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TOWARDS MULTI-PROJECT SIMULATION OF A LEAN PRODUCTION SYSTEM FOR CUSTOMIZED APARTMENT BUILDINGS

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ABSTRACT

In typical construction projects, general contractors devote significant resources to coordinate the work of multiple subcontractors. Subcontractors and general contractors interests are frequently misaligned, and they strive for local optima. In particular, subcontractors balance the demands of different projects as they search to deploy their resources most productively. The problems are exacerbated where customization, such as tailoring of apartments by clients, disrupts workflow. Separation of standard (structure, public spaces) from customized work (apartment interiors) may drastically improve the production system. Separation represents a fundamental change to industry practice. Evaluating separation requires experimentation on a multi-project scale; agent-based simulation is the only practical research method. Simulations of single project systems showed that Lean interventions improve productivity, cash flow and project duration. Recent work with agent-based simulation with two projects and eight subcontractors has shown that the standard/customized work separation provides additional advantages. Future work will extend the simulations to multiple projects.

1 INTRODUCTION

Production systems for customized housing have long been recognized as inefficient (Sacks and Goldin 2007), which means that outcomes for all parties involved (customers, contractors, suppliers) are less than optimal. The symptoms of the problem can be seen in what the Lean Management school of thought calls wastes (Womack and Jones 2003): waiting, rework, wrong information, no sustained learning or improvement, instability of work, of the wrong products supplied to customers.

The causes of these problems include poor flow (including out-of-sequence information flows relating to which customizations are needed in which apartments), misaligned work packages (in terms of work volume) and production rates (of the different subcontractors employed). Various solutions have been proposed to solve these problems. Among them: reduced batch sizes, pull production control, and production "cells" consisting of multi-skilled teams (Sacks and Goldin 2007); and splitting the production system to build the public parts of a building and the private customized elements separately (Korb and Sacks 2016). While the former can be applied to individual projects, the latter must be implemented on an industry-wide scale.

Given the major economic implications and organizational changes that these ideas would require in practice, simulation is an ideal tool for research of their consequences. Simulation – using live games, Discrete Event Simulation (DES), or Agent-Based Modeling (ABM) – can test the concepts in an analog to the real world, both at the level of a single project and at a multi-project level (Angelidis et al. 2013; Ash 1999; Knoblich et al. 2011), where sub-simulations of individual projects interact with others. There is a rich history of employing simulation as an aid in construction management research (Hammad et al. 2012;

Martinez 1996), and in particular in Lean Construction research (Tommelein et al. 1999).

In this paper we describe a series of simulations of single and multi-project systems carried out to test the efficacy of the proposed Lean interventions for the case of the production systems of multi-story residential building projects. The series included live games, DES and ABM simulations. The most recent used ABM to model a scenario with two projects and eight subcontractors, illustrating that the standard/customized work separation provides additional advantages beyond the basic Lean work flow interventions. Future work will extend the simulations to multiple projects.

2 BACKGROUND

2.1 Lean Construction and Multi-Customer Construction Projects

Lean Construction (Ballard 2000; Koskela 2000; Sacks et al. 2018) is an approach to construction management that draws heavily on the work of Toyota, where the "Lean Management" approach was developed (Liker 2004; Womack et al. 2007; Womack and Jones 2003). Lean takes a process-based approach to organizing the "value streams" within a company where value is created for the end customer, asking at each point in the process whether activities add value to the product or do not; if not, they are declared "waste", and steps are taken to improve the process in order to reduce the resources expended on wasteful activities.

For the case of multi-customer construction projects (such as multi-story apartment building), where information about customer requests for customization of their product arrive at unpredictable times, the subcontracting paradigm that reigns supreme in the construction industry (Korb and Ballard 2018) means that each subcontractor works at different rates and finishes at different times, introducing waiting and instability. Sacks and Goldin (2007) proposed a Lean Construction model with three innovations for this scenario:

- Shrink the batch size of work packages that are released to subcontractors: instead of an entire floor, work on apartments one at a time. In this way consecutive subcontractors can begin work sooner than is the case where they wait for an entire floor to be finished. By Little's Law (Hopp and Spearman 2011), reducing batch size should reduce overall project duration.
- Work in "Pull" instead of "Push". If each work station (subcontractor team) is told to work as fast as possible and process as much product as possible, that is called Push. If instead each work station works only in response to a clear signal from the next process downstream that requests more material to work on, that is called Pull. In the case of a multi-customer project, Pull means waiting until the customer has made all apartment customization decisions and all materials have arrived before beginning work. This should reduce the amount of work in progress and rework, while increasing customer satisfaction.
- Use multi-skilled crews instead of specialized trades. This is akin to the Lean concept of cell production, in which process steps are grouped together to reduce waiting time for the products and unnecessary movement and storage, all forms of waste (Black and Hunter 2003). This is intended to increase the utilization of workers, since it balances the pace of work. Reducing the number of handovers from team to team should also reduce the opportunities for problems and delays to arise.

