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DEVELOPMENT OF SIMULATIONS & PULL PLANNING FOR LEAN CONSTRUCTION LEARNING AND IMPLEMENTATION

Cynthia C.Y. Tsao[1] and Gregory A. Howell[2]

ABSTRACT

To manage projects based on Lean principles including global optimization, transparency, reliability, and flow, Lean learners need to learn an alternative approach that includes different language and techniques that better support production system management. By helping us model what happens in the real world while focusing on a few key concepts, simulations help Lean learners focus on how they would diagnose problems and determine how to deliver the project better. While Lean learners may think they are learning *something* during simulations, instructors are really getting them to reflect on *how things happen and why*. In essence, simulations help with "learning to see" waste and other problems on projects (Rother and Shook 1999) so Lean learners can develop strategies for waste removal and problem solving to generate value better.

How did the Lean Construction community adopt this training approach for Lean learners? This paper explores the Lean Construction community's use of simulations (particularly the Airplane Game and Parade of Trades®) and creation of the Pull Planning technique. This reflection provides a foundation for instructors to share training practices and collaboratively refine their teaching approaches to accelerate the rate of Lean learning and implementation.

KEYWORDS

Simulations, Pull Planning, facilitation, action learning/research, learning

RESEARCH MOTIVATION

Simulations help Lean learners evaluate from a flow- and efficiency- perspective how project team members are managing production system design and control on Architecture-Engineering-Construction (AEC) projects. By practicing this method of inquiry, Lean learners start learning to see the root causes (e.g., behaviors, contractual frameworks, resource availability, and traditional practices) behind the roadblocks to workflow found on AEC projects. Through simulations, Lean learners develop hands-on experience in measurement-based continuous improvement. This is important because managing continuous improvement and respect for people should not only be a business goal but rather a fundamental way of being that helps companies improve not only their competitive edge but also the quality of their employees' work lives (Spear 2010).

[1] Owner, Navilean, LLC; Founder, Building AEC Learning, Inc. (BAECL); Brookline, MA, 02445, USA, Phone +1 510/593-4884, cynthia@navilean.com

[2] Retired, Lean Construction Institute; Greg developed this paper with Cynthia starting in 2014. He passed away on June 15, 2020.

Accordingly, this paper seeks to document the development and evolution of simulations and Pull Planning to provide a foundation for future researchers to: (1) share their theoretical frameworks and best practices regarding Lean training and implementation and (2) work collaboratively to improve and refine their teaching approaches to help accelerate the rate of Lean learning and implementation in the AEC industry. This paper also seeks to help researchers recognize that effective simulations take time to develop, so rapid prototyping and sharing simulation improvements is critical in advancing Lean learning and implementation (Rybkowski et al. 2021).

RESEARCH METHODOLOGY

The authors developed this research through interviews with primary sources and supplemented the study with a literature review. The first author shared drafts of the study with the primary sources, followed up with them to confirm that their experiences were accurately portrayed, and made revisions based on their feedback whenever needed.

ALL PARTIES FORUM & USE OF SIMULATIONS

In 1979, Greg Howell and Glenn Ballard started collaborating in a productivity improvement initiative on the construction of an ethylene plant near Alvin, Texas. On the project, they found that they had a common interest in systems thinking and began investigating how to represent a systems-based approach on the meeting room wall for project teams as well as how to intervene in ways to improve project performance.

By the early 1980s, Greg Howell started assisting companies with improving construction productivity through Timelapse Inc. and amassed a collection of movies that illustrated construction productivity problems. At one point, he considered, “Is there only one solution for each problem, or is there actually a solution space that contains multiple solutions? Before you could implement any solution to the productivity problem, could you get everybody to agree on the change?” With help from Clark Oglesby and Hank Parker of Stanford University, Greg organized an All Parties Forum in the mid-1980s in Palo Alto to explore these questions with representatives from different AEC project stakeholders (e.g., business agents, contractors, and designers).

