

# Ontology for Virtualization of Lean Construction Games

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## Abstract

**Research Question:** How can serious games for Lean Construction courses, traditionally implemented in person, be efficiently virtualized for hybrid or online education?

**Purpose:** This paper creates an ontology (a set of concepts and categories in a subject area or domain that shows their properties and the relations between them) for the methodical identification, sequencing, and implementation of universal elements of any serious game into a computer-based instructional environment. For validation we provide practical lessons from having implemented this approach on several Lean Construction games in college courses.

**Research Design/Method:** We assemble core elements, including 'atoms', from game design literature into an ontology. Each element is individually converted into virtual mode; often more than one possible way exists. Having placed them into an ontology ensures that the outcome will be a fully functional game, yet transferred to its new mode. We apply this virtualization approach to existing Lean Construction games.

**Findings:** We find that games even with substantial physical components and interactions can indeed be successfully virtualized, retaining their full educational experience.

**Limitations:** While we have validated the ontology on several Lean games, it has not been tested for serious games in other areas, nor been used to inspire creating new ones.

**Implications:** We hope that this research will facilitate the increased use of gamification in Lean Construction and other courses, and may inspire further study of the underlying conceptual similarities of games and production processes. Adapting our approach can allow developing new serious games to convey knowledge about a specific topic.

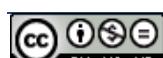
**Value for practitioners:** Gamification of higher education can be significantly advanced by the systematic, ontological identification of the main elements and relations needed to implement serious games. Given the long history of using games for the instruction of Lean Construction, this study is of particular value to Lean Construction educators.

**Keywords:** Ontology, gamification, serious games, higher education, Lean Construction

**Paper type:** Full paper

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## Introduction

Serious games that simulate real-world processes (or “games” herein) are powerful pedagogical tools to explore topics of study, improve retention thereof, and create a more interactive experience than traditional lectures (Sailer and Homner 2020). The pandemic has underlined the value of games in online instruction (Kéri 2021, Rybkowski et al. 2021).

Lean Construction (LC) emphasizes collaborative behavior (Schöttle et al. 2014). This makes games highly suitable for understanding of its underlying principles and the creation of group cohesion and trust. Although the present study is limited to the context of higher education, games offer companies in general the opportunity to instill a shared culture and body of knowledge. Serious games provide a testbed environment wherein players can experience the novel views championed by LC with particular clarity by streamlining the complexities of real-world construction projects to a simplified model. This encourages shared discovery among the players of the underlying principles of a game, whereby they build a team spirit that would be difficult to find in a traditional classroom environment.

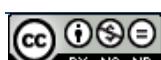
A substantial problem for educators who attempt to infuse their online teaching with games has been that most classroom serious games had been developed and intended for physical in-person implementation (Heim and Holt 2021). While the global pandemic is still ongoing at the present time, a substantial proportion of higher education institutions has sought to return to in-person teaching (Marris 2020). It can be expected that some of the online tools that have been honed during the pandemic, including serious games, will endure as distance education options, given the many advantages that they offer by their accessibility them across geographic boundaries. Beyond academia, corporate teams could also use games to train collaboration. But a substantial problem for educators who wish to infuse their online teaching with games has been that most serious games were originally developed and intended for physical in-person implementation (Heim and Holt 2021).

We therefore develop and apply a systematic approach to virtualize, i.e. change the delivery mode of serious games, by focusing on their core functional elements and logically sequencing them. This does not mean that all elements must be electronic – our approach is sufficiently flexible to allow players using their own paper and pencil if this works within their online participation and keeps the experience of the virtualized game streamlined.

## Educational Requirements

Engineering professionals and researchers contribute to creating and supporting the quality of modern life. As a quintessential applied science, engineering is at the forefront of technological development. Based on timeless principles, it has an ever-increasing body of knowledge that needs to be conveyed in formal accredited degree programs. Efficient and effective educational approaches are required to keep up with such swift changes in practice to prepare its graduates for future careers, whose challenges are still evolving.

Construction engineering and management is a discipline at the intersection of engineering and management that is tasked with planning and controlling construction projects throughout their life cycle, from design and execution to operation and eventual reuse or final demolition. Experiential learning is vital to augment textbook knowledge (Lynch and Russell 2009). In class, this entails e.g. team exercises, serious games, project assignments, guest lectures, and laboratory experiments. Outside class, field or office visits and summer internships or part-time co-op work are common. Accreditation criteria for engineering require “an ability to function effectively on a team whose members



together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives" (ABET 2019). To accredit construction management programs, ACCE (2020) requires that students understand "the role of the construction manager as a member of different multidisciplinary project teams." Moreover, professional organizations such as PMI (Task 10, Identify and Evaluate Integration Opportunities and Needs (Griffiths, 2012) and CMAA (Construction Manager Certification Institute, 2013) also publish a list of key skills that project managers or construction managers, respectively, must master as part of their certification programs.

## Lean Construction

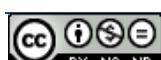
Lean Construction is a managerial approach embodied in specific techniques like the Last Planner System® (LPS, Ballard 2000). It originated in the 1990s by adapting the Toyota Production System to construction (Gao and Low 2013). Its body of knowledge is grown by the International Group for Lean Construction (IGLC), shared in dissertations (e.g. Koskela 2000, Ballard 2000), monographs (Koskela, 1992, Tzortzopoulos et al. 2020), and courses (Rybkowski et al. 2020) and advocated by the Lean Construction Institute (LCI). It centers on creating reliable plans that are trusted by all participants by aligning a plan's 'should' (the intended plan), its 'can' (what the project status allows), and its 'will' (actual actions taken by project participants). The LPS is a comprehensive method to implement Lean Construction per these overarching principles (Ballard 2000, Ballard and Tommelein 2021).