More recently, Korb and Sacks (2016) have revisited the question of multi-story apartment buildings with multiple customers. Taking a product-process alignment approach, they distinguish those elements of the product which are not subject to customization (and thus have no variation) from those that are (mainly the interior finishing elements of the individual apartments). The hypothesis in this work was that if the two sub-products could be split into distinct production systems, each system could be tailored to the degree of variation and other production characteristics, thus reducing waste and improving the project performance. Taking it a step further, the two sub-products could be constructed by completely different firms rather than the prevalent monolithic general contractor model. This is similar to what is currently done in multi-tenant office buildings. In both residential and office buildings, the shared and private spaces are separate, but in the former, a monolithic production system is typically used to construct them (the same subcontractors perform work on both the shared and private).

The main research question is whether splitting one project into two results in production system performance that is economically justifiable. One of the key features in this approach is the decoupling of subcontractor teams from specific projects, in which case they could be assigned to or service multiple projects in a given geographic area as demand and prerequisite completion required. Thus to research the questions comprehensively, the scope of focus must zoom out from a single project to encompass an entire local construction market.

2.2 Leapcon 1.0

In order to test the hypotheses of Sacks and Goldin (2007), a live simulation of an appropriate construction project was developed (LEAPCON 2015; Sacks et al. 2007). The game, called Leapcon, has been used for educational purposes around the world (71 universities and 41 companies in 37 countries). Each participant plays one of the predefined roles: project manager, subcontractor crews, representatives of the customer, etc.. The goal is to complete the interior finishing works of 32 "apartments", each represented by a model made of Lego bricks and tiles (shown in Figure 1), arranged four to a floor on eight floors.

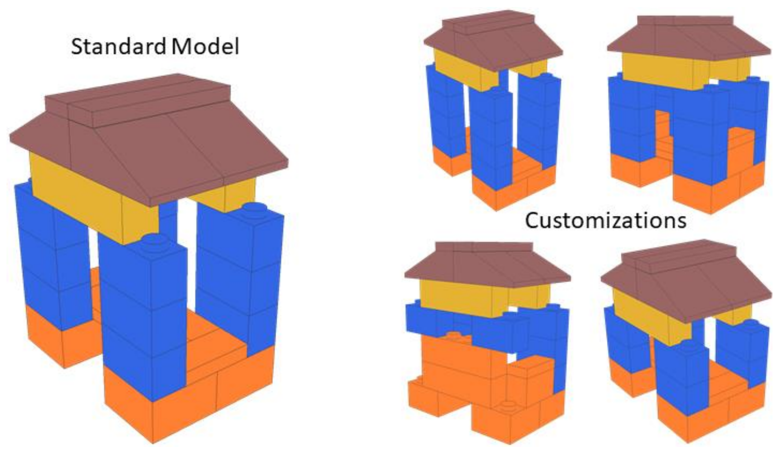

Figure 1: The Lego models used in the original LEAPCON game. Each of the four successive trades (flooring, partitions, HVAC, and plaster ceiling) are shown as different colors (orange, blue, yellow, brown, respectively). On the left, the standard model; on the right, some of the customizations the customer could choose.

The game was played twice in each session: a "traditional" round where the work is assigned to specialty subcontractors crews, who all push work, with a project manager directing the work. Only one sub is allowed to work in a given floor at a time. In the second "Lean" round, changes are made as follows:

- Batch size is reduced from a full floor to a single apartment. Effectively, this meant that there was no restriction on multiple crews working on the same floor simultaneously.
- Instead of building standard apartments in push, the crews only began work once the customization instructions arrive ("pull"), regardless of the sequence of change arrivals.
- Instead of specialization by trade, each crew was multi-skilled and could build the entire apartment.