In the initial meeting, attendees formed mixed groups, watched the time-lapse movies, studied the relevant data, and proposed improvements acceptable to all parties. After taking about an hour to develop the group solutions, the attendees gathered as a large group to review the various proposed solutions and implications for AEC industry practice. Many attendees enjoyed the exercise and suggested that they meet again with the same meeting format. As a result, Greg and Glenn started organizing a series of these forum meetings every six to nine months over the next 10 years.

During earlier All Parties Forum meetings, one attendee shared the simulation “Win as Much as You Can,” and another attendee, organizational development consultant Jerry L. Talley, introduced the group to the simulation “Build as Many Roads as You Can” (Howell 2011). Attendees enjoyed these simulations because they allowed the group to explore the advantages of competition versus cooperation. Competition/cooperation simulations are designed to make participants consider the larger opportunity to behave badly, as they decide whether they will work with or fight against others in the situation created by the simulation. The All Parties Forum meetings that featured simulations often generated deep, value-adding discussion for the attendees. As a result, attendees willingly tried different simulations whenever they were introduced at the meetings.

Greg noted, "I like to use simulations because I learn best by doing. Others don't so you can't rely on them entirely… I prefer exercises that isolate on a single issue or principle and make it very apparent at least by the end. This type of simulation is realistic in that it illustrates some bit of theory in action… or it puts people in a dilemma much like they experience in life… More 'realistic' simulations are just too complex and have too much going on to allow careful focus when processing… Running simulations is always manipulative because unlike lecture, the test comes first… Simulations put people in the middle of a dilemma or reveal some fundamental relationships operating but hidden in practice" (Howell 2009).

Following World War II, the Associated General Contractors' (AGC) New Mexico Building Branch endowed the construction management and engineering chairs at the University of New Mexico (UNM). Then, the AGC-New Mexico committee and board members were involved in soliciting, reviewing, and hiring candidates for these positions every five years (Graystone 2022). As a result, in 1987, UNM appointed Greg as the AGC Visiting Professor. Meanwhile, his wife Dana worked on a leadership team that was restructuring public education in New Mexico. Through her work, Dana attended an Institute of Cultural Affairs' course in facilitation taught by Tim Karpoff. Tim works with business, government, and non-profit organizations on strategic and project planning. Dana introduced Tim to Greg, and they began facilitating partnering and leadership development programs together. In these sessions, Greg continued to test and use simulations to help attendees develop common project goals.

These programs featured not only the simulations that emerged from the All Parties Forum but other simulations as well that explored team building and organizational issues. These simulations were very similar thematically as they tested groups in establishing who was in charge of the project and how to get to a group solution. Greg gained many personal lessons and insights from administering and participating in the simulations, so he became passionate in using, developing, and refining simulations. Since simulations could appeal to different learning styles of workshop attendees (Hawk and Shah 2007), he found them to be more effective (in comparison to presentations) in helping project team members consider different principles to guide their efforts and behaviors on projects. Greg also began exploring more Lego® simulations to study production system design challenges, including a partially developed Lego® Hotel simulation (Howell 2009).

Meanwhile, although attendees enjoyed the intense discussions about the state of AEC practice at the All Parties Forum meetings, they came up short in terms of developing a solution for organizational learning. As a result, the All Parties Forum attendees eventually decided to stop meeting. However, during the last meeting in a Northern California restaurant in the mid-1990s, Jerry Talley was exuberant because he noted that the lack of a common organizational learning solution indicated that there might also be a lack of a learning language for how work happens. He convinced Greg and Glenn to meet with him the next day to develop that language (Howell 2011).