Lean favors distributing management responsibilities horizontally, which should be close to the people at the workforce who perform the actual work. To enable such decision-making, the required level of trust and communication among the team will exceed that of traditional construction management approaches. Teams strive to optimize the means and methods of execution. Collective action is based on individual responsibility. Implementing lean construction thus can be hindered by a lack of 'buy-in' for the required management changes in addition to lacking understanding of its application (Bygballe and Swärd 2014).

Gaming is a favorite means in courses on Lean (e.g. Gonzalez et al. 2015, Esquenazi and Sacks 2006). This preference can be partially traced to the teaching style of its early proponents (Rybkowski et al. 2020). Moreover, by focusing on production processes at their systems-level, lean concepts are particularly well-suited to being cast into serious games for dissemination as educational materials. Another consideration is that Lean emphasizes qualitative aspects of the management process, which can well be explored and practiced in games, rather than solved mathematically, such as scheduling construction activities.

## Pandemic Challenges

The pandemic caused by the coronavirus (WHO 2020) is unprecedented in scale and severity since the 1918 influenza (Barry 2005). It has imposed a novel set of constraints on everyday life, including the mandatory masking, social distancing, and vaccines, cleaning, closed businesses, travel bans, and —pertinent to this paper— canceling most in-person classes and events from March 2020 through the following academic year in favor of online instruction. In response to the extended public health restrictions, colleges and schools spent substantial resources (Smalley 2020) to expand their access and capacity for multi-user collaboration tools that have proven to be critical for this shift to the virtual mode.



Reopening has seen a mixture of in-person classes (albeit under social distancing with reduced seat capacity and enhanced cleaning), hybrid in-person and online lecturing, and accommodations for students who cannot or do not wish to physically attend (Nierenberg and Pasick 2020). Virtual classrooms thus remain vital for this 'new normal' (Darby 2020).

Technological factors that have eased this rapid transition are broadband Internet (UN 2016) and portable devices (Statista 2020); the ubiquity of electronic mail; commercial video conferencing (typical of the synchronous mode), collaboration platforms to share files; course websites (typical of the asynchronous mode), and the proliferation of social media (Anderson and Rainie 2018). Many such tools were pioneered in distance education, which has itself grown (Allen and Seaman 2017), e.g. for certificate and executive tertiary degree programs, yet whose approach suddenly has become adopted by the mainstream.

But technology alone does not yield successful virtual instruction. While the efficacy of online education is being studied (Chirikov et al. 2020), if designed and applied well it can be as effective as the traditional mode (Colvin et al. 2014). The question then is how to rapidly, efficiently, and effectively virtualize materials as the pandemic necessitates? While we answer it for Lean games, our approach and results are not limited to those.

## Educational Games

Games have many thoughtful definitions (Schell 2008), common to which is that games are voluntary activities whose players simulate purposeful actions and reactions under a set of rules that finely balances structure (rigor) with flexibility (creativity). They are rooted in the inborn ability of humans and higher animals to practice behaviors for their real-world physical, cognitive, or social challenges (Gordon 2014, Burghardt 2005). A classic work by Huizinga (1938) coined the term *Homo Ludens*, referring to the instinctive human tendency to play games as a natural form of learning that even predates culture.

## Gamification

Games are played for education and entertainment (Annetta 2008), which are often intermingled. Besides being enjoyable pastimes, games are a fundamental mechanism of learning. As such, they can be designed to address a particular educational content, which is called gamification. It creates serious games, which does not mean a lack of enjoyment, but the purpose of conveying learning contents (Annetta 2008). Serious games are used for training as diverse as the military (Smith 2009), intelligence agencies (Machkovech 2018), science education (Cheng et al. 2015), biology (Coil et al. 2017), medicine (Whittam and Chow 2017, Bochennek et al. 2007), and within research studies (Covert et al. 2017).

Games are attractive to augment traditional lectures for several reasons. They are inexpensive, typically have durations similar to lecture periods (as several rounds with different options), and are typically risk-free. Since the instructor acts as facilitator, they actively engage students and address diverse learning styles (Felder and Silverman 1988). Favoring application over rote knowledge, they address a higher level of educational objectives (Bloom 1984) than lectures. As such, they can constitute a flipped classroom (Safapour et al. 2019) if the students study in preparation for the game itself. Specific to Lean, serious games simulate situations that practice vital skills for construction managers, e.g. analytical thinking, decision-making under uncertainty, and effective communication.



## Justification and Need

The pandemic has presented unique challenges. At its onset, an urgent need emerged in construction education to convert materials to virtual format. From anecdotal evidence and own experience, lectures were adapted to asynchronous mode as recorded lectures or narrated presentations, or to synchronous mode as video conferences. In-class quizzes and exams became take-home activities. Site visits used live streaming from field locations. Laboratory courses changed to instructors performing physical experiments or simulations for students to analyze. But the most difficult to virtualize were serious games. They commonly require physical objects (props) and actions (moves) by and among players, and had been designed for tabletop play. Our question thus becomes: Can any serious game for Lean construction education be virtualized? The authors posit that the answer is yes and will take two steps. First, a need exists for a formal framework (ontology) by which all of the elements (atoms) in Lean games (and other production simulations) are converted from physical to virtual exercises that are functionally identical without losing any vital learning insights. Second, such ontology must be validated by applying it to existing Lean games.

## METHODOLOGY

Our goal is to enable and test the needed, efficient, and effective virtualization of Lean games. Said simply, the contents must remain, but the medium must change. In this paper we will present how to accomplish this. Three objectives will address this goal:

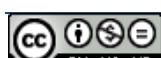
1. Parse game design literature to extract their core elements via an atomistic view;
2. Establish an approach whereby all elements - and the game itself - are converted from the physical to the virtual mode without loss of functionality or educational value;
3. Validate the correct and complete virtualization using this approach with three real-world case examples of existing Lean games and derive implementation guidelines.

## Approach

The following sections provide the background and details of our proposed approach for virtualization, starting with a definition of what constitutes an ontology, assumptions, scope, and limitations, and an overview of game design, in particular its atomistic view, which is the most basic level within a game at which the actual virtualization will proceed.

