MANAGING VARIABILITY IN HOUSE PRODUCTION

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ABSTRACT

The differences between construction and manufacturing are well known. There have been many arguments on whether lean production model is relevant to construction and what strategy should be taken for construction enterprises to pursue lean transformation. A central issue here is how to deal with high variability in construction process.

This paper presents a collaborating research performed by the University of Alberta and a local homebuilder. An analysis of historical production data confirms that the current house production flow is extremely variable, particularly at the beginning of the production process. The ripple effects of a change in production conditions can cause serious problems in scheduling and lead to big variation in construction operation durations. Based on a comparative study of home building and auto manufacturing, a comprehensive approach is proposed to reduce and manage the variability in house production through the resolution of particularities.

KEY WORDS

House production, Construction particularities, Variability, Residential construction, Strategy.

INTRODUCTION

Lean production theory has been introduced into the construction industry for more than 15 years. Although the research literature reports some positive results from the application of lean concepts and tools to construction, research in this area at large still stays in theory study stage, and most implementation cases followed a heuristic approach based on trial and error. Since construction and manufacturing differ significantly in nature, researchers and construction practitioners have struggled to develop a lean production system in the context of construction. Vrijhoel and Koskela (2005) point out that three interrelated peculiarities, namely site construction, one-of-kind production and temporary organization, distinguish construction from manufacturing. Moreover, complexity and project-oriented management make construction, alongside some manufacturing sectors including job shop, shipbuilding and aerospace production, a special type of production system – project production system (Ballard 2005, Bertelsen and Koskela 2005). The consequence of these particularities is high variability in the

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construction process. In contrast, process stability is a prerequisite and key aspect of lean production system in manufacturing (Howell and Ballard 1997a).

Lean manufacturing is basically composed of two interdependent parts: lean philosophy and lean techniques. Womack and Jones (1996) identified five key elements as the core of lean thinking: understanding customers' demands (value), lining up value stream to eliminate waste, implementing continuous flow, creating a pull system, and continuously pursuing perfection. These broad principles are simple and inspirational for companies in a wide range of industries, including construction. However, to apply these principles, people need a step-by-step action plan and specific techniques. In the past decades, plenty of lean tools have been developed to help companies become lean, but most of them are developed for manufacturing companies that strive to overcome the shortcomings of mass production and built on following assumptions:

- The production process is repetitive and stable. Standardization is the hallmark of mass production and the manufacturing industry has long history to minimize variation in process to ensure the productive activities into control.
- The system has stable gross output volume. The flexibility that lean production offers is only within a stable gross output between different products, and cannot address fluctuations in gross output level (Winch 2003).
- The performance of work can be accurately measured. In manufacturing, operation data, such as cycle time and lead time, can be easily obtained by site observation, and techniques like time study and work sampling have been used for decades in work measurement.

Generally two strategies in lean construction emerge for coping with variability issue. One is minimizing variability by resolving peculiarities, so that the lean techniques developed in manufacturing can be applied in construction. Industrialized housing (Gunn 1996), open building (Vrijhoef et al 2002) and site factory (Bashford 2004) are examples of such effort. The other strategy is to develop unique technologies based on lean principles in order to stabilize the construction workflow within the context of existing production situation. Last planner system (Ballard 2000) and Line-of-Balance (LOB) scheduling (Kenley 2005) exemplify this strategy. There have been various arguments in the selection and relationship between these two strategies (Vrijhoef and Koskela 2005). Since the construction industry contains many sectors, each with different characteristics in product, market, and industry convention, selection of lean transformation strategy must be based on an analysis of specific production context of the sector. This paper focuses on an analysis of production context in the home building industry and proposes a comprehensive approach to systematically reduce and manage the variability in house production.