FOUNDATIONS OF LPS, INTRODUCTION OF AIRPLANE GAME, AND CREATION OF PULL PLANNING

Led by Jerry, Greg and Glenn developed "Work Mapping" as a graphical tool. When they realized that "Work Mapping" was similar to the IDEF0 method for modeling decisions, actions, and activities (Grover and Kettinger 2000), they refined "Work Mapping" further and "called [it] Activity Definition Process, consisting of a process box with circles entering from [the] top, left, and bottom, representing directives, information and

materials, and resources, respectively (P2SL 2022). An arrow coming out of the left side of the box pointed at Output. There was also a check loop to answer the question if the Output matched what was expected in the Directives" (Ballard 2019). The Activity Definition Process then provided the graphical framework for the Last Planner® System (LPS). With this basic LPS framework in place, Greg left UNM and started the Lean Construction Institute (LCI) with Glenn, Iris Tommelein, and Todd Zabelle in August 1997. Greg and Glenn adopted the term "Last Planner® System" (Ballard 1994) because "the participants [in planning meetings] have been the 'last planners'; i.e., the front line supervisors who speak for the direct workers that are members of their work group" (Ballard and Howell 2003). Through LCI, they met with companies that were interested in improving project management and changing the status quo on AEC projects. Through those meetings, Greg and Glenn recruited projects to gather data to test and improve the LPS framework. Meanwhile, Iris provided the first operations science-based explanation about how pull-based Lean Construction processes were more "responsive to customer needs and therefore superior in performance" (Tommelein 1997, 1998, & 2015). This provided an initial justification for introducing Pull Planning into the LPS framework.

Meanwhile, David Neenan, founder of the Neenan Company (TNC) in Fort Collins, Colorado, had been organizing 2-day learning symposiums each year for their clients, consultants, employees, and trade partners. After assisting TNC with a symposium based on innovation, Hal Macomber started consulting with TNC in the mid-1990s and challenged TNC's Design Manager, Mike Daley, to "do something more than just be a foot soldier" (Daley 2022a and 2022b). With that challenge, Hal gave Mike a copy of *The Machine that Changed the World* (Womack et al. 1990) and instructed him to read it in terms of: (1) What are the authors' claims, and are they grounded? (2) What can you see in this book that is like the AEC industry? (3) What are our opportunities based on what you read in this book? Inspired by the book's Chapter 4 about "Running the Factory," TNC began a study-action effort in November 1996 to get through the first 15% of design within one day in-person with their clients and called this effort "Schematic Design in a Day" (SDIAD) (Miles 1998; Daley 2022b and 2022c).

Mike then read *Lean Thinking* (Womack and Jones 1996) and reached out to Jim Womack to learn more. Jim helped Mike contact Doyle Wilson, the homebuilder in Austin, Texas, that was featured in *Lean Thinking*. Mike, David Neenan, and Hal Macomber visited Doyle and saw him use "Lean Zone® Production Methodologies" to train the trade partners on his projects. Lean Zone® is a cellular manufacturing simulation developed by Michael Deese of Visionary Products for Santech Industries (Visionary Products 2014). Known colloquially by the Lean Construction community as "the Airplane Game," the Game helps workshop attendees learn about the value of managing work in smaller batches, introducing pull into a production system, and balancing workflow to increase productivity while achieving better quality.

Doyle also shared how his company was working under a standard process for building houses within 60 days using a one-day takt, and they were working on achieving a faster delivery by using a half-day takt (Macomber 2022 and Daley 2022b). This process resembled Pull Planning in some ways, but it was still a work in progress because it was hard for Doyle to get his trade partners organized like a manufacturing line, and weather delays further hampered their efforts (Daley 2022b). As a result, it was not yet fully developed and working during TNC's visit.

Around this time, Mike reached out to LCI after reviewing an LCI flyer shared by a coworker because LCI's goals resonated with TNC's learning and continuous

improvement efforts. Then, guided by the principles outlined in *Lean Thinking* and influenced by their visit with Doyle, Mike and Hal started working with Greg and Glenn at TNC's offices to test how the Activity Definition Process could improve the LPS framework. At this time, the early design of the LPS "did not have a macro level Pull scheduling for the overall schedule method, as I remember it, more at the task level from the lookahead to the two week" (Daley 2022c).