## Ontology

An ontology is a formal model of the structure of a system, including the elements and their relations that are observed within it (Guarino et al. 2009). It implies establishing a hierarchy of such elements, i.e. a taxonomy (ibid.). Ontologies are extensively applied in many fields (Ming et al. 2002), because they allow a more manageable and understandable conceptualization of complex data. Construction research has used an ontological approach (e.g. El-Gohary and El-Diraby 2011), but this appears to be the first time that it is applied to Lean gaming. To develop this ontology, we will explore fundamentals of game design, which will be employed in a novel way, for conversion, not creation. The overall approach will distill each game to its elements, find feasible ways to convert them



individually, and reassemble them to gain the same complete and functional game in its new virtual format.

## Assumptions, Scope, Limitations

While games range from simple outdoor activities to immersive virtual or augmented reality, this paper focuses on tabletop games, both board games and card games. Tabletop games are portable (including those that consist purely of a document); will engage two or more players who communicate to compete or collaborate; do not employ user interfaces; take from minutes to one or two hours; and need no software except simple spreadsheets or executable files to track, plot, or analyze the game progress. Moreover, their hardware is a specific 'site' layout (a board), standard decks or specialty cards, small tokens that represent players, resources, or other relevant objects, and common props like dice, coins, pencil, and paper. Some games assemble toy blocks as their tasks, especially Lego™ bricks. These particular characteristics are found in existing Lean games (Rybowski et al. 2020).

Some Lean games have a weak winning proposition, whereby their mere completion (within a given duration) suffices, rather than winning based a performance metric like shortest duration or lowest cost. This is not a flaw, as Lean games tend to be closed-ended and perform multiple runs of a simulation. While they are designed with process variability so that players can test their prowess, they often create a fixed product (a 'building').

We limit ourselves to the synchronous mode, wherein players communicate and act live. This does not mean that the ontology will not function for the asynchronous mode, which requires more student self-motivation (Craig 2020) and deserves separate study. It is also beyond our present scope to comprehensively analyze all Lean games, or compile the serious games that are used in construction education; this is also left for future research.

## Game Design

Classics like Chess, Backgammon, and Mancala evolved from earlier forms (Donovan 2018). They were not designed, but refined in innumerable plays. Their appeal stems from basic themes such as prevailing in conflict, balancing skill and luck, and offering variability and complexity - 'easy to learn, difficult to master' per Bushnell's Law (Bogost 2009). More recently such concepts have become best practices for game design (Koster 2013, Moreno-Ger et al. 2008). Modern designers use a methodical process to guide their creativity and expertise. This formalization resembles construction management, whose body of practice has been formalized to be taught (Abudayyeh et al. 2000) and researched (Levitt 2007).

While games are uncommon in engineering education (Ebner and Holzinger 2007), they are popular in construction education on project planning and control as two types: Production or competitive games. The former focus on emulating a production system. A typical Lean production game is the Parade of Trades (Tommelein et al. 1999) that we will virtualize. Its goal is to move sets of objects among its players who are 'trades'. Its insights are drawn by observing the systems behavior, not the individual player progress. The latter emphasize individual strategy and tactics among comparatively many risky options to win. As in Chess, player ability is reflected in moves that lead to a win or draw. The Oops game is competitive between players (or teams), whose decisions from which pile to draw a card and whether to buy information impacts the remaining moves and

eventual win. Both types teach important concepts and skills for Lean but differ substantially in their workings.

Unlike games that were conceived as computer implementations, e.g. CONSTRUCTO (Halpin 1973) and the bidding game (AbouRizk 1993), Lean games typically require physical props that are central to their functioning. To virtualize them one must find substitutions. This will be facilitated by fully understanding their role within the game. Therefore we will first develop the ontology, which will be based on understanding game elements and what they contribute. As discussed next, elements means the theme, mechanics, and atoms.

We borrow inspiration from the triadic game design (van den Berg et al. 2017, citing Harteveld 2011) that a serious game has three interrelated facets: Reality (a model of it, comparable to the learning area, here Lean Construction); Meaning (value proposal, the educational concept that players should explore); and Play (all elements that the designer has created). Items within Play are (*ibid.*, p. 4): Genre (e.g. 1-player simulation); Story (e.g. general contractor builds a high-rise); Mechanics (e.g. assigning crews to tasks); Technology' (e.g. Lego™ bricks), and Aesthetics (e.g. an intuitive board). We assume that game design process is complete so that Reality and Meaning exist. We refine Play into a taxonomy of theme, mechanics, and atoms that are explained in the following section.

Genre is overly generic and need not be adopted. We redefine Theme broader than Story as the topic that a Lean game addresses. Mechanics will be treated in more detail based on comprehensive listings in the literature. And Technology (which meant key props, not computers) is broadened into Atoms to cover all practical elements of the game play.

Aesthetics is important for both physical and virtual game formats, because it makes a game easier to follow, provides context, and enhances the playing experience. However, as it is not functionally required to achieve virtualization, we will omit this component.

## Theme and Mechanics

While a theme is not required for board games, and abstract strategy games dispense with it, in serious games the theme is the area of learning. It provides the context within which players understand the various game mechanics and their basic components called *atoms*, which we will explain in the next section, and apply discipline-specific terminology. And it inspires the aesthetics for props, board, and instructions, e.g. cliparts to symbolize specific roles or resources, fonts, and backgrounds to create atmosphere for the gameplay.

Game mechanics are the processes by which a game progresses to be ultimately won. This allows categorizing games by their mechanics, e.g. area control, auctions with bidding or trading, dice rolling, grid movement, network building, role playing, set collection, tile placement, and worker placement, among 166 recognized ones (BoardGameGeek 2019). Different mechanics foster aspects of a game like its board, resources, uncertainty, turns, player interactions, and scoring. They are not mutually exclusive and most games employ multiple ones. Mechanics are the essence of a game and are vital to the experience (Laurie 2014), as players master a new game by trying variants and reason from it (Koster 2013).

Given the importance of the theme to learning, it should be stated at the start of a virtualization. Mechanics are then extracted to guide breaking a game down into its atoms.