VARIABILITY IN HOUSE PRODUCTION

In 2005, a collaborating research project was initiated by the University of Alberta and a major local homebuilder in Edmonton, Canada, attempting to develop a lean system for house production. As a medium size home building company, our industrial partner has annual production volume of about 1,000 units, including single-family houses, semi-detached houses, townhouses, and low-rise condominiums. As the first step of research, 560 single-family houses whose construction processes were started in the period between May 1, 2005 and June 15, 2006 are analyzed. In the company's production tracking system, 36 critical milestones along the construction process are recorded. According to standard construction schedule, a house will be completed in 18 weeks, and each week is looked as a construction stage. The break points between stages are detailed in Table 1.

Table 1: Construction Stages of Home Production

Construction Stage	Stage Start Point
1 Stake-out	Construction department receives file package
2 Cribbling	Stage-out finish
3 Backfill / Services	Cribbing finish
4 Framing main floor	Grade beam finish
5 Framing second floor	Second floor framing start
6 HVAC & Plumbing	Framing finish
7 Roofing / Electrical	Roofing material loaded
8 Smart trim / Siding	Smart board start
9 Insulation / Boarding	Insulation start
10 Tapping	Tapping start
11 Texture / Finishing stage 1	Prime
12 Cabinets / Railing	Install cabinets
13 Painting	Interior painting start
14 Hard flooring	Tile flooring start
15 Finishing stage 2 / Carpet	Finishing start
16 Finals	Heating final starts
17 Touch-ups	Paint touch-ups
18 Pre-occupancy	Pre-occupancy
End	Possession date

Since the construction of some houses had not been completed in the study period and some data in the tracking system are missing or erroneous, the actual sample size in each stage varies depending on data availability. Outliers with known causes are excluded from sample set so that the results will not be distorted by abnormal condition. Table 2 shows the results of the statistical analysis of total duration of each stage based on qualified data.

The analysis confirms that the current house production flow is extremely variable. In 18 stages, nine of them have standard deviations larger than 5 days, and eight stages' coefficients of variation are larger than 50%. Moreover, most of the stages with large standard deviations and high coefficients of variation are in the first half of the process. A further analysis indicates that variation in lead time[5] is the primary contributor to process variability. In Stage 4 and Stage 5, same crew works in same working condition and performs similar amount of work, but the duration of Stage 4 is three times longer than

[5] Lead time is the time that elapses from booking crew for a given construction operation until that operation actually starts.

that of Stage 5. The reason is that the duration of Stage 4 includes lead time of framing, which accounts for on average 30 days with standard deviation of 22.1 days.

Table 2: Statistics Summary of Construction Stage Duration

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Construction Stage	**Stake Out**	**Cribbing**	**Backfill / Services**	**Framing Main**	**Framing Second**	**HVAC / Plg**	**Roofing / Elect**	**Smart Trim / Siding**	**Insulation / Boarding**	**Taping**	**Tex / Stage 1**	**Cabinets / Railing**	**Painting**	**Hard Flooring**	**Stage 2 / Carpet**	**Finals**	**Touch-ups**	**Pre-Occ**	**Construction File to Field - Pre-Occupancy**
Sample Size	541	510	453	341	394	304	309	297	277	254	224	208	210	195	154	154	154	154	
Average Duration	10.48	26.57	17.6	39.6	9.8	8.0	30.0	13.0	17.0	10.0	10.0	5.0	9.0	7.0	4.5	4.5	4.5	6.0	232.5
% of Total	5%	11%	8%	17%	4%	3%	13%	6%	7%	4%	4%	2%	4%	3%	2%	2%	2%	3%	100%
Standard Deviation	10.1	14.1	22.1	21.9	5.4	4.5	14.1	7.2	6.4	3.6	5.4	2.3	3.8	2.5	1.2	1.2	1.2	2.0	
Coefficient of Variation	97%	53%	126%	55%	55%	56%	47%	55%	38%	36%	54%	46%	42%	36%	27%	27%	27%	33%	

