Rybkowski, Zofia; Zhou, Xun; Lavy, Sarel; and Fernandez-Solis, Jose (2012) Investigation into the nature of productivity gains observed during the Airplane Game lean simulation. *Lean Construction Journal* 2012 pp 78-90
www.leanconstructionjournal.org

Investigation into the nature of productivity gains observed during the Airplane Game lean simulation

Zofia K. Rybkowski[1], Xun Zhou[2], Sarel Lavy[3], Jose Fernández-Solís [4]

Abstract

Research Question: What is the nature of productivity gains observed during live playing of the lean simulation, the "airplane game"?

Purpose: The purpose of this research is to investigate and identify the nature of productivity gains observed during live playing of the lean simulation, the airplane game. The intent is two-fold: (1) to identify the specific mechanistic impact of each lean principle, as it is successively introduced; and (2) to identify the productivity contributions of non-mechanistic phenomena such as learning curve and/or Hawthorne Effect. The game serves as a proxy for controlled experimentation in the field—experimentation that is difficult to conduct on actual construction projects but that is important when making claims regarding generalizability of results.

Research Method: To identify the specific mechanistic impact of each lean principle, researchers used Microsoft Excel to graphically map the airplane simulation, station-by-station and second-by-second. Metrics such as time to first batch, number of successful planes and work-in-process were derived from the Excel graphic and evaluated after each round to understand the specific impact of each successively-introduced lean principle. To identify the specific impact of non-mechanistic processes on productivity (such as learning curve and Hawthorne effect), researchers compared average results from live playings against results derived from the Excel graphic.

Findings: Comparison of results obtained from the Excel graphic demonstrate the following: (1) reducing batch sizes primarily results in reduced time to first batch; transitioning from a push to pull system primarily results in reduction of work-in-process; and transitioning from an uneven loading of work to a work-leveled system primarily results in an increased amount of final product; and (2) the contribution of productivity gains from non-mechanistic phenomena such as learning curve and/or Hawthorne effect is relatively minor (i.e. approximately 70% of productivity gains in

[1] *Primary Contact:* Assistant Professor, Department of Construction Science, Texas A&M University, College Station, TX, U.S.A., zrybkowski@tamu.edu
[2] Graduate Student, Department of Construction Science, Texas A&M University, College Station, TX, U.S.A.
[3] Assistant Professor, Department of Construction Science, Texas A&M University, College Station, TX, U.S.A.
[4] Assistant Professor, Department of Construction Science, Texas A&M University, College Station, TX, U.S.A.

time to first batch can be attributable to the mechanistic benefits from the four tested lean principles; 30% can be attributed to non-mechanistic phenomena).

Limitations: We chose a deterministic model to enhance clarity. However, a stochastic simulation would have better represented time distributions observed in reality.

Implications: Our results are intended to help lean researchers and participants understand the nature of productivity gains observed during live playing of the lean simulation, the "airplane game." They are also intended to give lean practitioners the assurance that, if performed correctly, introduction of lean principles on a construction project will produce productivity gains.

Value for practitioners: This paper is intended to address some common concerns from players and to help inform those who administer the game.

Keywords: lean principles, skepticism, airplane game, simulation, eureka moment, learning curve, Hawthorne Effect, controlled experimentation

Paper type: Full Paper

Background

This research investigates outcome metrics from a simulation exercise frequently used to illustrate the benefits of lean interventions. The purpose of this research is to: (1) identify the mechanistic impact of each individual lean intervention as each intervention is successively introduced, and (2) to understand the potential impact of non-mechanistic phenomena such as learning curve and/or Hawthorne effects that can sometimes influence results during live simulation experimentations.

The reason we are focusing on the specifics of a lean simulation exercise is that, for case study results to be considered generalizable on a grand scale, they must be supported by results from properly controlled experimentation. Controlled experimentation can be difficult to orchestrate on actual construction sites because it requires the availability of large numbers of identical buildings, as well as the removal of confounding variables that may otherwise invalidate the results. One benefit of the airplane game is that it introduces lean interventions one-by-one during each successive round of play, enabling participants to understand the impact of each individual lean intervention. Those who may question the generalizability of benefits observed during individual case studies may derive assurance from lean simulations. In a sense, these simulations serve as proxy for controlled experimentation in lean construction.

Visionary Products, Inc.™ developed a lean simulation exercise called "Lean Zone Production Methodologies" (Visionary Products Inc. 2007; 2008). The lean construction community uses the simulation exercise to introduce lean production principles to new participants (Rybkowski et al. 2008). Because participants assemble a Lego™ airplane, the Lean Construction community refers to the simulation as "the airplane game."