The changes did indeed lead to improvements: reduced Work in Progress (WIP – number of apartments under construction at any one time), better cash flow, reduced lead time for the project, better customer satisfaction, increased throughput, better quality, reduced rework, better worker utilization. However, the live game was limited in that it required many people-hours just to do one full iteration; sessions averaged two hours and required at least 10 participants. It was difficult to generate dense data from which trends could be observed, nor was it feasible to test the effects of each of the three improvement separately. Thus a DES was created in Stroboscope (an excerpt appears in Figure 2). Over thousands of runs, generalized WIP and cash flow curves were obtained, for each of the different combinations of improvements (i.e. comparing the relative impacts of multiskilling alone versus shrinking the batch size alone) (Esquenazi 2006; Esquenazi and Sacks 2006; Sacks et al. 2007). An agent-based version of the same scenario was also compiled, using StarLogo TNG (Ben-Alon and Sacks 2015, 2017) (Figure 3 shows the graphical output of the simulation and a snippet of the "graphical programming" code used to drive the simulation). The results of both computer simulations correlated well with one another and confirmed the efficacy of the production system improvements suggested by the live simulation results.

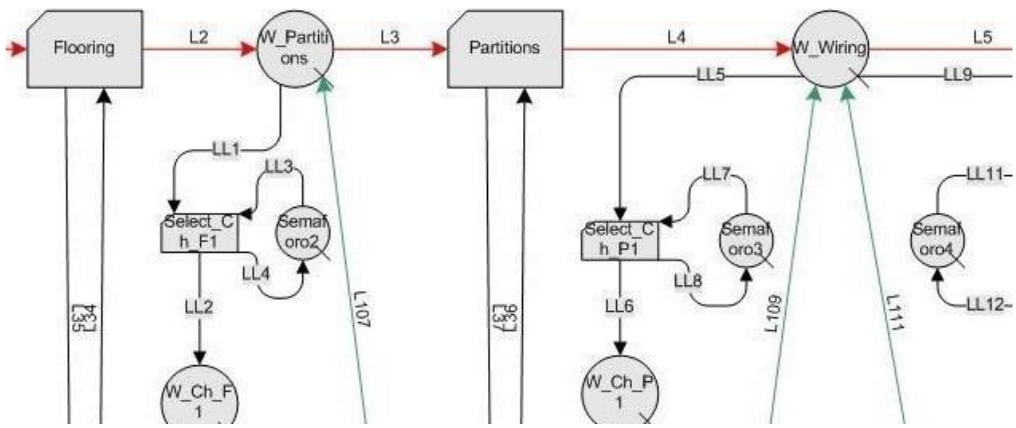

Figure 2: Excerpt from the DES simulation created by Esquenazi (2006) in Stroboscope, showing the main tasks in constructing the apartments (the four trades) across the top row.

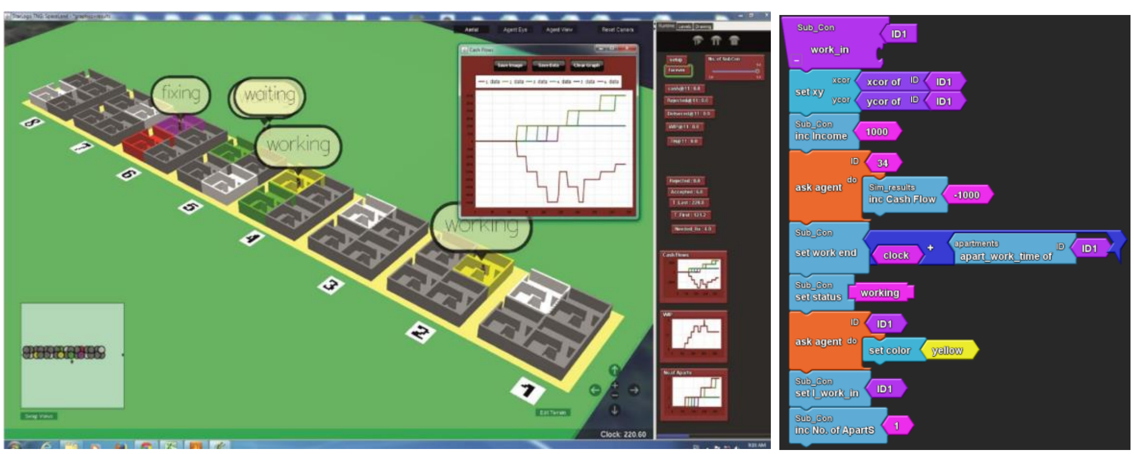

Figure 3: Left: the Starlogo TNG "Spaceworld" version of Leapcon 1.0 created by Ben-Alon (2015), showing the eight floors with four apartments each. Apartments are color-coded by status. Right: Excerpt of Starlogo TNG code block of the model, showing the graphical-programming approach.