FACTORS LEADING TO VARIABILITY

A construction system comprises five interlinked elements: input, conversion process, output, controllable conditions and uncontrollable conditions, as shown in Figure 1 (Salim and Bernold 1995). This aggregate construction model provides a framework to explore the causes of variability. In house production, input resources are converted to output products through certain construction technologies. Changing conditions may affect both the conversion process and input resources, while the changes in construction technology and resource availability also have significant impact on controllable conditions, such as scheduling and supply chain management. Therefore, any elements in the system can be source of variation, and a small variation may be magnified through ripple-through effect. For example, bad weather (heavy rain) impedes the excavation operation on the scheduled day. Since the excavation trade contractor only has temporary contract with the homebuilder on that day to perform the excavation, and generally it have already scheduled other jobs in consecutive days. Therefore the delayed job has to be rescheduled and the lead time will be variable, depending on the number of jobs that the excavation trade contractor has already scheduled. Moreover, since the downstream operations, such as footing and cribbing, cannot start until the excavation is completed, the site manager has to cancel original bookings and tries to get the new commitments from downstream trade contractors based on the newly scheduled excavation date. However, from the perspective of a downstream trade contractor, a sudden schedule change means the risk that its crew may be left idle. Actually, it is common practice in the home building industry that trade contractors do not accept pre-booking (the preceding operation has not been completed at the time of booking) in seller's market and over-book (accept jobs more than their capacity) in buyer's market in order to protect themselves from the risk of idleness. Consequently, lead times of trade contractors are unpredictable, varying from next day to several weeks.

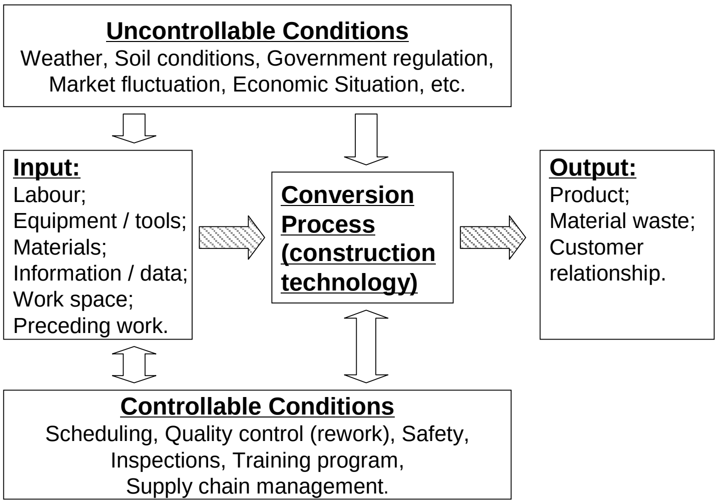

Figure 1: Aggregated Process Model (Based on Zhang et al 2005)

The problems in management, such as quality control and supply chain management, and some uncontrollable conditions, such as labour shortage caused by booming economy, impact all stages and lead to certain level of variability. However, construction activities in the beginning of the process are more vulnerable due to impacts of some additional factors, including weather, soil condition and market fluctuation. This situation further deteriorate when high variability compels site managers to abandon the schedule and push the construction process from one operation to another as long as they can get required resources.

UNDERSTANDING HOUSE PRODUCTION

Before moving on with discussion of the strategy to deal with variability and its causes, it is worthwhile to understand the production context of home building. Compared to other sectors of the construction industry, house production is a unique sector that provides the closet analogy to manufacturing (Winch 2003). At the level of production, three main similarities have been identified: high production volume, controllable production flow, and in-process inventory. These similarities provide the possibility to model house production after manufacturing through the resolution of peculiarities.

HIGH PRODUCTION VOLUME

Housing market is similar to auto market. Both homebuilders and automakers sell directly to the final customer, and most purchasers are individuals who lack technical expertise to describe what they want and make their purchases by choosing from pre-designed options. The potential production volume is high for a mid-size or large homebuilder, due to the similar functional requirements of clients. This production volume matches the most specialized end of automobile production.