## Atomistic View

The most detailed level of the virtualization analysis will be called atoms, because they are not just elemental building blocks of any game, but “each atom is a game in its own right, and has to feel fun and satisfying” (Koster 2010, n.p.). Connected atoms form the primary ontology of any game, as is shown in the case studies as listed in the Appendix. It is essential that all elements of a game be retained when distilling them in the atomistic view, so that it will remain complete and properly functioning after the virtualization.

Atoms consist of input, process, and output for the player. Virtualization operates at this basic level within the game for three reasons: First, players learn to play the game through its atoms. Second, each game consists of a limited number of atoms. And third, each atom has a distinct function within the game that requires individual treatment.

Once an atom has been successfully virtualized, it becomes as an archetype and can be reused in virtualizing another game that has the same or substantially similar atom. Koster (2012) argued that the following features are necessary: preparation, a sense of place, a mechanism, a range of challenges, a range of abilities, skills, a feedback system, a problem to address, and the sense that failure has a cost. For example, moving a chess pawn is an atom that is subject to context, mechanics, and positive or negative consequences. As used by Koster, ‘Preparation’ refers to prior atoms. ‘Mechanic’ is a simple move, e.g. ‘roll a die and move a token by the number of pips [dots]’.

In simulation terminology, the outcome of an atom is equivalent to a state change in one variable (Martínez and Ioannou 1995). But atoms alone do not compose a complete game. It also has ‘auxiliary’ elements, e.g. a board and instructions, which are required for a complete virtualization. The following Table 1 lists the terms and definitions that compose our complete ontology, which we will validate by applying it to three existing Lean games. While it is comprehensive, it can easily be adjusted by users as needed:

Table 1: Ontology with Element Definitions

Element	Definition
Rules	A complete description of theme, mechanics, and atoms of gameplay
Board	If applicable, location-based layout within which gameplay takes place
Props	Any small objects that one or more atoms use, e.g. tokens, cards, dice
Uncertainty	Player randomly changes an atom state (e.g. draw card, roll dice)
Players	Feasible number of players and, if applicable, roles of players for single gameplay
Communicate	Two or more players transmit data about an atom state change
Collaborate	Two or more players interact within an atom (e.g. handle prop)
Moves	Player creates one atom state change (e.g. move token, draw card)
Turn	Player creates set of state changes that comprise one unit of gameplay
Round	All players have performed one turn in proper order within gameplay
Record	State changes are noted when a move, turn, or round is complete



The taxonomy of Moves, Turns, and Rounds are nested atoms that games often use. Having reviewed this atomistic view raises the question if a 'grammar' exists by which all atoms are arranged into games, and whether this means that all games can be diagrammed (Koster 2005), akin to the flowcharts with which software developers capture algorithms. Exploring this fascinating idea toward designing new games is beyond our current scope.

## Virtualization

It is now possible to virtualize Lean games. Taking the items in our ontology in their physical form as input and brainstorming ways to virtualize them in online communication and collaboration technology as possible outputs, we identify four levels of increasing difficulty when compared to the physical and in-person equivalents of traditional lectures:

1. Written materials, e.g. game instructions, need the least effort and handouts may exist as electronic documents already. Students are likely familiar with using this format;
2. Communication can use chats or emails, or group or breakout video conferencing;
3. Teamwork requires frequent detailed communication between players or teams;
4. Props are small two-dimensional (2D) or three-dimensional (3D) physical objects within a game mechanic. The active role of a prop informs how it can be virtualized: Does its type, shape, value, color, or another property matter? Can it be replaced with another object, e.g. card or coin? How many exist? Does its spatial arrangement with another prop matter? Is it used to keep a physical tally of the current game status, e.g. cumulative cost?

The more synchronous and physical an atom, the more challenging it is to virtualize. Yet our virtualization recognizes that typically several ways exist, so that the game can be creatively customized to a class environment, available technologies, teaching approach of the instructor, and learning styles of the students. While each virtualization concludes with documenting the chosen options for each element, in practice it will of course be followed by creating any needed virtual props as files or links, and testing the final game, e.g. with a teaching assistant. After the actual live game play with students, it is advised to debrief (Nicholson 2013) with all participants to any capture improvement ideas for future courses.

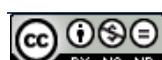
## Validation

There is a considerable number of games used to instruct LC (see Rybkowski et al. 2020). From this wide variety, three Lean games have been virtualized and played in a real classroom environment. Experiences from these sessions are distilled into debriefs. Full ontology tables with virtualization descriptions for each element are in the **Appendix**.

### Oops Card Game

- Theme: Planning under Rework Risk
- Mechanics: Card Drafting for Matching Tile Placement in Square Grid

The Oops game simulates several aspects of managing risk in construction projects in a simplified manner - the need for sound decision-making under incomplete information, how risk affects its outcome, and how knowledge and risk change over time. Its trade-off is between the lower cost of planning to reduce risk and the higher cost if a risk materializes



and causes rework. Its rules have been published elsewhere (Singh 2017, Hajifathalian et al. 2016, Howell and Liu 2012) and are abbreviated here. The game's objective is to place 9 cards onto their number in a 3×3 grid. Its main constraint is that the to-be-placed card must share at least one edge with a prior placed card. The 10 means 'bad weather' that costs a turn. After planning versus risking the next move is decided, the top card is drawn from a shuffled face-down pile, revealed, and placed into the Plan pile, onto the grid, or stored for rework in the 'Oops' pile. Costs are recorded. Cards can be moved out of the Oops in any order. The goal is to complete the 'building', i.e. fill the entire grid of cards, by the fewest moves and at the least cost.