3 RESEARCH METHOD FOR LEAPCON 2.0

Given the need for large-scale industry change implied by Korb and Sacks (2016) proposal to split the production system of multi-customer building projects according to shared and private spaces, the intervention cannot be experimented with directly. There is no feasible way to bring large arrays of commercial companies to make the sorts of radical changes necessary to test the research hypothesis. Thus simulation is a natural choice for in-depth study of the industry scenario. Other benefits include the ability to perform multiple experiments within the simulated scenario and compare them for internal validation.

The strategy selected was to begin with a live simulation, using experimental subjects as participants, to explore the parameters of the problem, to develop the mechanics of the scenario and to gather data. Once the scenario was stable, a computerized version was implemented to generate dense data sets and to test different combinations of elements of the proposed improvements.

Leapcon 1.0 was simulated in both DES and ABM. However, ABM alone was used for modelling Leapcon 2.0, since construction crews, customers and project managers function as agents, thus making compilation of the simulation intuitive and straightforward. One of the strengths of ABM is the ability to observe emergent behavior of the system, where the agent-level instructions alone have been defined, and this is exactly what the researchers hoped to do. In addition, since a need was foreseen to scale up to a multi-project environment and to include different classes of subcontractors, each with local starting parameters but similar behavioral modes (i.e. maximize productivity), the ABM approach was clearly a logical choice, since it is well-suited to those requirements.

The researchers preferred a simulation software tool with text coding rather than drag-and-drop visual programming. In terms of the eventual goal to move to a multi-project setting, text-based code would allow expansion (including to new use cases) more easily than graphical programming. Netlogo, billed as having a "low threshold [to entry], [but also] no ceiling" to limit its users (Wilensky and Rand 2015), was selected.

4 LEAPCON 2.0 SIMULATION SCENARIO

The Leapcon 2.0 simulation was developed to test the concepts proposed by Korb and Sacks (2016). One of the key concepts was separating the shared elements of the product from the private ones that can be customized. The shared elements of each floor of a typical multi-story building, which are not customizable, were modeled by adding model elements to represent a floor lobby to four instances of the individual apartment models used in Leapcon 1.0. These shared elements - a base plate and bricks and tiles to model flooring and mechanical, electrical and plumbing system mains - connected the four separate apartment models on each floor, as shown in Figure 4. The base plates represented the structure of each floor. The flow of the project was regulated by releasing a base plate to the interior finishing crews at periodic time intervals, representing gradual progress of the structural works.

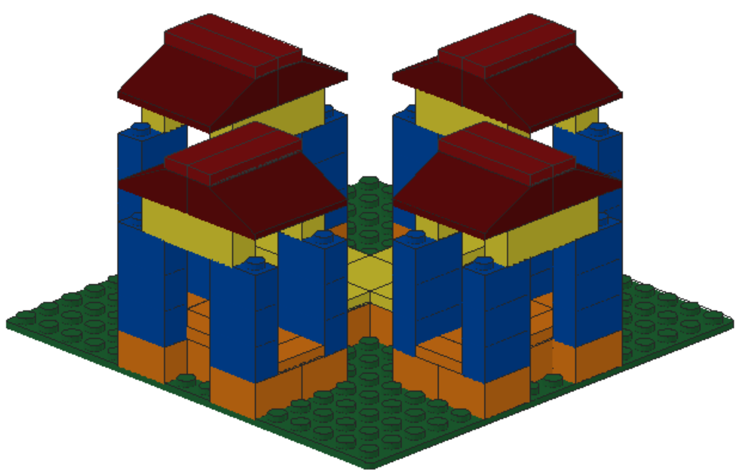

Figure 4: A standard floor model for Leapcon 2.0, with four customizable apartments.

The second major difference that distinguishes Leapcon 2.0 from the earlier scenario requires simulation of a multi-project framework. As a first step in this direction, instead of one building of eight floors, Leapcon 2.0 models two buildings of four floors each. In the live simulation, the start of the second building was delayed by three minutes from the start of the first, to offset the two. Each building featured a project manager and four subcontractor crews, in addition to the client representatives. In the second round of the simulation, the Lean improvements made in Leapcon 1.0 were applied, but furthermore, the teams of four subcontractor crews were split: Two of the crews from each building are designated "shared" crews, in charge of building those elements of the model that aren't subject to customization – most of the flooring, some of the interior partition walls that face the "lobby", and the building system mains that connect between the lobby and the apartments themselves. The other two crews from each building now function as multi-skilled "private" crews, joining with their peers from the other building to form a pool of four crews who can respond in either project whenever and wherever customization orders come in.