CONTROLLABLE PRODUCTION FLOW

The production strategy is another area that homebuilders and automakers have much in common. One important decision in production strategy planning is to balance the trade-off between standardization (to facilitate the economics of repetitive production) and flexibility (to satisfy clients' demands for customization). Automakers generally employ a "ship to forecast" or "make to forecast" strategy, producing cars and shipping them to dealers according to market forecast. Unlike most construction firms who adapt a "design to order" strategy, homebuilders usually use a combination of strategies to meet the different requirements of customers while protecting themselves from fluctuations in demand. Our industrial partner, for one, constructs both spec houses (built according to market forecast before any specific purchaser makes an order – i.e. make to forecast), and pre-sale houses (where work commences only after the customer selects and customizes a house model and places an order – i.e. make to order). In 2005, about 40% of the total output of the company was spec homes.

IN-PROCESS INVENTORY

Currently in Edmonton a typical single-family house takes 180-230 days from ground breaking to possession, but the total cycle time[6] of construction operations on critical path is less than 90 days. This means that more than 50% of the time houses are left idle, without any construction activity on site. From production system point of view, these idle houses, which wait for next construction activity to start, are in-process inventory. This concept is important because in-process inventory may serve as buffers between operations, which break the dependency of operations and shield downstream work from upstream variability (Howell and Ballard 1997b). A well designed inventory management system, such as Toyota's kanban system, can effectively maintain continuous workflow for each work station while significantly reducing the size of inventory (Ohno 1978).

PARTICULARITIES OF HOUSE PRODUCTION

Although home building and auto manufacturing has some important similarities, significant differences also exist and impede the application of lean techniques. The particularities of home building include site construction, temporary organization, and fluctuation in demand. In fact, these particularities are the inherent root causes of production variability. For example, site construction is the real reason why bad weather is such an influential factor in house production, and temporary organization explains why a single delay can cause serious labour availability issue and a changing economic environment may lead to longer production cycle time (Bashford et al 2005).

FRAMEWORK TO MANAGE VARIABILITY IN HOUSE PRODUCITON

The similarities between the house production and manufacturing discussed above suggest that it is possible for home building – the most analogous sector in the construction industry – to achieve a stable production process by resolving particularities. Figure 2 shows schematically the proposed techniques applied to the production system. In practice, all six techniques should be considered because the application of these techniques is interdependent. For example, without panelised construction, variation in early stages of the construction process would be too big to be handled by a kanban system. On the other hand, the success of panelised construction requires that the prefabrication plant operates on full capacity continuously, and this necessitates the

[6] Cycle time is the time that elapses from the beginning of an operation until its completion, i.e. the actual construction time.

application of in-process buffer to ensure a continuous workflow and a companywide dynamic scheduling system to integrate the prefabrication with on-site construction.

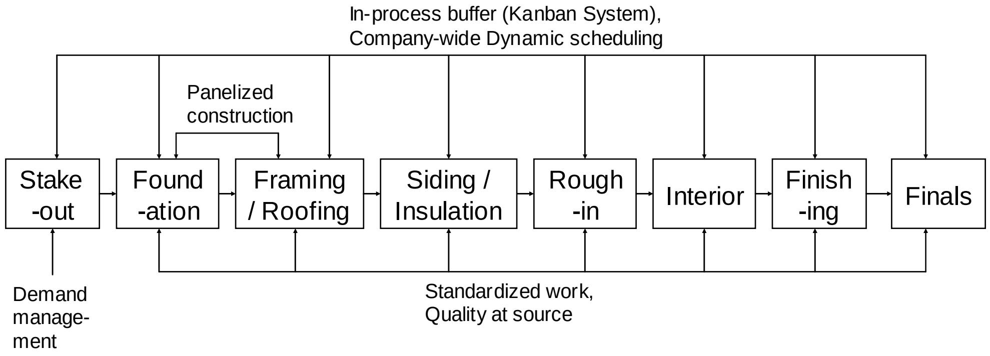

Figure 2: Techniques for Managing Variability in House Production

DEMAND MANAGEMENT

The idea behind demand management, as related to house production, is to maintain uniform pace of construction start. Bashford et al (2003) discuss the implications of this work-flow levelling strategy, but they do not explain how this strategy can be applied in the reality that most homebuilders organize their construction at the pace of sales. Two demand management measures are recommended here to deal with differing pace of sales:

- Controlling the release of spec houses to construction. As mentioned before, the homebuilders generally construct both spec and pre-sale houses. Although the pace of sales is not controllable, the release of spec houses is a management decision and can be used to adjust the overall number of new houses going into the production system. A graphical representation of this demand management measures is shown in Figure 3.
- Delayed delivery. When an occasional sales peak appears, the production manager will hold some jobs in backlog to make the workload uniform.