Understanding outcome metrics from the airplane game is important because the game is often used to introduce OAEC (Owner, Architecture, Engineering, and Construction) stakeholders to fundamental lean construction principles (Ballard 2000a; Ballard 2000b; Ballard 2008; Bertelsen 2002; Koskela 1992; Koskela 2000; Salem et al. 2006) and to convince same stakeholders of the benefits of lean interventions.

Through informal polling, it is the authors' impression that lean simulations or games serve to deliver a "eureka moment" (Lee 2002) to participants, convincing them of the validity of the claims made by the lean construction community in a way that traditional PowerPoint presentations sometimes fail to do. We assume that lean games are relatively effective because they are used by consultants almost without exception wherever lean principles are being taught (Verma 2003).

Both the lean production and lean construction communities have long recognized the need to rigorously demonstrate the impact of lean principles. In 2000, Detty and Yingling used computer simulation to illustrate that lean principles need not be accepted by "faith" (p. 430) alone. In *The Goal*, Goldratt (1986) described an improvised game played by boy scouts in order to illustrate how reducing variability enhances rate and minimizes unwanted inventory, thereby improving productivity. Lean construction pioneer, Greg Howell, translated Goldratt's game into a workshop version—called the *Parade of Trades*—for the construction industry (Howell 1998; Tommelein et al. 1999). Tommelein et al. (1999), and Choo and Tommelein (1999) represented the *Parade of Trades* game using computer simulation. Alarcón and Ashley (1999) extended understanding of the game to better ascertain cost effectiveness strategies. Sacks et al. (2005; 2007; 2009) developed an alternative Lean simulation exercise called LEAPCON. Verma (2003) published a collection of lean games.

The airplane game, as with other lean games, is intended to demonstrate the potential impact of each lean intervention on process outcomes. The specific lean interventions demonstrated are described in recognized, pivotal readings of the lean community (Liker 2000; Ohno 1998; Womack and Jones 2003). Lean interventions must be introduced in a specific order (e.g. workstations are arranged sequentially before pull is introduced), the importance of which is discussed in Black and Hunter (2003). As lean interventions are successively added during each round of play (e.g. cellular arrangement, reduced batch sizes, pull versus push, etc.), metrics are collected, and improvements consistently noted.

During the airplane game, individuals work in teams to assemble a simple Lego™ airplane and successively introduce lean principles to their work process during each round of play. Despite clear improvements in terms of increased number of successful planes, reduced time to first plane, and reduced WIP (work-in-process), it is the authors' experience that some audience participants still remain skeptical after playing the game. Some participants argue the benefits may be due, in part or instead, to the natural progressive improvement participants make along a learning curve[5] (Bills 1934; Ebbinghaus 1913; Wozniak 1999) whenever tasks lend themselves to improvement from repetitive practice. Other participants argue the observed improvements may also be due to the Hawthorne Effect[6] (Champoux 2003, Frank 1978; Mayo 1993; Newstrom and Davis 2002;

[5] Learning Curve is a graphic depiction of rate of learning. The slope of the curve is steepest in the earliest stages of repetition of a task and flattens with time. Learning Curve or Experience Curve, may enhance a firm's productivity (Wright 1936; BCG 1969; Yeh and Rubin 2010). However, as this research focuses on simply identifying the contributory nature of productivity enhancements modeled in the airplane game simulation, additional exploration of the role of learning or experience curve in construction is beyond the scope of this paper.

[6] The term "Hawthorne Effect" has come to refer to a phenomenon where individuals modify their behavior in response to a perception that they are being observed. The term is eponymous with the Hawthorne Works of the Western Electric Company where, from 1924-1932, experiments were conducted to determine if

Roethlisberger 1941; Roethlisberger and Dickson 1939) where the mere act of observing human behavior appears to modify that behavior. The relevance of their concern is that of repeatability and generalizability. In other words, if a construction project adopts lean principles, are improved outcomes primarily due to the reliable mechanics of lean principles—or instead to the possibility that stakeholders simply get better at their jobs with repetitive practice (learning curve) or to the fact that these individuals may know they are under observation during facilitation by a lean consultant (Hawthorne effect)?

This skepticism prompted investigators to generate a computerized simulation of the airplane game using Stroboscope (Rybkowski et al. 2008). However, since the inner workings of Stroboscope (Martinez 1996) and other simulation software programs remain opaque to many participants, the authors are finding some participants still remain unconvinced that the mechanics of lean principles is a substantial contributor to the observed enhanced productivity.

To address this concern, this research attempts to illuminate the principles of the Airplane Game in a more visually transparent way. We exploit the graphic capabilities of Microsoft Excel™ to provide a cross-time "snapshot" of the participants and their pieces, second-by second, station by station, and to compare outcome metrics from the graphic snapshot against metrics collected during live playing of the game. The purpose is to "tease out" the quantitative benefits that can be attributed to learning curve and/or Hawthorne Effects from those benefits that can be entirely attributed to the logical workings of lean.

