain management are more effective than other educational methods. The authors focused on exploring how serious games can contribute to experiential knowledge relevant to the domain. Although the evidence is compelling, it suggests only that serious games *contribute* to experiential learning. It remains unclear whether serious games are also *more effective* than other educational methods. An experimental research design could help to answer this question. Although there is a long-standing debate in serious gaming literature about appropriate assessment methods, both a pretest and a posttest with a control group seem to be favored to assess the effectiveness of a serious game (Bellotti et al. 2013; Chin et al. 2009; Clark 2007).

There are also a number of issues with the serious game itself. Most important, one player criticism was that all buyer-supplier relationships are conceptualized as being at arm's length. According to one of the game rules, a player needs to throw a die at the beginning of each turn (week) to determine in which manufacturing stage an order is delayed. Bcause the orders at each supplier are subject to this rule, the game does not help students to experiment with different types of relationships and appropriate management styles, such as those described by Bensaou (1999). On the other hand, arm's-length relationships are actually the most common in construction practice. In that respect, the authors argue that the proposed game has at least made people think about whether such relationships are indeed desirable for achieving more efficient supply chains. Because a prototype was play-tested by construction management educators (rather than practitioners), it may also be questioned whether the game sufficiently conveys day-to-day supply chain practices. Other minor issues that came to the surface are that some game rules were initially hard to understand (particularly those for the assembly actions) and that writing down all moves was not so intuitive and errors were easily made. Future research can focus on these game design issues and on testing the game with practitioners.

Finally, the lack of a structured debriefing downplays learning possibilities. A crucial part of experiential learning, apart from the (game) experience itself, is reflection on that experience. For methodological reasons, it was decided to foster independent reflections through obligatory student assignments. The authors are confident that the decision not to steer student answers in a certain direction helped to safeguard objectivity. However, not everyone is equally capable of analyzing, making sense of, and assimilating learning experiences on their own. Skilled facilitators can play an important role in addressing this natural gap by guiding the reflective process in a collective debriefing (Fanning and Gaba 2007). The absence of a debriefing may have limited student reflections and weakened the study's findings accordingly.

## Conclusions

This paper presented a serious gaming approach to learning construction supply chain management. Based on the study's findings, it is concluded that serious games can contribute to experiential learning about construction supply chain management. Serious games are viable educational tools for supporting experiential learning. They can enable students to experientially learn how to improve the performance of a construction supply chain through (1) coordinating design and construction tasks in a coherent manner; (2) taking constructability aspects into account when designing; and (3) continuously balancing scope, time, and cost throughout a project. Experiencing such supply chain optimizations in a playful way promotes better understanding of how and why waste occurs and may, ultimately, contribute to more efficient construction supply chain management practices.

## Appendix. Game Rules and Objectives

### *Key Rules*

Each week (round), follow these steps:

1. Throw the die; the number indicates the stage in which 1 brick (if any) is delayed; pay US$3 to undo the delay;
2. Move all other bricks through the factory—from the left, one stage to the right; and
3. Assign crews to design and/or construction tasks (actions); each crew can do one action per round.

### *Client Brief*

Client pays US$135 for the following:

- Start with a strong basis of $4 \times 4$ studs;
- No yellow bricks;

- Minimally 4 lime studs;
- Minimally 7 dark azure studs;
- Minimally 2 blue studs;
- Minimally 4 dark blue studs;
- Minimally 8 red studs;
- Minimally 7 orange studs;
- Minimally 8 green studs;
- Finish within 23 weeks; and
- Build as high as possible, with a minimum of four floors.

## Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data sharing policy can be found here: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001263."

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