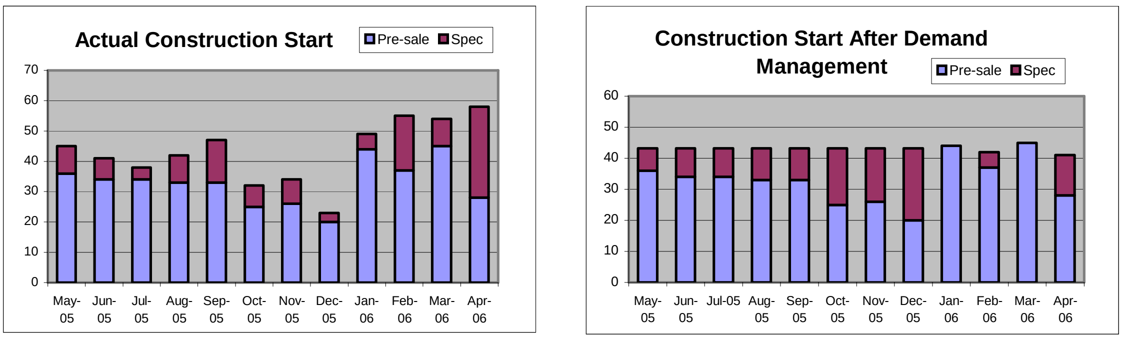

Figure 3: Demand Management

PANELLIZED CONSTRUCTION

Panelised construction is a method where the building is subdivided into basic planar components, elements, or systems that are typically prefabricated in factory, and then shipped directly to the construction site and assembled into the finished structure. By using prefabricated frames, wall panels, floors, partitions, and component kits of doors, windows and roofs, the envelope of a single-family home can be assembled in a week. Since most of the structure construction work is moved to factory, the site operation is simplified and can be done by a single contractor. As a result, the entire process becomes more controllable.

IN-PROCESS BUFFERS

In manufacturing, buffering is the most commonly used method to accommodate process variability. Even in lean production system, buffer/supermarket is necessary when circumstances make it difficult to sustain continuous flow (Tapping et al 2002). Figure 4 shows a lean production system developed for our industrial partner using value stream mapping technique (Yu et al 2007a). The size of buffer is decided by the uncertain level of preceding operation and the production rate of following operation. A computer-based kanban system brings continuous workflow and allows a homebuilder to form long-term partnership with trade contractors.