Given TNC's preference to work as a Design-Builder, Mike suggested that they start with value for the client, that is, to determine the Conditions of Satisfaction (CoS) for the client and start working backwards from there (Daley 2022a). Daley (2022c) clarified, "we started using the big sheet to begin at the end and work backwards, since computer scheduling (the present system at the time) could not work backwards." As a result, they first clarified what generated value for the client, and then mapped the value stream starting from the end – thus creating the technique of "Pull Planning."

Once they refined this approach, TNC integrated Pull Planning into SDIAD and later renamed it the Collaborative Design Process (CDP) when "they realized they had a solid way to have the 'customer define value' which was the first principle [identified] in *Lean Thinking"* (Daley 2022b). Daley (2022b) noted that "the third principle, 'Make it Flow,' seemed easy to understand [within the AEC industry] as it was every superintendent and subcontractors dream that never actually occurred on the jobsite or within design. The fourth principle was 'Pull,' and it was easy to see how this was 180-degrees from what was done in the design and construction industry as all we did was push. Womack says to start at the end and Pull backwards. Traditional scheduling software did not allow this to occur. Per other companies adopting lean, TNC went simple" and hung a 7' tall x 40' long (2 m x 12 m) sheet of ripstop nylon on the wall (Daley 2022a) and attached small pieces of paper with tasks handwritten on them to it by spraying the ripstop nylon with 3M repositionable adhesive spray. Then, the CDP process began with "client move in" and worked back to the beginning of design (Daley 2022b). Meanwhile, inspired by their visit with Doyle Wilson, TNC started facilitating the Airplane Game during their projects and learning symposiums *(ibid)*. After attending TNC's leaning symposiums as a keynote speaker, Jim Womack invited Mike to start participating in Lean Enterprise Institute (LEI) conferences to share TNC's experience with other companies and industries.

In December 1997, LCI invited TNC to attend a quarterly LCI meeting hosted by Bob Miles and John Strickland of Industrial Design Corporation (IDC) in Portland, Oregon (Miles 1998). IDC was incorporated in 1985 as a subsidiary of CH2M HILL Companies, Ltd. (CH2M Hill AA 2021), and then CH2M Hill was acquired by Jacobs in 2017 (Chuang 2017). Mike attended that meeting and met others in the LCI community, including Ed Beck of the Linbeck Group and Todd Zabelle of Pacific Contracting. At the meeting, Hal gave an impromptu presentation about TNC's approach to planning based on a project's Conditions of Satisfaction, and Greg tested an early prototype of the Parade of Trades® (Macomber 2022 and Strickland 2022). A common sentiment among attendees was that they were all aspiring to improve flow during design and construction on their projects. Mike noted it was encouraging to meet others who were also striving to improve project delivery like TNC. Todd remarked that it was like "we were all at the [Mos Eisley] cantina in Star Wars… all the freaky animals from outer space focused on flow" (Daley 2022a). In a similar vein, Greg remarked that meeting attendees were "a tribe of like-minded malcontents" (Strickland 2022).

After Mike presented about TNC's Lean journey during the LCI meeting, TNC started working with IDC in February 1998 to deliver Lean Design & Construction to a

design/build client (Miles 1998). Meanwhile, Linbeck also invited TNC to come to Houston in May 1998 to help train one of their project teams. Mike agreed and helped set up 7-8 games of the Airplane Game for around 50 people. They hung up a light green ripstop sheet on the wall, and TNC helped Linbeck pull plan that project with their partners. According to Ballard (2019), "the first use of stickies on a wall, at least for doing Pull Planning, happened in 1998 in planning Linbeck Construction's Next Stage Project. An all-star team from around the country had been selected to design and build this 7,000-seat enclosed theater for performing arts. Mike Daley, an architect with the Neenan Company (an early LCI member company) suggested that we do it backwards. He overcame our hesitations, thank goodness. Incidentally, this project was the first on which the LPS was used to manage design" (Ballard 2000, 2019).