Materials and Methods

The methodology of this research was driven by the following intentions: to understand the nature and amount of contribution on enhanced productivity made by mechanistic, successive introduction of lean principles versus non-mechanistic phenomena such as learning curve and Hawthorne effect. To accomplish this, we: (a) simulated playing the game mechanistically via Microsoft Excel; (b) played the game using live participants; (c) identified the impact of each successive lean intervention on collected metrics from part a; and (d) compared results from parts a & b to identify the magnitude of contribution from mechanistic versus non-mechanistic phenomena.

To simulate playing the game and to enable future replication of the experiment, we followed directions specified in the published game manual (Visionary Products 2007) and asked players to assemble a Lego airplane using stations, as shown in **Figure 1**. However, we made some changes. Since the benefits derived from transitioning from tradition to cellular plant layout are intuitively obvious, in our opinion, we chose to focus our simulation efforts on Phases 2-4 only, and not on Phase 1.

Phases 2-4 investigated the effects of:

- Phase 2: Cellular layout (batch size of 5, push system, unleveled work load;
- e.g. "5 Push")

illumination levels correlated with factory worker productivity. Because productivity increased regardless of whether lighting levels were raised or lowered, it was subsequently speculated that increased levels of productivity were due more to a perception by workers that they were being observed than to increasing levels of illumination.

- Phase 3: One-piece flow (batch size of 1, pull system, unleveled work load;
  - e.g. "1 Pull")
- Phase 4: Load-leveling (batch size of 1, pull system, leveled work load;

  e.g. "1 Even")

-
  - Also, the original game identifies defective planes. We assumed all planes were perfect during our simulations.

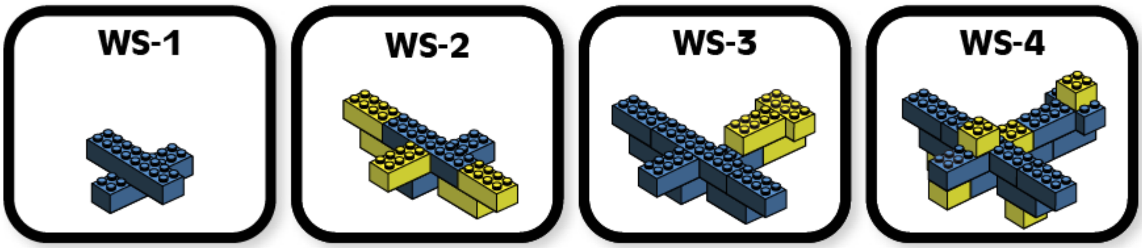

Figure 1. The first four workstations of the Airplane Game
(Reprinted with permission from Visionary Products, Inc. 2008).

To model the Airplane Game, we used workstation times (in seconds) per assembly reported in Rybkowski et al. (2008) as follows:

- WS-1→ 3 s.
- WS-2→ 13 s.
- WS-3→ 7 s.
- WS-4→ 17 s.

In Rybkowski et al. (2008), workstation assembly times had been determined by timing how long it took for players to put together 20 assemblies at a rapid, steady pace, and then taking an average time per assembly. In this simulation, passing times from workstation to queue and from queue to workstation were assumed to be one second each. Throughout all phases, participants remained in the workstations to which they had originally been assigned.

For the Excel simulation, *rows* were numbered 1-360 seconds to show the state of production at that time point in the game. *Columns* represented locations dedicated to specific assembly functions, such as workstations for assembling parts (WS=Workstation), queue areas for holding completed intermediate assemblies (Q=queue), or transitional zones for passing parts ("pass"). Columns were therefore labeled as follows:

WS1; pass; **Q1;** pass; **WS2**; pass; **Q2**; pass; **WS3**; pass; **Q3**; pass; and **WS4**

An Excel-based graphic simulation was generated for each successive phase of the game, as is shown in **Figure 2**. Although Visionary Products, Inc. only requires participants to shift from 5 Push to 1 Pull, we have chosen to make the shift more nuanced in the simulation and have added one step between 5 Push and 1 Pull: 1 Push. The purpose of adding this step is to sharpen our understanding of the isolated impact of each successive lean intervention, including the transition from larger to smaller batch sizes.

Results

There are two sets of results intended to help identify the nature of productivity gains observed during the live playing of the lean simulation, the airplane game. The first set of results—metrics from Microsoft Excel-based simulations—are intended to identify the specific mechanistic impact of each successively introduced lean principle. The second set of results—metrics from 8 live playings of the airplane game—are intended to identify the productivity contributions of non-mechanistic phenomena such as learning curve process and/or Hawthorne Effect. The game is intended to serve as a proxy for controlled experimentation in the field—experimentation that is difficult to conduct on actual construction projects but that is important when making claims regarding generalizability and reproducibility of results.