Another change that was made in Leapcon 2.0 was the mix of customizations. Leapcon 1.0 featured eight different "options packages" that were assigned at random to each apartment. In the new simulation, an attempt was made to match reality more closely in terms of the distribution of customizations observed in construction projects. A set of customizations with a distribution similar to that gleaned from a set of 65,000 customization orders collected on a major residential project development (Korb and Sacks 2016), was prepared. Figure 5 shows a histogram of the customization types, distributed according to the number of design changes per apartment in each type: some small amount of apartments have no changes at all from the standard, some have changes in all four design parameters (from the original Leapcon 1.0 options packages), and others have from one to three changes. The timing and sequence of delivery of design changes was also adjusted: instead of Leapcon 1.0's linear rate (one change every 15 seconds), a normal distribution was adopted, with greater rate of deliveries in the middle of the simulation. Finally, instead of random sequencing (as was the case in Leapcon 1.0), now the deliveries correlate approximately with the sequence in which the floors were built. This reflects the fact that the customer service departments of typical general contractors do attempt to pressure on customers on lower floors to make up their minds earlier to conform to the progress of construction. Nevertheless, a degree of randomness was retained in the sequence and timings.

Figure 5: Histogram of number of changes per apartment in Leapcon 2.0.

5 LEAPCON 2.0 ABM IMPLEMENTATION

The strategy for compiling the ABM simulation had three phases, described in the following sections:

1. Implement a Netlogo version of Leapcon 1.0 and validate it against the existing results (of the live, DES and ABM simulations).
2. Create an ABM in Netlogo of the Leapcon 2.0 live game, on the basis of the Leapcon 1.0 Netlogo model, with two buildings under construction instead of one.
3. Develop a multi-project environment for simulation of the interactions of general contractors and subcontractors in a broad industry market environment across many projects. This step has not yet been implemented and is the subject of ongoing work.

5.1 Validation of Leapcon 1.0 Results

The first step was to rebuild Leapcon 1.0 in Netlogo. This was done because reliable, internally valid results exist from the works of Esquenazi (2006) and Ben-Alon (2015), allowing validation of the tool while building familiarity and skill on the part of the researchers with the tool and with the model.

A breed of agents called "subs" was created, while some of the "patches" (set areas on the surface of the "world" of the simulation) were used as the apartments to be constructed. Patches lent themselves well to model apartments, since apartments are immobile, and the functionality of Netlogo allows agents (subs, in this case) to interact with the parameters of the patches they occupy at any given time step. The setup for the simulation world (i.e. after running all the simulation commands but before begging the clock on the project and the work) appears on the left side of Figure 6. The four subs, labelled 1 to 4, appear on the bottom row in their waiting positions. The building floors (stories) are labeled S1 to S8, running up the Y axis. The apartments, whose status is green at the start (indicating that they are ready to accept subs), are numbered 1 to 32, with four apartments on each floor. In the image on the right side of Figure 6, the simulation has begun, and is about midway to completion. As subs complete a given apartment, the color of that apartment turns to their color. Apartments that have received an options package (labeled A to H) display that letter next to their apartment number. A late-arriving change may require back-tracking on the part of the subs to fix an apartment, as is the case in apartment 9.

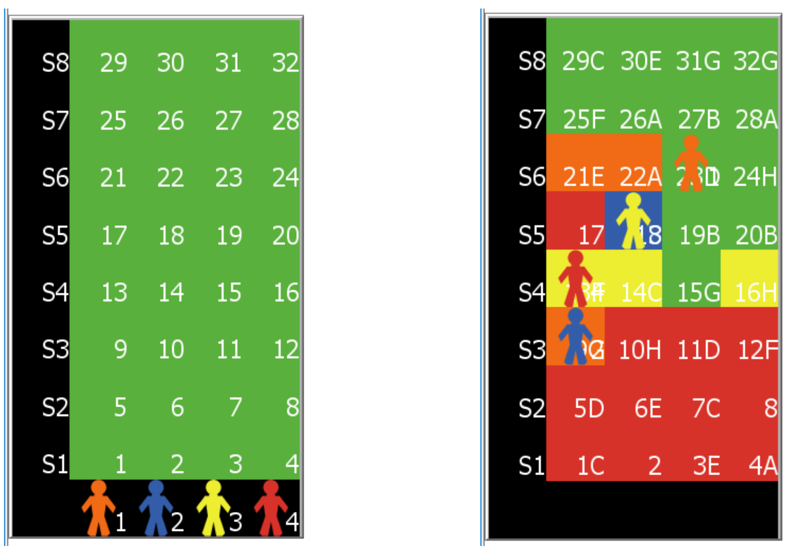

Figure 6: Left: The "world" of Leapcon 1.0 as shown in Netlogo, after running the setup commands but before beginning the simulation run. Right: The same, but midway through a typical simulation run.