After the Linbeck meeting, Greg and Glenn started using the Airplane Game in LCI's "Introduction to Lean Construction" workshops. They also used sticky walls with index cards to help with early collaborative planning sessions and developing the LPS further in Lean implementation experiments. In the meantime, TNC often attended early LCI meetings, shared how they adapted the use of the LPS on their projects, and experimented with how to achieve ideas proposed by Greg and Glenn. For example, when Glenn suggested embedding buffers into the work week, TNC experimented with not scheduling anything on Fridays to better manage the variation and challenges that emerged during the work week (Daley 2022a).

Subsequently, Ballard and Howell (2003) described using sticky walls for what they then called "Pull Planning." At that time, "Pull Planning" referred to introducing pull into the planning process, especially for Phase Planning to determine the work sequence and key work handoffs between project milestones. According to Ballard (2019), "When we introduced Pull Planning as a new component in the Last Planner System, we used 'Phase Pull Planning' to emphasize that we were extending the territory where Last Planner was to be used, for the first time proposing to specify SHOULD, at least in part. The [next] Process Benchmark for the Last Planner System will extend that territory further, to take on Project Execution Planning" (Ballard et al. 2019) (Ballard and Tommelein 2021). Furthermore, Ballard (2019) "stopped using the term 'Phase Pull Plans' unless it refers specifically to phase scheduling since it long since became evident that the method is appropriate as the first step in any kind of planning because it reveals dependencies and clarifies CoS for making handoffs."

As project teams started using Post-it® sticky notes for Pull Planning, they found that they had difficulty keeping the sticky notes attached to the walls because of the rigors of Pull Planning – meeting attendees attached, removed, and then reattached sticky notes frequently as they considered different ways of managing work handoffs and structuring workflows (Tsao et al. 2004). When the 3M company introduced Post-it® Super Sticky notes in 2003 (Green 2007), the use of sticky walls with 3M repositionable spray adhesive fell out of favor as project teams became more capable of using 3M's Super Sticky Post-it® notes on walls to develop, refine, and preserve Pull Plans.

Even with the development of software options to assist with LPS implementation, the use of sticky notes on walls for Pull Planning remains a popular Lean implementation practice as they provide a tangible and accessible means for first-line planners/foremen in design and construction to interact "hands-on." Sticky notes allow project teams to quickly sort out options for organizing workflows through planning modules (aka "work zones" or "work locations") and clarifying the handoffs of work between specialties/trades. Furthermore, the tangible nature of sticky notes is an effective means

to help first-line planners/foremen develop ownership of the identified work tasks and subsequent work sequence. This is critical because it helps first-line planners/foremen develop better buy-in into the collaboratively developed work plan. Consequently, many project teams continue to use sticky notes on walls for the initial Pull Planning effort. Then, they may decide to transfer that information into LPS-based software for managing the refinement and implementation of the Pull Plans, especially if the project site does not have enough space to support wall-based Lean implementation.

Nevertheless, Pull Planning has emerged as a popular first step for many companies that begin to implement Lean on AEC projects (McGraw-Hill 2013). However, the McGraw-Hill report had a surprising finding – amongst the 193 survey respondents, 36% reported implementing Pull Planning while only 30% reported implementing the Last Planner® System (LPS). As a result, Lean instructors should help companies understand that Pull Planning is only one of five planning levels of the LPS, so the other levels (i.e., Milestone Planning, Make Ready Planning, Weekly Commitment Planning, and Daily Learning) can provide additional possibilities for value generation and waste reduction.

PULL PLAN TECHNIQUES, CONCEPTS, + TERMINOLOGY

Ballard (1997) and Ballard and Howell (2003) describe 'Phase Scheduling" as a component of the LPS and recommended Pull Planning as the method for developing phase schedules. When Greg and Glenn introduced Pull Planning to help project teams with structuring work to achieve a milestone as a part of Phase Planning, they called their efforts "Pull Planning" to reinforce the concept that customers should request work handoffs from suppliers to introduce "pull" into the planning process.