## Oops Virtualization

Using the template in **Appendix 1**, the virtualization lists functions in the Description column. Its original form is stated in the Physical column to support conceiving options for replicating its function in the Virtual column. For example, the 3×3 grid can be set up in a document or spreadsheet where newly uncovered card values will be recorded. This can be a file that is emailed to each student or as a collaborative online file that all players can modify live. Only the numeric value of the cards matters, so that they can be shuffled and revealed in various ways. There are several ways to obtain the playing cards. For example, each player can use a standard deck of their own ownership, write numbers onto pieces cut to card size, use one of the virtual card decks available in the Internet, or even receive cards by postal mail before a session as a last resort. Moreover, cards can be replaced by rolling a regular dice that is owned by the player (ignoring too-high rolls), electronically simulating the numbers via a spreadsheet command, accessing a dice simulator website, or having the instructor randomize and announce the next card to teams or the entire class. This illustrates how various creative ways exist for the same item. Most virtualized items are sufficiently generic that other Lean games could use similar solutions if suitable.

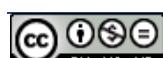
## Oops Debrief

Testing in class used a collaborative online spreadsheet that was screen-shared and team chats to coordinate moves instead of breakout rooms, which worked well. Variations and extensions are imaginable depending on class time and interest, such as whether to include the 10 as an unforeseen condition (adding time and cost without making progress); using the ace as a wildcard; a new 'gravity' rule that the building must be built from the ground up (i.e. 1-2-3, then 4-5-6, and finally 7-8-9, yet any later card can be placed on top of a prior one); and - after a practice round - turning it into a competition among teams, who state a bid cost for which they feel they can build it and then publicly demonstrate it.

## Parade of Trades Card and Dice Game

- Theme: Variability in Sequential Trade Partner (Subcontractor) Productivity
- Mechanics: Card Drafting Limited by Modified Dice as Passed Action Token

The Parade of Trades game simulates the successive handoff among subcontractors (trades) of completed repetitive work units. Units are e.g. houses in a subdivision, floors, or apartments. Its published rules (Abbasian-Hosseini et al. 2018, Senior 2011, Tommelein et al. 1999) are summarized as follows: Five to seven players act clockwise around a table. Each is a trade, e.g. concrete, mason, carpenter, plumber, electrician, or painter. Tasks are represented by moving several dozen cards or tokens from first to last player. For a turn, a player receives tasks into the in-pile from the predecessor. The player 'completes'



tasks and moves them into the in-pile of the successor. Passing a die among this parade of players is a constraint in two ways; holding it means the ability to perform tasks, rolling it is the capacity how many tasks can be completed. The minimum of in-pile or capacity gets completed. First and last players connect, so that the die passes in a circle. To simulate a pull policy round, the die is passed counter-clockwise, against the direction of the card movement. For a push policy round, it is passed clockwise with the cards. A third round uses a modified die that only shows medium values for pips (dots), which narrows the range of numerical outcomes for less variability. The goal is to finish the project in the shortest time (with the fewest turns), i.e. the last player has placed all cards into an out-pile. Multiple teams can also compete with each other for achieving the fewest turns.

## Parade of Trades Virtualization

While Oops and Parade of Trades appear different, analyzing the latter in **Appendix 2** identifies the same props - cards or tokens. Yet while Oops drew shuffled cards, Parade of Trades rolls a die as its uncertainty mechanic. Parade of Trades has no board but piles between player pairs. A sketch of this arrangement is provided by Senior (2011) and Choo and Tommelein (1999), among others. Physical incidents of dropping cards or the die off the table can be converted to a die roll with a low probability. Player roles are purely aesthetic, because they act identically and only their clockwise sequence matters, yet add realism when shown in a player map. They interact when the predecessor player moves cards into the in-pile for the successor player. The analysis reveals that the essence of this atom is the card count. It can be announced by one player and confirmed by the other, so that both record their new total holdings. An interesting challenge arises in changing from a pull to a push policy and using modified dice with a narrower range of pips. The direction can be indicated by an arrow on the player map for which neighboring player will receive cards. Modified dice can be virtualized by ignoring low and high rolls on a die simulator website beyond the valid range of pips, or by adjusting the randomizing command in a spreadsheet. As the game entails many numeric announcements between players, it is advised to create templates that each player can use to keep track. A better option to facilitate the gameplay is a collaborative spreadsheet that all players can modify as the game progresses. Such template lists player names, trades, sequence (in columns), and running totals of initial inventory, die roll, moved cards, and final inventory (in rows). Further cells could calculate the lost production potential, add checksums, or plot graphs.

## Parade of Trades Debrief

Part of its popularity arises from the players' realization of how variability and the policy shape the system behavior, and how shortages in predecessors impact downstream players. In practice this means resources sitting idle. Older computer implementations (Han and Park 2012, Choo and Tommelein 1999) could still be used to replicate results. As Senior (2011) has described, various enhancements have evolved, e.g. giving the trades construction-related names, increasing their number from 5 to 7, reducing the number of tokens from 100 or 50 to 35 (five times players) to retain statistical properties of the game while reducing tedious repetitions, changing the average and range of modified dice from 4-6 or 3-7 to 3-4 or 2-5, which adjusts the capacity and reliability of trades (Mitropoulos et al. 2014), and streamlining the templates to record the game progress. Abbasian-Hosseini et al. (2018) listed rearranging the strictly sequential parade into small network with two parallel paths for realism (Lindhard 2014), and management interventions to overtime and



overstaffing (Han and Park 2011). They used continuous probability density functions for trades in their computer simulation of the game and suggested costs for storing (excess) inventory, as well as a bonus or penalty for finishing early or late. A new idea is that the capacity of each trade could vary based on internal (other trades) and external factors (weather); different types of tasks according to the color or suit of the cards; allowing trades to have two (or more) crews by repeated die rolls; and capping the permissible inventory to e.g. 6 items, which would throttle the throughput. These and other changes that readers may invent can be virtualized in the same manner as the current version.