Some of the results that the simulation creates are shown in Figure 7: a Line of Balance (LoB) chart, which is a graphical form of displaying which work (colored lines) is done in which location (Y axis) at what time (X axis) over the life cycle of the project. The colors of the lines are the same as the colors of the respective subs. The time of delivery of the change order information for each apartment appears as a purple dot on each apartment's respective row. On the left is the traditional round, and on the right is the Lean round.

To implement each of the three improvements from traditional to Lean, the simulation employed three "switches" on its interface which could be activated in different combinations. In the second LoB chart, subs retain their coloration, but each one is now a multi-skilled team. As change orders arrive, a sub goes to the apartment and does all the work there fully to completion. The order of work follows the order of the information delivery.

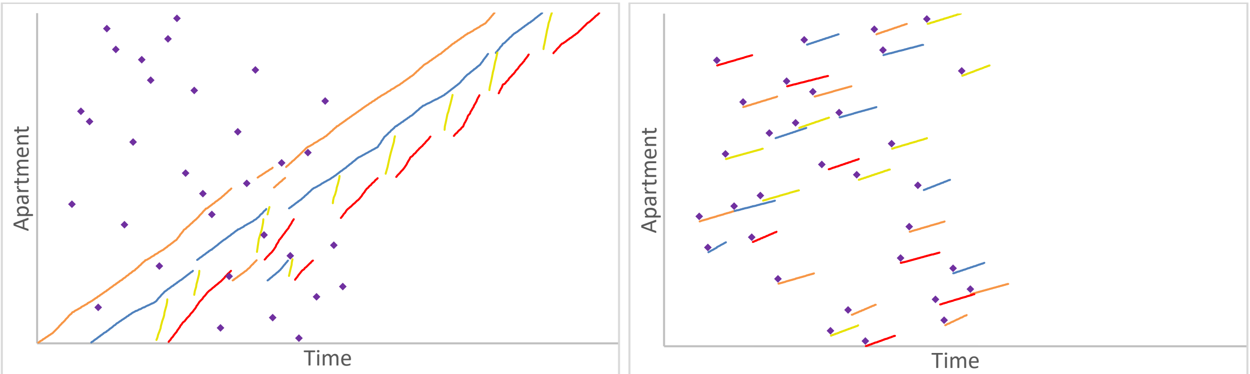

Figure 7: LoB charts from the Leapcon 1.0 simulation in Netlogo. Left: traditional. Right: Lean.

After the simulation was built, the BehaviorSpace extension in Netlogo was used to run one thousand repetitions of each of the eight combinations of improvement scenarios to generate more dense data and typical trend lines. One of the graphs, for the WIP of all eight scenarios, is shown in Figure 8. These results were found to be in accordance with the results generated by Esquenazi (2006), thus validating the model and the Netlogo tool.

Figure 8: Average WIP for 1,000 simulation runs of all eight combinations of improvements.

5.2 The Leapcon 2.0 ABM System in Netlogo

The changes to the computerized model (i.e. from scenario 1.0 to scenario 2.0) were the same as those made to the live game:

- The eight-story building was split into two four-story buildings.
- The workforce was doubled from one set of four subcontractors and a project manager to two sets, each one in charge of one of the two buildings.
- The information delivery sequence was the same as that from the live game, no longer random as it was in Leapcon 1.0.

- An additional switch was added for the "Shared/Private Split" improvement. If this switch is activated, four of the subs are "shared" subs in charge of building the common elements on each floor, while the other four become a pool of "private" subs who can go from building to building as necessary to build the private works in the apartments in the sequence that the change orders arrive.
- Completion of the "structure" was a precondition to being able to begin work on any given floor.

Figure 9 shows the Netlogo world for Leapcon 2.0. On the left, the two sets of subs can be seen, and the names of the floors: A1-A4 for building A and B1-B4 for building B. The right side is a screen shot during the simulation run. All structural bases have been delivered except B4, which is still black, meaning the floor is not ready for work. Subs 1 to 4 work on building A and subs 4-8 on Building B. As changes come in, they reset the relevant apartment to green, which is why so many of floors A1 and A2 are still green despite Sub 1 already having worked on floor A3.