Excel-based simulations are shown in **Figures 2** and **3**. During each subsequent round, the game requires participants to introduce one additional lean intervention. Arrows indicate the time the first batch of planes was complete during each round of play. White space within a Work Station column show when a workstation is idle.

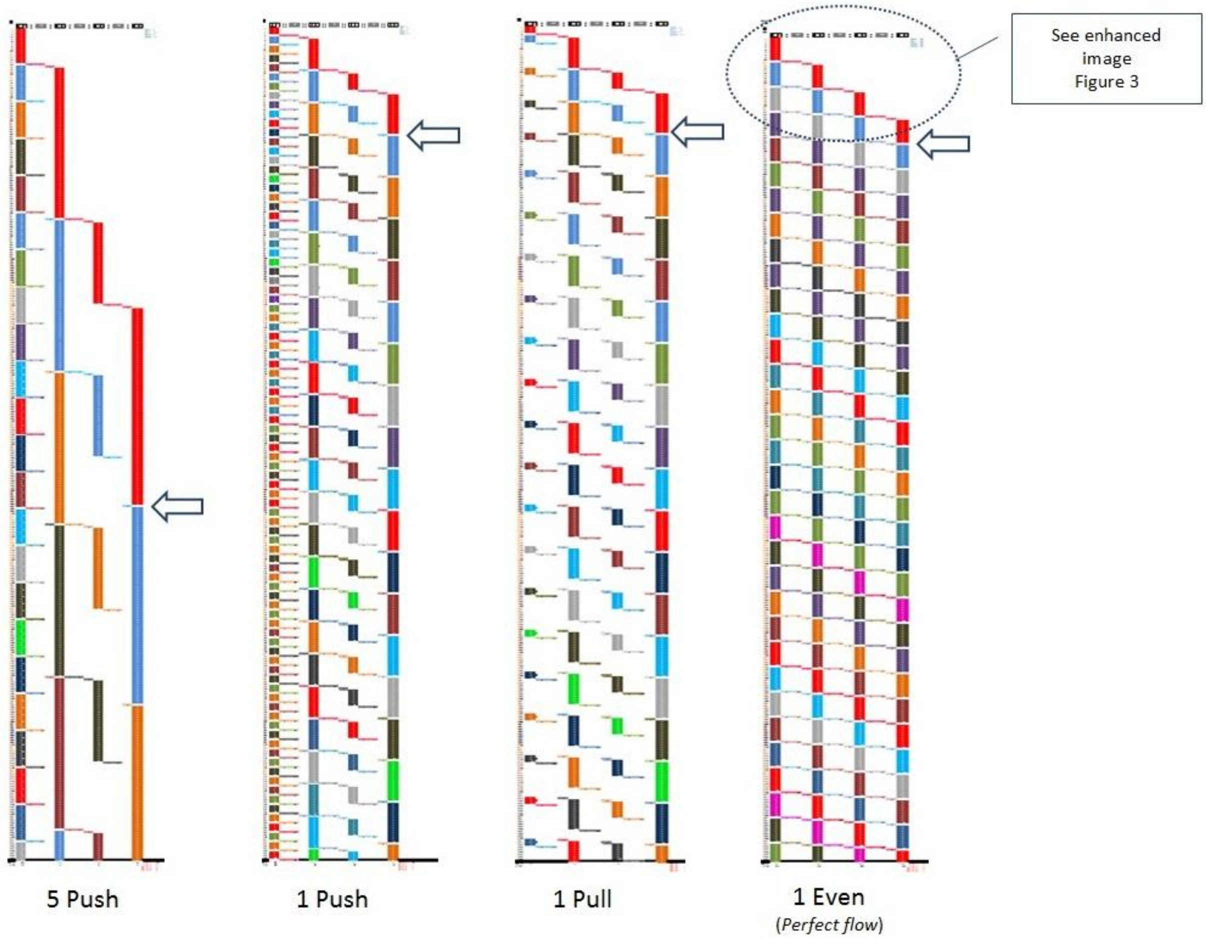

Figure 2. Excel-based second-by-second simulation map of the Airplane Game using the average times noted by Rybkowski et al. 2008.

The 1-even simulation was constructed by adding assembly averages for all four workstations and dividing the work evenly among the four workstations ((3 + 13 + 7 + 17)(s.)/4 workstations = 10 s./station). The Excel-based simulation of 5 Push→1 Push→1 Pull→1 Even using the assembly times defined in Rybkowski et al. (2008) yielded the results shown in **Table 1**.