Just as important as *mechanics* of a game is its *meaning*: Here it is the significant dependence on the predecessor. Players often call for more output by their predecessor to fill the capacity that their die roll allows, as working ahead is impossible. This fosters a sense of teamwork that emulates perceptions of real-world trade partners. Another lesson is the relative position in a production sequence. Uncertainty in individual production has a cumulative effect, yet individual actions may not improve the system throughput, while bottlenecks throttle it. A frequent debriefing item is the importance of average capacity versus variability as modeled by die ranges: A die with half of its faces marked '2' and half marked '8' (i.e. a 2-8 die) has an average of 5, while a 1-7 die has a lower average of 4 and lower productivity. While 2-8 and 4-6 dice have the same average, the variability (reliability) of the latter is lower and its throughput will be higher. Individual game results may contradict these outcomes due to statistical chance. In such cases, the moderator could show tabulated prior games or perhaps a computer simulation thereof (Senior 2011).

## LEAPCON

- Theme: Efficiency in Mass Production
- Mechanics: Cooperative Variable 3D Set Building by Assembling Modules

The LEAPCON game (short for Lean apartment construction) simulates how schedule policies of push versus pull scheduling, batching, multi-tasking, and re-sequencing affect the work progress (Sacks et al. 2007, Sacks et al. 2005, Sacks and Goldin 2005). A lengthy printable kit with instructions, comments, templates, cards, and purchase list for Lego™ bricks is available from its inventor. Players sit around a table. Each player has one of 10 roles: For the Owner as design selector (sales), or inspector; for the General Contractor (GC) as project / owner managers, crane operator, or quality controller; or Subcontractor for flooring, partitions, HVAC, or ceiling. The board has eight floor plans of four numbered apartments each. Design cards display the possible apartment finishes from default (A) to custom options (B-H), i.e. slightly different arrangements of colored Legos™ (one color per Subcontractor). Every 15 seconds the Owner randomly draws paired design and apartment number cards and sends them to the GC, who directs Subcontractors. Custom options are considered change orders. Subcontractors perform their work in sequence to produce a small Lego™ assembly that is placed onto its apartment. The crane supplies materials as requested. In the initial round, only one subcontractor can work one any floor. Its push policy only handles completed batches of four apartments, so that a successor can only start once an entire floor is completed. Floors must be completed from the bottom up. Both GC and Owner inspect entire floors for quality of adhering to the chosen design and if all bricks are stacked tightly. Flaws are individually rejected and must be reworked as soon as possible, which changes the otherwise repetitive schedule. After a reset (disassembling the Legos™), the second round has a pull policy with process improvements: Subcontractors are now multi-skilled and can be flexibly assigned to apartments by the



project manager, multiple subcontractors can work per floor, and apartments are individually inspected and accepted in any order. The Subcontractors' goal is to correctly finish as many apartments as possible in 10 minutes, the GC wants to maximize profit (\$1500 per accepted apartment and \$1000 per in-progress apartment), and the Owner seeks accepted apartments. A table is used to record in-progress, finished, accepted/defective apartments, timing of first and last apartment completion, and calculate the throughput in finished apartments per hour.

## LEAPCON Virtualization

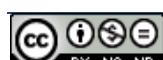
The mechanics of LEAPCON profoundly differ from the prior case examples of card-and-dice games. Since its mechanics involve placing Legos™, virtualizing it is a challenge. An elaborate yet realistic way would be to install free Lego™ CAD software with a catalog of bricks from which players compose a small partial assembly, color it, and send the saved file to the next player by chat or email. Players must install the tool on their computer for the game session. File names should be standardized to list which 'apartment' it contains and what player (role) has last handled it to prevent confusion from many files changing hands throughout the game. While this option is demanding, it retains the full experience of 'building many Lego™ apartments' and passing them to others. A much simpler option is found by analyzing what matters - their geometric arrangement into an 'apartment' shape and their color to indicate specific trades. Each design can thus be converted into a blank shape in a spreadsheet by giving the cells bold edges. As each player 'builds' their part of an apartment, they could colorize said cells and then save and share the spreadsheet file.

## LEAPCON Debrief

A mechanic that needs indirect implementation in the virtual game is Lego™ bricks that are not stacked tightly (a 'quality defect'), because Lego™ CAD always attaches them perfectly and spreadsheet shapes are fixed. A randomization like a die roll with small defect probability (e.g. 1 in 6) can be substituted. Such controllable rework can actually be a virtue in the virtual game - its impact could be studied at different probabilities.

While the game is designed for 10 players, it can host more by inventing new roles, e.g. project engineer, intern, or interior designer. While adding trade partners is possible, coordinating among more than four may make the game unwieldy. Larger class sizes should thus be split into separate teams. Conversely, roles can be condensed ad hoc to match the number of students in class. It is best to first combine the project and owner managers and the design selector and inspector. The ontology helps identify extraneous roles that can be simplified. The crane role is eliminated as its bottleneck role would mire the virtual game.

In actual play we found that the slow file sharing required significantly reducing the apartments from 32 to 8, akin to producing fewer units in Parade of Trades (Senior 2011). Some 16-24 apartments are feasible in one session if a collaborative spreadsheet is used. Both options allow multiple rounds to compare batching and sequencing in push versus pull policies statistically. A quality issue occurred as bricks seemed connected in a perspective view in CAD when they really hovered near each other. The rework mechanism fixed this. Sequential interactions were from the design selector (sales) via trade partners to quality control / superintendent; GC roles were more ad hoc. Short file names (apartment number and role) were useful. Floor numbers were redundant. It was useful to rename all players so that their playing number and role is visible be evident in the video conference screen



(e.g. Zoom™). For reference the instructor screen continuously shared the player map, design options, and apartment map, and moderated verbally and in the video conference.

The game shows the complexity of managing trades, simulates disruption caused by design changes, and challenges rules-of-thumb on batching trade partner work. Applying Lean principles can approximately double its throughput (Sacks 2020), e.g. by following a strict protocol in the supply and completion of design changes; eliminating work batching (that several units - a batch - be completed before the next trade starts on it; and allowing multitasking. A downside is that it simplifies so that not all features of traditional or Lean strategies are explored within the game rules and duration: Vertically separating trades, e.g. formwork removal and plumbing installation improves safety; batching is reasonable if a task depends on a slower predecessors or is not economical unless batched; and specialty work like mechanical, electrical, or plumbing (MEP) cannot be performed by any crew. Yet they do not diminish its quality - serious games necessarily are simplified models of reality.