As project teams experimented with Pull Planning, Pull Planning etiquette started emerging as well. For example, Pull Planning etiquette and procedure suggests that meeting attendees only place their sticky notes on the wall when a customer invites them to do so. This is how "pull" is introduced into the planning process. Then, meeting facilitators may ask attendees to move only their own sticky notes and ask permission to move the sticky notes of others. This not only fosters a culture of respect amongst meeting attendees, it ensures that everyone is not only aware of but approves any sequencing changes to their work tasks. However, if there are meeting space or time constraints, facilitators can help the team move sticky notes to sort out proper sequencing if all attendees pay close attention and regularly make suggestions for improvement.

Planning backwards is a challenging process that forces meeting attendees to start at the end milestone and determine what work must be put into place to achieve it. This step helps "shake out the waste" that is deeply embedded in past work plans, and project teams start developing more customer-focused work plans that improve transparency of how work is handed off between companies to generate value for the end customer. After this initial "backwards-pass" in Pull Planning, project teams may conduct (Tsao et al. 2014):

- **"Forwards-passes"** to confirm the logic, add forgotten "value-adding" tasks, and add "required but non-value-adding" tasks.
- **"Tightening-passes"** to find opportunities for improving the overall duration between the start and end milestones through a combination of strategies, including (1) managing work in parallel, (2) reducing tasks durations by increasing crew sizes or decreasing the size of work zones, (3) introducing time or space buffers to improve workflow, (4) using prefabrication or modularity to

minimize on-site work in congested work zones by moving work to less-crowded work zones or off-site, and (5) takt planning (Frandson et al. 2013).

- Additional **"Backwards-passes"** to refocus the work plan and shake out additional waste from the work plan so it is more customer-focused and subsequently, more efficient at value generation.

Then, by managing a combination of these three types of "passes" during Pull Planning, project teams can improve the quality of the Pull Plan before starting work plan implementation (i.e., extracting and developing Make Ready Plans and Weekly Commitment Plans from the Phase Pull Plan, tracking their statuses, and refining the work plans when needed in response to changing on-site conditions and project circumstances).

It is critical to note – while it is preferred to start a Pull Planning meeting with a backwards-pass, sometimes project teams have difficulty doing so. When that happens, facilitators can start with a forwards-pass to get *some* planning started, but at one point, it is still helpful to double-check with a backwards-pass to ensure that team members have truly "pulled" the work tasks from the end milestone. Also, based on the difficulty of the work scope being planned, project teams may take anywhere from one to several meetings to complete the backwards-, forwards-, and tightening-passes. Then, while it is better to complete all three passes before starting implementation of the Pull Plan, many projects may not have the luxury to do so. In those circumstances, team members may decide to proceed with implementation with only one backwards- or forwards-pass complete.

Furthermore, as "[Pull Planning] is appropriate as the first step in any kind of planning" (Ballard 2019), project teams can use Pull Planning to manage different levels of the LPS, that is, project teams can "pull plan" the Milestone Plan, the Phase Plan, the Make Ready Plan (Tommelein and Ballard 1997), or even the Daily Plan, depending on project needs. For example, project teams may "pull plan":

- A Milestone Plan to establish the overall project execution strategy
- A Phase Plan to get from a "Weathertight" milestone to a "Ready for Rough Inspection" milestone 2-3 months later
- A Daily Work Plan in hourly detail to coordinate a single-day equipment shutdown process

Meanwhile, members of the Lean Construction community have given various names to collaborative planning between key milestones, including "Pull Planning," "Reverse Phase Scheduling," "Reverse Phase Planning," "Phase Scheduling," and "Phase Planning." Although "Phase Planning" can continue to be used to indicate collaborative planning sessions between key milestones and "Pull Planning" can represent the "backwards-pass" technique of collaborative planning at different levels of the LPS, LCI has been encouraging its members to use the term "Phase Pull Planning" to distinctly indicate "Pull Planning" at the "Phase Planning" level between key milestones. Doing so introduces consistency in language and improves the quality of Phase Pull Planning practice by making it easier for project teams to recognize, share with, learn with, and continuously improve with each other because they are aligned not only in Pull Planning techniques but concepts and terminology as well.