	WS 1	Pass	Q1	Pass	WS 2	Pass	Q2	Pass	WS 3	Pass	Q3	Pass	WS 4	
1	-													WS 1:10
2	-													WS 2:10
3	-													WS 3:10
4	-													WS 4:10
5	-													
6	-													
7	-													
8	-													
9	-													
10	1													
11		x	1											
12	-			x										
13	-				-									
14	-				-									
15	-				-									
16	-				-									
17	-				-									
18	-				-									
19	-				-									
20	-				-									
21	2				-									
22		x	2		1									
23	-			x		x	1							
24	-				-			x						
25	-				-				-					
26	-				-				-					
27	-				-				-					
28	-				-				-					
29	-				-				-					
30	-				-				-					
31	-				-				-					
32	3				-				-					
33		x	3		2				-					
34	-			x		x	2		1					
35	-				-			x		x	1			
36	-				-				-			x		
37	-				-				-				-	
38	-				-				-				-	
39	-				-				-				-	
40	-				-				-				-	
41	-				-				-				-	
42	-				-				-				-	
43	4				-				-				-	
44		x	4		3				-				-	
45	-			x		x	3		2				-	
46	-				-			x		x	2		1	*Time to first plane*

Figure 3. Enlargement of Excel-based simulation of the Airplane Game showing rows depicting time (in seconds) and columns depicting Workstations, Queues and Passing between workstations and queues.

Table 1. Tabulation of results from Excel-based simulation of the Airplane Game.

	Time to 1st Batch	# of planes	WIP 1	WIP 2	WIP 3	WIP 4	Total WIP
5 Push	206	10	88	5	5	4	102
1 Push	46	18	69	1	1	1	72
1 Pull	46	18	1	1	1	1	4
1 Even	46	29	1	1	1	1	4

Results from 8 live playings of the game, as well as overall averages, are shown in **Table 2**. We arranged "ideal" results alongside average results obtained from eight live playings of the game, as shown in **Table 3**. We omitted 1 Push in the live playing of the game due to time limitations, so have restricted our comparisons to 5 Push, 1 Pull, and 1 Even.

Table 2. Outcome metrics from eight live playings of the Airplane Game.

Team #	Batch size & transfer type	Time to first batch (seconds)			Number of successful planes			Total WIP		
1	5 Push	202			10			38		
	1 Pull		27			22			3	
	1 Even			50			22			3
2	5 Push	196			10			70		
	1 Pull		36			16			18	
	1 Even			46			41			13
3	5 Push	303			0			26		
	1 Pull		39			16			1	
	1 Even			41			24			2
4	5 Push	236			12			48		
	1 Pull		44			21			4	
	1 Even			42			35			3
5	5 Push	277			7			50		
	1 Pull		42			9			4	
	1 Even			36			27			3
6	5 Push	255			10			19		
	1 Pull		41			14			8	
	1 Even			51			21			2
7	5 Push	360			4			40		
	1 Pull		55			11			3	
	1 Even			56			25			4
8	5 Push	360			2			25		
	1 Pull		49			14			4	
	1 Even			45			27			4
	Averages	274	42	46	7	15	28	40	6	4

Average outcome metrics from live playings were then compared against outcome metrics from the excel simulation map. Note that although the differences between a live play and the Excel simulation map are relatively large at first (i.e. 274 s.- 206 s.=68 s. for time to 1st batch), they become negligible as participants complete their third, or "1-even," round (i.e. 46 s.- 46 s.=0 s.). This suggests that players are indeed slower during the earliest rounds of a live playing of the game, and that efficiency gains from learning curve and/or Hawthorne Effects no longer affect results by the third round.

Table 3. Comparison of outcome metrics from live plays (averages) and the Excel simulation map

Rnd of play	Batch size & transfer type	**Time to 1st batch** (seconds)*			**# of successful planes** (units)			**Total WIP** (units)		
		Live play	Excel simulation	Difference	Live play	Excel simulation	Difference	Live play	Excel simulation	Difference
1st	5 Push	274	206	68	7	10	-3	40	102	-62
2nd	1 Pull	42	46	-4	15	18	-3	6	4	2
3rd	1 Even	46	46	0	28	29	-1	4	4	0

* Note: Approximately 70% of the improvement in time to 1st batch is due to the mechanistic benefits of lean principles (1 - 68/(274-46) x 100)

Discussion

A number of conclusions can be drawn from the second-by-second excel-based simulation. We can see from the greyed in boxes in **Table 1** that the primary impact of:

- transitioning to smaller batch sizes is reduced time to first batch (206→46);
- moving from a push to a pull system is reduced WIP (72→4); and
- load-leveling is increased quantity of final product (18→29).