## Conclusions

The games discussed here were functionally identical in their physical and virtual modes. While this conclusion can be true of any game to which an unconstrained degree of automation is applied, this study showed that the degree and nature of virtualization of many game components can significantly vary without a significant degradation of the gaming experience. The ensuing economy of resources needed for a given game can facilitate the decision to virtualize it. In summary: Rules are similarly communicated in writing and by instructor explanations for both physical and virtualized games. Little difficulty exists in converting items such as player roles and their seating from physical to virtual by names, numbers, and perhaps a player map. Of medium difficulty for effective virtualization is the uncertainty mechanism necessary in each game, as players may own dice or cards, access a website that simulates a dice roll, or randomize with a spreadsheet command. Virtualizing props ranges from straightforward to needing creativity. Since only the integer value of cards matters, they are easily randomized. Somewhat challenging are Legos™ that become a 3D assembly in the free CAD software. This affirms our observation about relative difficulties depending on the degree of 'physicality' of items to virtualize.

## Discussion

Besides the individual debriefs, we derive general advice from having played these Lean Construction games with our students in both their original and virtualized formats:

- Software: All players should download and test software well before the class;
- Simplify: Many instructions as originally written are too long to quickly review in class. The ontology helps condensing them into 1-2 essential pages. Simpler is also often better, especially for interactions and recording templates. This does not mean plain, as suitable fonts and cliparts easily add atmosphere;
- Reading: Instructions are best read aloud while players quietly read along. Demonstrating how individual rules work will also further understanding;
- Map: Screen-sharing a player map with roles is helpful during virtual gameplay;
- Templates: Fillable tables will give structure to the gameplay, avoid incorrect moves, track progress, and add or chart results. Their layout should be tested;

- Practice: After the instructions, a practice round should be played to prepare all players. If it works well, it could be considered to constitute the first round;
- Players: Absences may only be known at class time, so that mechanics must be flexible for a range of player counts. It can be solved by extra roles to add or drop ad hoc. Larger player counts can be split into teams who play in parallel;
- Speed: Virtual games tend to be slower than traditional versions in handling props and communicating, probably due to their limited opportunities for the informal discussion of rules among participants. In the authors' experience, two hours of play may allow for an explanation of the game, one practice round, two rounds of the actual game, plus a relatively brief discussion of the results;
- Rounds: Given the limited time, extra rounds (e.g. three samples of a policy) could be replaced by showing a simulation of the gameplay with its statistics;
- Mail: While our ontology can virtualize any Lean game, if it has single-player mechanics only, mailing physical supplies to players remains a feasible option if the player accessibility is limited in some way, e.g. due to Internet connectivity or speed, screen size (if using a smartphone instead of a tablet or computer), or personal competence in using technology. This possibility does not preclude the option for offering a screen-only version of any item such as a card deck or die.

## Contributions to the Body of Knowledge

Education is faced with unprecedented and ongoing challenges since the pandemic was declared (Cuconotta and Vanelli 2020). Foremost has been the shift from in-person to online instruction. As distance education techniques became part of a 'new normal', some content appeared difficult to adapt. In construction education, this is especially true for Lean games, which often require physical interactions. To alleviate this problem, we have:

- Extracted literature on gaming, game design, and serious games to define game elements and their respective functions as part of an atomistic view of games;
- Created a virtualization ontology to support generating equivalent options for the elements at the atom level and reassemble them into a functional game;
- Validated the ontology with three well-known Lean Construction games, whose educational value has been retained. Debriefs have been compiled for each.

The new virtualization ontology presented herein can be recaptured as three steps:

- Identify theme and mechanics: Stating the theme in terminology of its learning area is a reminder of its educational purpose to prepare its atom-level analysis. Themes can be e.g. 'planning', 'coordinating', and other basic Lean concepts.
- Extract atoms and tabulate: While atoms constitute 'mini games', our ontology also includes auxiliary elements. Three applications are found in the **Appendix**.
- Brainstorm options for each: The actual conversion handles each game element by generating options for the available communication and collaboration tools. Creativity techniques may be applied if needed. Intricate items are resolved by determining what feature matters (e.g. value). Entries for the case examples are somewhat archetypical and readers can easily apply them to other games.

## Recommendations for Future Research

The new ontology is not limited to virtualizing existing Lean games, but also reveals potential improvements—the debriefs give suggestions—or even develop new ones.

Given the plethora of lean concepts and the infinite number of possible approaches to each concept, entirely new games can be conceived by modifying the virtualization using a creative yet structured process, thus adding to the body of Lean games (Rybkowski et al. 2020). This enables instructors to efficiently design newly gamified educational contents, e.g. supply chain issues (van den Berg et al. 2017). Process simulations (Johnson and Drougas 2002) appear well-suited for being adapted, so that it would be interesting to study the relation of games and simulation further. As mentioned, the asynchronous mode was excluded from our scope and should be explored in the future. We hope that this paper ameliorates the challenge of virtualizing Lean games and inspires gamification in construction education.