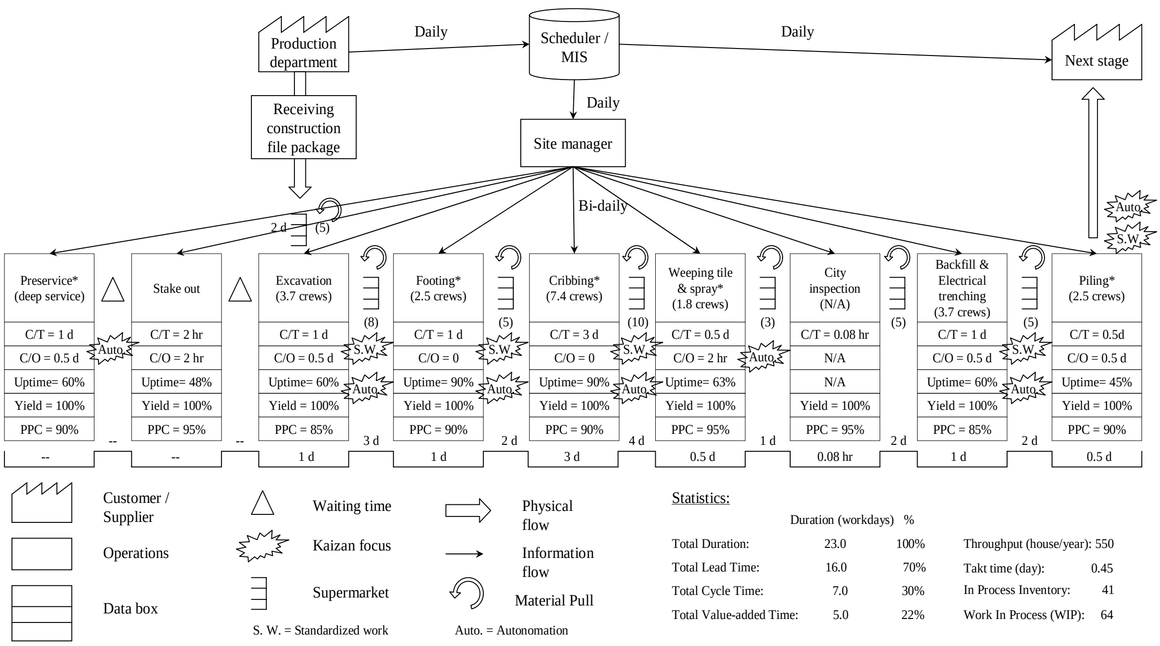

Figure 4: A Lean Production System with In-process Buffers (Construction Stages 1 to 3).

STANDARDIZED WORK AND QUALITY AT SOURCE

Although inventory is necessary to stabilize the process, it is a type of waste. To minimize the size of buffer, other two lean techniques are adopted to improve the reliability of operations. Standardized work clarifies the work scope and quality standards of each operation, and thus reduces the handover problems. Quality at source requires site managers to check quality as construction is in progress, and trade contractors must complete all repair work before they leave the site. Through the elimination of rework and hand-over problems, the variability in cycle time is reduced.

COMPANY-WIDE DYNAMIC SCHEDULING

There is a fundamental change in the new proposed production system (Figure 4). The houses in construction are not looked as many separate small projects but products passing through a series of process stations (construction operations). As a result, the management focus is shifted from controlling individual construction activity to meet schedule to synchronizing production pace and controlling flow. To support this change, a company-wide dynamic scheduling system is necessary. This computer-based system tracks the real-time situation of houses and resources, and provides a common platform for site managers and trade contractors to schedule their future work. The basic functions of the system includes: (1) distributing booking information within the company and between the company and trade contractors (e-kanban system), (2) collecting operation data and dynamically adjusting scheduling model based on statistical analysis, (3) monitoring production flow and providing early warning of abnormal fluctuation.

CONCLUSION AND ISSUES FOR FUTURE RESEARCH

This paper has tried to show that it is feasible to reduce and manage variability in house production through resolution of particularities. Demand management concept is used to shield the production system from the fluctuation of demand. Panelised construction minimizes the impact of site construction by reducing and simplifying on-site construction work. A lean production system with in-process buffers creates continuous workflow for trade contractors and facilitates the formation of long-term partnership between homebuilders and trade contractors. However, the resolution of peculiarities involves new construction methods and fundamental changes in the business process. It is a risky journey for homebuilders who make investment and take great effort to pursue lean production by making house production more like manufacturing. Therefore, a clear understanding of benefits and investments is essential. Another issue here is whether we have the techniques to support the proposed approach. In collaboration with our industrial partner, a series of research projects have been initiated at the University of Alberta on panelised construction (Yu et al 2006 and Yu et al 2007b), home building process redesign (Yu et al 2007a), and company-wide dynamic scheduling system development.

REFERENCES

Ballard, G. (2000) "The Last Planner System of Production Control." *Ph.D. dissertation,* University of Birmingham, Birmingham, U. K.

Ballard, G. (2005). "Construction: One Type of Project Production System." *Proceeding of 13th Annual Conference of the International Group for Lean Construction*, Sydney, Australia.