DEVELOPMENT OF THE PARADE OF TRADES®

By the early 1990s, Greg Howell had many simulations at hand as he worked with Tim Karpoff to facilitate partnering and leadership development sessions. Around the same

time, Greg and Glenn's solicitation to AEC companies for project data to test and improve the LPS framework started yielding results. Projects provided data on planning reliability, so Greg began searching for simulations to help explain the importance of plan reliability.

During a camping trip in New Mexico, Greg read *The Goal* (Goldratt and Cox 1984) and had difficulty understanding the description of the dice simulation that the main character, Alex Rogo, played at lunch during a hike with his son's boy scout troop. The next morning, Greg attempted to make sense of *The Goal's* simulation by working with his daughter Emily to make a spinner with a popsicle stick and using pine nuts on a picnic table. Through their efforts, Greg concluded that *The Goal's* simulation got him closer to a simulation that showed the impact of dependence and variation on group performance, but it was still not quite right and he continued to search for a better simulation.

Greg then started exploring ways to use dice by purchasing every kind of dice that he could buy (e.g., different-sided dice and different-numbered dice). At one point, he realized that the problem with the dice he purchased so far was that they all had different distributions that yielded different averages. Finally, while visiting an educational supply store with his wife Dana, Greg found blank dice and discovered that he wanted dice with different distributions but the same average. Then, a dice simulation could illustrate that dependence and variation really matters.

As mentioned earlier, Greg and Glenn played an early form of the Parade of Trades® simulation at the 1997 LCI meeting in Portland, Oregon. At that time, they used 100 chips, and the dice and chips moved in the same direction. Play lasted a long time due to the use of 100 chips and the scoring method. On acetate sheets, each trade tracked their rolls on the horizontal axis and the chips moved on the vertical axis. Then, after drawing a status line for each trade, they would line up the acetate sheets on an overhead projector and see how work was tied up by the gap in the lines. After improving the simulation through additional workshops, the Parade of Trades® became an effective simulation for use during LCI Introduction to Lean Construction workshops. At one point, a superintendent attendee suggested naming the simulation the "Parade of Trades" due to inspiration from the closing parade sequence at the end of the movie Animal House.

Meanwhile, Tommelein et al. (1999) explained how "the Parade Game illustrates the impact workflow variability has on the performance of construction trades and their successors." Then, by the early 2000s, Sven Bertelsen of LCI Denmark helped Greg realize that the dice were moving in the wrong direction – they needed to move in the opposite direction of the chips. This change enabled instructors to more closely simulate how construction work begins on AEC projects when using the Parade of Trades®.

After learning about the change of dice direction and inspired by Greg's initial attempts in LCI workshops to line up acetate sheets to illustrate the performance of the different trades as well as the charts included in Tommelein et al. (1999), Cynthia Tsao developed an Excel spreadsheet in 2005 that generated cumulative charts that illustrated trade productivity as students played during an undergraduate Lean Construction course (Tsao et al. 2012; Tsao et al. 2014). While it may be cumbersome to manage such a spreadsheet during practitioner trainings, utilizing such a spreadsheet during trainings in academia would help illustrate the impact of variation on continuous workflow.

By the early 2010s, after much searching, Greg finally found a manufacturer who was willing to custom fabricate dice with blue pips (containing 1,2,2,5,5,6), dice with red pips (containing 2,3,3,4,4,5), dice with green pips (containing 3,3,3,4,4,4), and dice with black pips (containing 1,2,3,4,5,6). However, it should be noted that the dice manufacturer was concerned about the intention of the use of these "loaded" dice. Nevertheless, this

innovation enabled Lean instructors to become more capable of preventing the discovery that the dice were different during play. However, if Lean learners discovered the dice difference during play, facilitators could congratulate the students in noticing the difference and encourage them to continue playing to minimize play distraction.