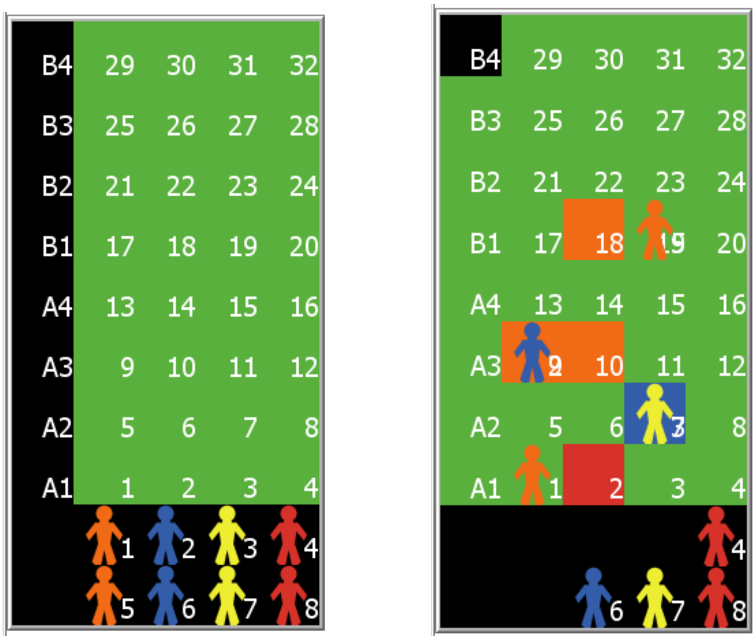

Figure 9: Leapcon 2.0 (traditional round) in Netlogo. After setup (left) and during the run (right).

5.3 Leapcon 2.0 Simulation Results

The live version of Leapcon 2.0 was played a number of times with live participants. The sessions were video-recorded, enabling the researchers to measure the amount of time each participant spent in each location, and thus create a LoB chart for both the traditional and Lean rounds. An example of the charts from one simulation, showing the improvements to project performance, can be seen in Figure 10. In the figure, the dotted lines represent "rework" where a sub was forced to return to a floor to fix something, either due to information arriving or defects that were discovered. In parallel, the ABM simulation was used to create LoB charts for the traditional and Lean rounds; these appear in Figure 11. Note the similarity to the results from the live version.

Leapcon 2.0 has shown that when the shared and private sub-projects are split, the building's structural frame and the building systems and finishes in the common areas are complete sooner and more smoothly, while the product cycle times perceived by customers (the time from delivering their customization requests to receiving their finished apartments) are significantly reduced. Subcontractors see their productivity rising since they wait less for preceding work to be completed and have matured work packages. General contractors almost entirely eliminate the demolition and rework that ensues that otherwise result from pushing forward on standard apartments.

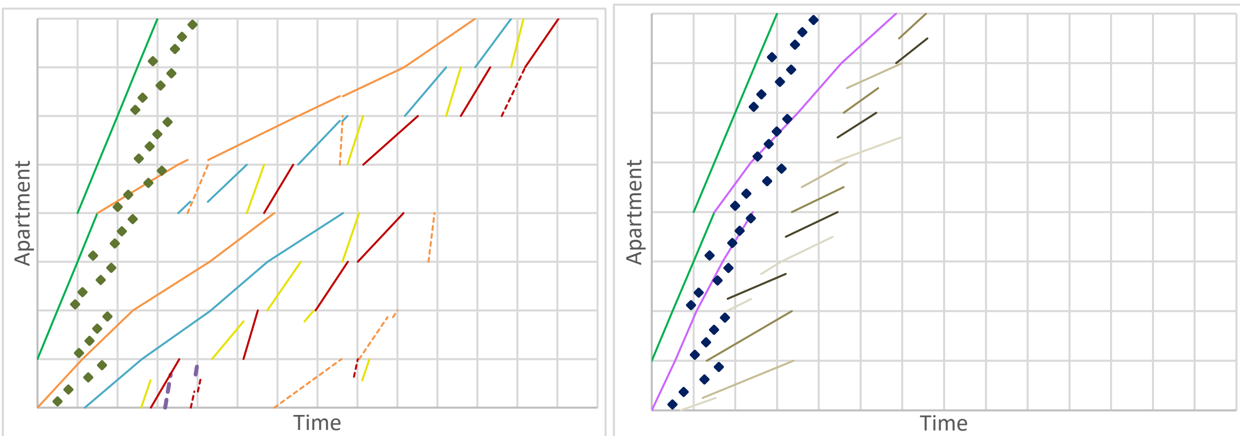

Figure 10: LoB chart of one of the live simulations of Leapcon 2.0. On the left, the first "traditional" round; on the right, the "Lean" round, where the shared and private works have been separated.