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## Appendix

Table A.1: Virtualization Analysis for Oops Game

Element	Description *	Physical	Virtual Options
Rules	See <i>Literature sources</i>	One instruction sheet	Document; plain text
Board	Left half: Map with Yard, Plan, Oops, arrows labeled with costs between them and to right half Right half: 3x3 numbered grid Site to place cards	Layout on two sheets to fit cards	Document; spreadsheet
Props	10 standard cards in increasing value from ace (1) to 10, 10 means 'bad weather'; dice; pen	Sequentially revealed **	Make cards; use or build dice; dice simulator website; randomizer spreadsheet command
Uncertainty	Shuffled face-down cards in Yard	Randomize non-repeating **	Randomize from 1-10; if dice roll two and discard any repeats, 11, 12
Players	Team has card handler, recorder, error checker, other roles possible	Team with multiple roles	Vary team size to evenly divide class; or single player (all roles)
Communicate	Call decision before picking card; call card fit; call cost; as needed	Within team, with instructor (moderator)	Public chat; video conference
Collaborate	Only within team between roles	Assist as needed	Private chat; breakout room
Moves	Decide strategy; move one card; record cost	Pick card from Yard / Plan / Oops; place into Plan / Oops / Site per Rules, write with pen	Options: Fill cell in Board; type cost into Record
Turn	One full set of Moves	See <i>Moves and Record</i>	Instructor clarifies and moderates
Round	0. Practice round 1. Risk-seeking strategy 2. Risk-averse strategy 3. Best judgement strategy	1. Always 'risk' 2. Always 'plan' 3. Discuss then decide	Virtualized identically
Record	Table columns for move number (day), card value, decision, cost; 20 rows plus row for total moves and sum of costs	Empty template for each strategy	Table in plain document or spreadsheet (better); can be individual or collaborative (better)

\* Items for game kit of one team; \*\* vital in virtualization.



Table A.2: Virtualization Analysis of Parade for Trades Game

Element	Description *	Physical	Virtual Options
Rules	See <i>Literature sources</i>	One instruction sheet	Document; plain text
Board	Sitting in circle	Table	Player map; player number list
Props	<ul style="list-style-type: none"> <li>▪ Small items to pass among players</li> <li>▪ Dice</li> <li>▪ Pen; stopwatch</li> </ul>	Standard card deck (rank and suit matter not) or coins or bolts, etc.	<ul style="list-style-type: none"> <li>▪ Make cards</li> <li>▪ Use or build dice; dice simulator website; randomizer spreadsheet command</li> <li>▪ Timer website; clock</li> </ul>
Uncertainty	Card count to pass onward; 'defect' = card falls off table (back to in-pile); 'accident' = dice falls off table (ends turn)	Dice roll **	Randomize card count; randomize defect or accident (e.g. 6)
Players	Each is distinct trade per Rules, e.g. 1. Excavation, 2. Foundation, 3. Structure, 4. Enclosure, 5. Finishes	Clockwise seating order around table	Increase team size by inventing more trades, should not be fewer than 5
Communicate	Minimal, visual (see cards)	As needed	Public chat; video conference
Collaborate	Interface at card piles; pass dice	Pick or place cards	Call randomized value; call card count and recipient; record own in- and out-pile
Moves	Roll dice; review in-pile; decide card count; move cards to out-pile; record roll and running totals	One player is active	Players call moves in standard way, e.g. "Trade rolls 4, moves 3 to Successor"
Turn	One full set of Moves	See <i>Moves and Record</i>	Instructor clarifies and moderates
Round	1.-2. Pull policy 3.-4. Push policy	1. Standard dice (1-6) counter-clockwise 2. Modified dice (3-4 versus 2-5, or other variations) 3. Standard dice clockwise with cards 4. Modified dice	Virtualized identically
Record	Table columns for move number (day), in-pile count, dice roll, out-pile count; 25 rows plus row for total moves and sum of costs	Each player has empty template	Table in plain document or spreadsheet (better); can be individual or collaborative (better)

\* Items for game kit of one team; \*\* vital in virtualization.

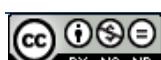


Table A.3: Virtualization Analysis for LEAPCON Game

Element	Description *	Physical	Virtual Options
Rules	See <i>Literature sources</i>	One instruction sheet	Document; plain text
Board	Eight floor plans with four apartments each	Eight sheets	Apartment map; apartment number list; decrease apartment count if necessary
Props	<ul style="list-style-type: none"> <li>▪ Lego™ bricks</li> <li>▪ Design cards; apartment number cards</li> <li>▪ Pens; stopwatch</li> </ul>	Boxes with sorted Lego™ bricks; printed cards	<ul style="list-style-type: none"> <li>▪ ** Install Lego™ CAD software; set up spreadsheet of Lego™ assembly to colorize</li> <li>▪ Make cards; randomizer website; randomizer spreadsheet command</li> <li>▪ Timer website; clock</li> </ul>
Uncertainty	<ul style="list-style-type: none"> <li>▪ Paired apartment numbers and design options</li> <li>▪ Quality flaws</li> </ul>	Timed card draws	<ul style="list-style-type: none"> <li>▪ Randomize two values at time signal; review Lego™ file</li> <li>▪ ** Dice roll (6 = bricks not tight)</li> </ul>
Players	Each has distinct role within either Owner, GC, or Subs group	Groups seated among table, role ID labels	Player map with sequence; rename chat participant; increase or decrease extra roles (need several Subs)
Communicate	Intensively within and among groups	As needed	Public or private chat (textual); video conference (verbal); breakout rooms
Collaborate	Interface at paired cards; Lego™ assemblies	Pick or forward cards; add brick, forward, or inspect Lego™ assembly	Call randomized value; create Lego™ file, add bricks of one color, name e.g. "Apt. 8 partitions", share file (chat, message, or email); colorize cells in collaborative spreadsheet
Moves	Specific tasks per role description, e.g. draw card; add brick of one color; inspect	Multiple players from each group may act in parallel	Players call moves in standard way, e.g. "Apt. 17 design E" or "Rework HVAC apt. 23", not necessary for adding brick or sending Lego™ file
Turn	One full set of Moves	See <i>Moves and Record</i>	Instructor clarifies and moderates
Round	<ol style="list-style-type: none"> <li>1. Push policy</li> <li>2. Pull policy</li> </ol>	<ol style="list-style-type: none"> <li>1. One Sub per floor, deliver floors from bottom up</li> <li>2. Multi-skilled Subs per apartment, deliver apartments in any order</li> </ol>	Virtualized identically
Record	Counts, timings, and throughput formula	Empty template for instructor (moderator)	Share screen of table in document; spreadsheet (if possible); or plain list

\* Items for game kit of one team; \*\* vital in virtualization.