AIRPLANE GAME + PARADE OF TRADES® REFINEMENT

To eliminate the challenge of transporting heavy materials for the Airplane Game, Will Lichtig and Greg Howell adapted the "Make-a-Card" simulation "to demonstrate the advantages of Kanban and Pull over traditional Push and Batch" for LCI based on "The original manufacturing version of [the] simulation… developed by Mike Studley for ACT in England, and… modified by HP and Lockheed, by Kevin Meyer and John Vermillion at Abbott in Salt Lake" (LCI 2021). As Ballard (2019) noted, "The last straw for me was pulling a muscle in my back when I took Legos® for 60 people to play in Buenos Aires. We tried other approaches, for example, using only words, but they were not as effective [as Make-a-Card] because they lacked the 'moving material around' aspect."

Meanwhile, while the Visionary Products version of the Airplane Game featured four rounds of play (Visionary Products 2007), LCI found that three rounds of play were sufficient for providing key takeaways for project teams:

- **"Batch" Round 1** – players remained silent, built in batches of 5, set up workstations out of sequence, placed materials far from convenient reach of workstations, and allowed only the last workstation to work on quality control
- **"Pull" Round 2** – players remained silent, built with one-piece flow (to introduce pull into the system), organized workstations in sequence, placed materials within easy reach, and still only allowed the last workstation to work on quality control
- **"Balance" Round 3** – players communicated, built with one-piece flow, organized workstations in sequence, placed materials within easy reach, added quality control at any workstation, and balanced work between the workstations

In 2005, Cynthia Tsao introduced using different colored Legos® when facilitating the Airplane Game during instruction at the University of Cincinnati (Tsao et al. 2012). Shortly afterwards, she shared this improvement with Greg Howell while co-facilitating a training session at Baker Concrete Construction, Inc., headquarters in Monroe, Ohio.

Due to concerns from some Airplane Game facilitators and attendees that part of the productivity gains from Round 1 to Rounds 2 and 3 could be attributed more to a learning curve, Rybkowski et al. (2012) investigated this question and found that "[70% of] productivity improvements can primarily be attributed to the mechanistic benefits of lean principles themselves and less significantly to non-mechanistic phenomena."

In March 2020, the Covid-19 pandemic introduced a new challenge to the Lean community – how do we continue training to support project implementation while keeping attendees safe? As a result, Lean instructors started exploring how to facilitate typical Lean training workshops within a virtual environment. Future research can help document the development and improvement of these virtual simulations and their effectiveness in Lean learning. However, two simulations in particular have emerged to support the lessons typically provided by the Airplane Game and Parade of Trades® in-person simulations – "Batch, Pull, and Balance" and "The Online Parade of Trades®."

As one of the leading AGC Lean Construction certification instructors, Colin Milberg of ASKM & Associates initiated the development of these virtual trainings and tested them in Administering and Playing Lean Simulations On-Line (APLSO) virtual meetings

hosted by Texas A&M (Rybkowski et al. 2021). Then, after adding cumulative production charts to improve "The Online Parade of Trades®," Cynthia Tsao initiated and coordinated the decision at the end of 2020 to share these virtual simulations with others for free through a Creative Commons Usage Agreement in exchange for improvement feedback and facilitation data (*ibid*). As a result of this decision, for example, over 70 instructors from 10 countries have downloaded a copy of "The Online Parade of Trades®."

FUTURE RESEARCH AND CONCLUSIONS

Future research could explore: (1) the perspective of the pre-Lean period for other researchers who have contributed to the IGLC and LCI communities, (2) the development, adoption, or customization of other key simulations that help with Lean learning [e.g., Silent Squares (LCI 2022), DPR Pull Planning Game (DPR 2022), and Villego® (BOB bv et al. 2012)], and (3) the appropriate timing and usage of various simulations for Lean learning based on project phases, project team moods, etc. (Tsao and Alves 2021).

This paper provided insight into the motivations and drivers that inspired early Lean Construction community members to develop better methods for training Lean learners on how to start thinking and behaving differently to achieve better AEC project outcomes. Documenting the evolution of simulations usage in Lean learning helps all instructors work within a better foundation and theoretical framework as they facilitate and improve the training workshops that support Lean learning and project implementation.

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