Although we also observed some reduced WIP (102→72) and increased product (10→18) when moving from 5 Push to 1 Push, we argue this was a secondary benefit, as the largest contribution was to reduce time to first batch (206→46). There was no interference with the other interventions.

Since we have constructed a second-by-second, deterministic (non-stochastic) simulation of the Airplane Game that is computer-based and therefore unaffected by variable assembly times sometimes observed during a live playing of the game, we are confident that all benefits observed in the tabulated results shown in **Table 1** can be attributed to the mechanistic intervention of lean principles themselves and not to phenomena such as Learning Curve and/or Hawthorne effect (e.g. unlike the live playing of the game, the Excel-based simulation could neither be affected by a learning curve nor an awareness of being observed). Note that when we compare live playing to simulated playing in **Table 3**, relative magnitudes within the respective rounds are similar. However, when the live playing is compared to the simulated playing during Push processing with Batch Size 5, time to first batch is greater, number of planes fewer, and WIP is smaller for the live playing. This is consistent with the observation that players are still learning and are therefore slower during their first round of the game. It is also consistent with the reality that average workstation assembly times inputted into the Excel simulation were taken from experienced players (those who had already overcome an early learning curve). Note that the gap between live and simulated playing metrics decreases, essentially becoming negligible, during subsequent rounds of the game (5 Push→1 Pull→1 Even), as shown in the third column of time to 1st batch, number of successful planes and total Work-in-Process, as shown in **Table 3**. It appears that Learning Curve (or impact from a possible Hawthorne effect) has flattened out during the final round of the game since results from the live and simulated plays during this round match almost precisely.

One limitation of this research is that the simulation was deterministic, rather than stochastic in nature. The authors acknowledge this limitation and invite researchers who have interest to take the work to the next level. Readers should also be reminded that we did not simulate Phase 1 of the airplane game as originally designed by Visionary Products, as explained earlier. Phase 1 is intended to show participants the impact of arranging workstations sequentially in a co-located cell before any other lean principles are to be introduced. This is important because introducing one-piece flow without first arranging workstations sequentially in a co-located cell can actually worsen rather than enhance productivity due to the large fixed cost associated with transporting batches from one workstation to another. This assumption needs to be kept in mind when interpreting the results.

Still, the question begs: Why does any of this matter? After all, isn't the airplane game just a simulation? But simulations such as the airplane game are important because they represent the closest we can come to controlled experimentation in a field that resists randomized controlled trials—the gold standard of scientific experimentation. It is difficult, if not impossible, to set up controlled experiments when there are as many confounding variables as there are in construction projects. The typical "action research" (Westbrook 1995) construction management case study does not lend itself to statistically significant hypothesis testing because N=1. Simulations, by contrast, offer controlled conditions that can supplement case study experimentation, rendering results from lean implementations more convincing. All of the lean principles demonstrated by the airplane game (e.g. cell design and co-location, small batch sizes, pull, and load-levelling, for example) are continually being introduced, experimentally tested, and their outcomes documented by lean construction academics and practitioners in papers too numerous to mention, but freely accessible via the internet (Lean Construction Institute 2011; Lean Construction Journal 2011). For example, Target Value Design employs cell design and co-location to enhance communication and design delivery and to reduce project costs up to 20% (Ballard and Reiser 2004; Ballard and Rybkowski 2009; Denerolle 2011; Rybkowski 2009), the Last Planner System implements pull during reverse phase scheduling (Ballard 2000b; Rybkowski 2010); the concept of small batch sizing has informed phased plan review of hospital projects in California, considerably reducing approval time (Feng and Tommelein 2009; Alarcón et al. 2011). The airplane game responds to skepticism that benefits observed during lean case study experimentation might not be repeatable or generalizable. As a controlled experiment, the airplane game can bolster confidence that, when lean principles are properly applied to a construction project, measureable benefits will definitely be realized, regardless of the experience level of the workers or their being subjected to observation by lean consultants.

This paper helps those who administer the airplane game accurately respond to questions about the nature of productivity improvements observed during the game as well as respond to understandable skepticism that players are simply moving faster as they master the game, or simply improving because they are being observed. Our results show that, while some improvement can be attributed to learning curve and/or the Hawthorne Effect, the majority of it cannot be. For example, for the improvement observed in time-time-first batch, approximately 70% is due to the mechanistic benefits of lean ((1-(68/(274-46)) x 100) = 70.2%); therefore less than 30% is due to non-mechanistic phenomena.

The only other explanation for the majority of observed outcome improvements during the airplane game simulation are the contributions made from introduction of lean interventions. This, in turn, suggests that the productivity gains observed on actual construction projects are likely due to the physical mechanics of lean itself (Hopp and Spearman 1996) and not only to the fact that participants are improving with practice and/or being observed during lean experimentation. Ultimately, the game is relevant because the lean interventions introduced during it have been translated into tools such as the Last Planner™ System of Production Control (Ballard 2000b, Rybkowski 2010).