Bashford H. H. (2004) "The On-Site Housing Factory: Quantifying Its Characteristics." *NSF-PATH Housing Research Agenda* v.2, Position Paper: 27-33, (available at http://www.pathnet.org/si.asp?id=1118).

Bashford H. H., Walsh, K. D. and Sawhney, A. (2005) "Production System Loading-Cycle Time Relationship in Residential Construction." *Journal of Construction Engineering and Management*, 131(1), 15-22.

Bashford H. H., Sawhney, A., Walsh, K. D. and Kot, K. (2003) "Implication of Even Flow Production Methodology for U.S. Housing Industry." *Journal of Construction Engineering and Management*, 129(3), 330-337.

Bertelsen, S. and Koskela, L. (2005). "Approaches to Managing Complexity in Project Production." *Proceeding of 13th Annual Conference of the International Group for Lean Construction*, Sydney, Australia.

Gann, D. M. (1996) "Construction as a Manufacturing Process? Similarities and Differences between Industrialized Housing and Car Production in Japan." *Construction Management & Economics*, 14(5), 437-450.

Howell G. and Ballard, G. (1997a). "Lean Production Theory: Moving Beyond 'Can Do'." In: Alarcon, L. (ed.) *Lean Construction*, A.A. Balkema, Rotterdam, The Netherlands, 497 pp.

Howell G. and Ballard, G. (1997b). "Implementing Lean Construction: Reducing Inflow Variation." In: Alarcon, L. (ed.) *Lean Construction*, A.A. Balkema, Rotterdam, The Netherlands, 497 pp.

Kenley, R. (2005) "Dispelling the Complexity Myth: Founding Lean Construction on Local-Based Planning." *Proceeding of 13th Annual Conference of the International Group for Lean Construction*, Sydney, Australia.

Ohno, T. (1978) *Toyota Production System: Beyond Large-Scale Production*, Productivity Press, New York, NY

Salim, M. and Bernold, L. E. (1995). "Design – Integrated Process Planner of Rebar Placement." *Journal of Computing in Civil Engineering*, 9(2), 157-167.

Tapping, D., Luyster, T. and Shuker, T. (2002) *Value stream management*, Productivity Press, New York, NY.

Vrijhoel, R., Cuperus, Y. and Voordijk, J. T. (2002). "Exploring the Connection Between Open Building and Lean Construction: Defining a Postponement Strategy for Supply Chain Management." *Proceeding of 10th Annual Conference of the International Group for Lean Construction*, Gramado, Brazil.

Vrijhoel, R. and Koskela, L. (2005). "Revisiting the Three Peculiarities of Production in Construction." *Proceeding of 13th Annual Conference of the International Group for Lean Construction*, Sydney, Australia.

Winch, G. M. (2003) "Models of Manufacturing and the Construction Process: the Genesis of Re-engineering Construction." *Building Research & Information*, 31(2), 107-118.

Womack, J. P. and Jones, D. T. (1996) *Lean Thinking: Banish Waste and Create Wealth in Your Corporation.* Simon and Schuster, New York, NY.

Yu, H., Al-Hussein, M., and Nasseri, R. (2007b) "Process Flowcharting and Simulation of House Structure Components Production Process." Submitted to *Proceedings of the 2007 Winter Simulation Conference*, Washington, D.C.

Yu, H., Al-Hussein, M., Nasseri, R. and Cheng, R. J. (2006) "Development of Landmark Pre-cast Concrete Foundation System for Residential Construction." *Proceedings of CSCE 2006 Annual Conference*, Calgary, Canada.

Yu, H., Tarry, T., Al-Hussein, M. and Nasseri, R. (2007a) "Value Stream Mapping for Home Building Process Improvement." Submitted to *Journal of Construction Engineering and Management*.

Zhang, J., Eastham, D. L. and Bernold, E. B. (2005) "Waste-based Management in Residential Construction." *Journal of Construction Engineering and Management*, 131(4), 423-430.