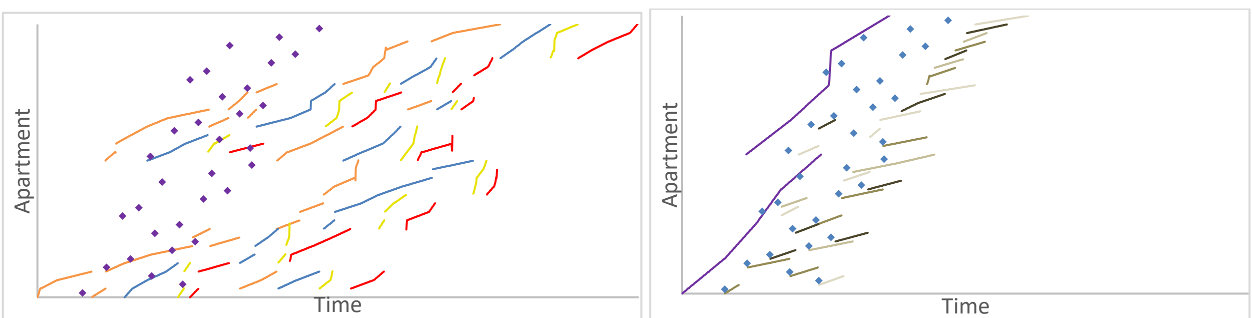

Figure 11: LoB charts for the traditional and Lean rounds of Leapcon 2.0 from the Netlogo version.

6 MULTI-PROJECT SIMULATION

The next steps of the research require expanding the ABM to an arbitrary number of projects, with many more subcontractors. Expanding the model will require implementing algorithms for each subcontractor to make resource allocation decisions (to select to which projects to assign crews in any given work period), using elements of the game theory model of subcontractor resource allocation behavior (Sacks and Harel 2006). ABM is well-suited to this task since the programming is done at the level and through the eyes of the subcontractor. Once the researchers identify the decisions they need to make, and how they arrive at a conclusion, the agents in the model can be instructed accordingly.

This multi-project approach has great promise for predicting the dynamics of real-world scenarios, since in the real world, subcontractor behavior is not only guided by the specifics of one project but the totality of the projects they work with, which has been called the "portfolio view" of work flow in construction (Korb et al. 2017; Sacks 2016). The simulations should allow examination of the system behavior under different conditions, such as under- or over-supply of work, scarcity/abundance of the different subcontractor crew types, degrees of apartment customization, project sizes and size distributions, including the effects of dynamic changes to these parameters. The simulation should be configurable to simulate actual local industry sectors.

7 DISCUSSION AND CONCLUSIONS

This paper discussed the use of ABM to simulate the impacts of Lean Construction improvements in various build scenarios. The sequence of simulations – Leapcon 1.0 in live, DES and ABM versions, Leapcon 2.0 in live and ABM versions – are important steps in working towards a full multi-project simulation to examine the dynamics of system and subcontractor behavior across multiple projects. The underlying motivating question is "How can changes to the business and logistic industry structures influence the outcomes for all involved – general contractors, subcontractors, clients and others – across multiple projects?" Both Leapcon 1.0 and 2.0 have shown that the implementation of improvements based on Lean Construction principles cuts delivery times while consuming fewer resources, which means lower costs for producers, less waiting time for customers, and fewer headaches for managers.

As with any simulation approach, there can be difficulties implementing the findings in the field. While it is relatively easy to instruct human participants in a live simulation, or to program agents in an ABM, to perform multi-skilled cell production, in the field it is more difficult to reconfigure trade crews and to reconstruct entrenched work practices. General contractors will have no less a challenge, since instead of dividing the work into trade-specific work packages and bidding out each one (usually at lowest cost), in the proposed paradigm they need to structure the product and work flow quite differently. Therefore, only by extending the simulation to cover multiple projects across an entire industry sector, can we test the hypothesis that the proposed interventions will have a positive impact across a local construction market. This is the next step in the sequence of simulations.

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