Conclusion

Results of this research enable lean educators to address concerns about the underlying nature of benefits observed during playing of the airplane game. We embarked on this investigation in order to identify the nature and proportion of benefits that can be attributed to the mechanics of lean principles versus the nature and proportion of benefits that can be attributed to learning curve and/or Hawthorne Effects. We believe this research has demonstrated that observed productivity improvements can primarily be attributed to the mechanistic benefits of lean principles themselves and less significantly to non-mechanistic phenomena. By contrast, lean interventions themselves represent the primary driver for observed productivity improvement. This result should give lean construction practitioners confidence in the repeatable and generalizable effectiveness of lean.

References

Alarcón, I., Christian, D., and Tommelein, I. D. (2011). “Collaborating with a permitting agency to deliver a healthcare project: Case study of the Sutter Medical Center Castro Valley (SMCCV),” *Proc. 19th Annual Conf. Int’l Group for Lean Construction* (IGLC 19), Lima, Peru, 13-15 July, 402-415.

Alarcón, L. F. and Ashley, D. B. (1999). “Playing games: Evaluating the impact of lean production strategies on project cost and schedule.” *Proc. 7th Conf. of the Int’l Group for Lean Construction* (IGLC 7), Univ. of California, Berkeley, 263-273.

Ballard, G. (2000a). “Lean project delivery system.” <http://www.leanconstruction.org/>. (April 3, 2010).

Ballard, G. (2000b). “The last planner system of production control.” Ph.D. dissertation, Univ. of Birmingham, Birmingham, UK.

Ballard, G. (2008). “The lean project delivery system: An update.” *Lean Construction J.*, 1-19.

Ballard, G. and Reiser, P. (2004). “The St. Olaf College Fieldhouse Project: a Case Study in Designing to Target Cost.” *12th Annual Conference of the International Group for Lean Construction*, Elsinor, Denmark, 234-249.

Ballard, G. and Rybkowski, Z. K. (2009). "Overcoming the hurdle of first cost: a case study in Target Value Design." The *2009 Construction Research Congress* (Construction Institute of ASCE), Seattle, WA, April 5-7, 10 pp.
Bertelsen, S. (2002). "Bridging the gaps—towards a comprehensive understanding of lean construction." *Proc., 10th Conf. of the Int. Group for Lean Construction*, Gramado, Brazil.
Bills, A. (1934). *General Experimental Psychology*. Longmans, Green, London.
Black, J. T. and Hunter, S. L. (2003). *Lean Manufacturing Systems and Cell Design*, Society of Manufacturing Engineers, MI.
Boston Consulting Group. (1970). *Perspectives on Experience*. Boston Consulting Group, Inc., Boston, MA, 109 pp.
Champoux, J. E. (2003). *Organizational Behvior: Essential tenets* (2nd ed.). Southwestern, Mason, OH.
Choo, H. J., and Tommelein, I. D. (1999). "Parade game," Tech. Rep. 99-1, Constr. Engrg. and Mgmt. Program, Civ. and Envir. Engrg. Dept., University of California, Berkeley, CA.
Denerolle, S. (2011). "Technical Report: The application of Target Value Design to 3 hospital projects," Project Production Systems Laboratory, University of California, Berkeley.
Detty, R. B., and Yingling, J. C. (2000). "Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study." *International Journal of Production Research*, 38 (2), 429-445.
Ebbinghaus, H. (1913). *Memory: A Contribution to Experimental Psychology*. Teachers College Press, New York, NY.
Feng, P. P. and Tommelein, I. D. (2009). "Modelling the Effect of the Alternative Review Processes: Case Study of a State Permitting Agency." *Proceedings of the Construction Research Congress*, Seattle, U.S.
Franke, R. H. and Kaul, J. D. (1978). The Hawthorne experiments: First statistical interpretation, Am Social Rev, 43: 623-643.
Goldratt, E. M., and Cox, J. (1986). *The Goal*. North River Press, Croton-on-Hudson, N.Y.
Hopp, W. J., and Spearman, M. L. (1996). *Factory physics*, IRWIN, Chicago.
Howell, G. A. (1998). "The dice game." Played at the *6th Conf. of the Int. Group for Lean Construction*, Guaruja, Brazil.
Koskela, L. (1992). "Application of the new production philosophy to construction." *Technical Rep. No. 72,* Center for Integrated Facility Engineering, Dept. of Civil Engineering, Stanford Univ., Stanford, Calif.
Koskela, L. (2000). "An exploration towards a production theory and its application to construction," D. Tech. thesis, Helsinki Univ. of Technology, Espoo, Finland, <http://www.vtt.fi/inf/pdf/publications/2000/P408.pdf> (April 3).
Lean Construction Institute. (2011). <http://www.leanconstruction.org/> (August 21)
Lean Construction Journal. (2011). <http://www.leanconstruction.org > (August 21)
Lee, R. (2002). *The Eureka! Moment: 100 Key Scientific Discoveries of Modern Times*, Routledge, New York.
Liker, J. E. (2000). *The Toyota way*, McGraw-Hill, New York.
Martinez, J. C. (1996). *STROBOSCOPE State and Resource Based Simulation of Construction Processes*. PhD Dissertation, Civil and Environmental Engineering Department, University of Michigan, Ann Arbor, MI 518 pp.
Mayo, E. (1993). The human problems of an industrial civilization, Volume 3, 2nd edition, McMillan, New York. 53-73.

Newstrom, J. W. & Davis, K. (2002). *Organizational behavior: Human behavior at work* (11th ed.). McGraw-Hill, Boston.
Ohno, T. (1988). *Toyota production system: Beyond large scale production*, Productivity Press, Cambridge, MA.
Ronen, B. (1992). “The complete kit concept.” *Int. J. Prod. Res.*, 30(10), 2457-2466.
Roethlisberger, F. J. (1941). *Management and morale*. Harvard Univeristy Press, Cambridge, MA.
Roethlisberger, F. J. and Dickson, W. J. (1939). *Management and the worker: An Account of a research program conducted by the Western Electric Company, Hawthorne Works, Chicago*. Harvard University Press, Cambridge, MA.
Rybkowski, Z. K. (2009). “The application of root cause analysis and target value design to evidence-based design in the capital planning of healthcare facilities,” Ph.D. dissertation, Univ. of California, Berkeley.
Rybkowski, Z. K . (2010). “Last planner and its role as conceptual kanban.” *18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel, 63-72.
Rybkowski, Z. K., Wong, J.-M., Ballard, G., and Tommelein, I. D. (2008). "Using controlled experiments to calibrate computer models: the Airplane Game as a lean simulation exercise." *16th Annual Conference of the International Group for Lean Construction*, Manchester, UK, 309-319.
Sacks, R., Esquenazi, A., and Goldin, M. (2007). "LEAPCON: Simulation of lean construction of high-rise apartment buildings." *J. Constr. Eng. Manage.*, 133(7), 529-539.
Sacks, R., Goldin, M., and Derin, Z. (2005). “Pull-driven construction of high-rise apartment buildings.” Proc., 13th *Conf. of the Int. Group for Lean Construction*, R. Kenley, ed., UNSW, Sydney, Australia, 217-226.
Sacks, R., Treckmann, M., and Rozenfeld, O. (2009). “Visualization of work flow to support lean construction.” *J. Constr. Eng. Manage.*, 135(12), 1307-1315.
Salem, O., Solomon, J., Genaidy, A., and Minkarah, I. (2006). “Lean construction: From theory to implementation.” *J. Manage. Eng.*, 22(4), 168-175.
Tommelein, I. D., Riley, D., and Howell, G. (1999). “Parade game: Impact of work flow variability on trade performance.” *J. Constr. Eng. Manage.*, 125(5), 304-310.
Verma, A.K. (2003). "Simulation tools and training programs in lean manufacturing–Current status: final report." National Shipbuilding Research Program, *NSRP-ASE-0301-11*, Old Dominion Univ., Norfolk, VA.
Visionary Products Inc. (2007). "Lean zone production methodologies ["Airplane Game" Instruction Manual]." Forth Worth, Texas.
Visionary Products Inc. (2008). "Lean zone production methodologies: A cellular manufacturing simulation for 6 to 8 participants." <http://www.visionaryproducts.biz/index.cfm?action=view&pdfid=232.> (February 28 2008)
Westbrook, R. (1995). “Action research: A new paradigm for research in production and operations management.” *International Journal of Operations & Productions Management*, 15(12), 6-20.
Womack, J. P., and Jones, D. T. (2003). *Lean thinking: Banish waste and create wealth in your corporation*, Simon and Schuster, New York.
Wozniak, R. H. (1999). *Classics in Psychology, 1855-1914: Historical Essays*. Bristol, UK: Thoemmes Press.
Wright, T. P. (1936). “Factors affecting the cost of airplanes.” *Journal of Aeronautical Sciences*,3, 122-128.
Yeh, S. and Rubin, E. S. (2010). “Uncertainties in technology experience curves for energy-economic models,” *Proc. of NAS Workshop on Assessing the Economic Impacts of climate Change*, April.