PRODUCTION RATE - CONSTRUCTION QUALITY RELATIONSHIPS IN US RESIDENTIAL CONSTRUCTION

Kenneth D. Walsh[1], Howard H. Bashford[2], and Anil Sawhney[3]

ABSTRACT

Little's Law describes the relationship between throughput, cycle time, and work-in-progress (WIP) for a process. This relationship has been shown to apply over a long time horizon in production or "high-volume" residential construction, wherein specialized trade contractors perform related sequences of work in a tightly connected production system. This finding suggests new approaches might be needed in construction management, and that other relationships from production mechanics could apply to construction operations. The dramatic and rapid workload variability in residential construction makes direct application of Little's Law in real-time problematic, but more importantly fosters flexible crewing that confounds definition of utilization. Trade contractors employ very few crews directly, and have wide networks of additional crews they can bring on line, with ever less knowledge of their ability and quality of production. As a consequence, one might hypothesize that work-in-progress and/or throughput would exhibit a relationship to construction quality. Residential building permit and inspection data from a major residential market were analyzed to confirm the existence of such a relationship. This analysis reveals a larger question about the reasons for code compliance inspection failure and their implications for identifying production system waste.

KEY WORDS

Residential construction, Production mechanics, Variability, Code Compliance Inspections

[1] AGC-Paul S. Roel Chair in Construction Engineering and Management, Department of Civil and Environmental Engineering, San Diego State University, San Diego, CA 92182-1324, TEL:619/594-0911, FAX: 619/594-8078, kwalsh@mail.sdsu.edu

[2] Associate Professor, Del E. Webb School of Construction, Arizona State University, Tempe, AZ, 85287-0204, TEL: 480/965-4513, FAX: 480/965-1769, howard.bashford@asu.edu

[3] Associate Professor, Del E. Webb School of Construction, Arizona State University, Tempe, AZ, 85287-0204, TEL: 480/965-7417, FAX: 480/965-1769, anil.sawhney@asu.edu

INTRODUCTION

High volume residential builders perform no building operations with their own forces, but rather use a large network of specialized trade contractors to put actual work in place (Bashford et al. 2002). Homes are usually constructed as several nearly identical copies of a few plans, in a thematically connected subdivision or tract. These high volume builders have become the dominant providers of single-family homes in the US market, with the largest 20% of the builders controlling a 35% market share in 2003. The role of the builder is to acquire and improve land, conduct market studies and marketing plans, sell the homes, and manage the progress of construction. Managing the progress of construction generally includes monitoring progress on each home, arranging and coordinating subcontractor visits, arranging and tracking code compliance inspections, and interfacing with the homebuyer for arranging cosmetic choices and options. The trade contractors, in turn, are given the responsibility for putting work in place, and usually for providing customer service and support for some warranty period (commonly one year after closing).

The trade contractors have developed very specialized crewing approaches, in order to reduce training requirements and improve efficiency. Because the homebuilding process often includes relatively small quantities of a large number of items, mostly separated logically in terms of their delivery by relevant trade contractors, many trade contractors have very short duration activities to perform at a given home. Consequently, crew assignments can include several homes on a given day, and the timing of their work at a given home is thus often uncertain. Homebuilders have responded to this by using a time-gating approach, and turning over the home to trade contractors in whole day increments, regardless of the actual duration of the task to be completed (Walsh et al. 2003a).

Local building departments conduct building code compliance inspections at several points in the construction process. In most cases, the builder's on-site superintendent arranges for these inspections, and responds appropriately based on the results of the inspection. When the work passes an inspection, the homebuilder will arrange for the continuation of work. When the work fails the inspection, the homebuilder must determine the reason for the failure, contact the relevant trade or trades, and arrange for corrective action. Upon completion of the corrective action, the homebuilder must arrange for re-inspection, and once again respond accordingly. Code compliance inspections are also quite short, usually with durations in the range of a few minutes (Mayo and Bashford, 1993). Because the building department often does not (or can not) provide an estimate of the time of a given inspection, code compliance inspections are usually given an entire day, similar to subcontractor time gates.

Work progression through the various trade contractor stages might be conceived as similar to the progression of pieces through a factory, except in this case the piece is stationary and the machines (work crews) move from piece to piece. Little's Law (Hopp and Spearmann 2001) describes the relationship between throughput (TH), work in progress (WIP), and cycle time (CT) for work flow in a factory as follows:

$$WIP = CT \times TH \quad \text{(Eqn. 1)}$$

This expression has been shown to be applicable in high-volume residential building (Bashford et al. 2004), at least over a long time period. However, because sales variability is very high, and fluctuations occur over a much shorter time than the cycle time to construct a home, this simple relationship is of less practical usefulness than might at first be assumed. Rapid sales tend to load production buffers, which are then unloaded at a later time by increases in production capacity or by periods of low sales. These processes of buffer loading and unloading must be considered when attempting to understand the production system.

Bashford et al. (2004) observed the applicability of Little's Law over long time periods, using building permit data from the City of Chandler, Arizona. Data available for this study included the permit issue date and the permit final date. From these dates, cycle time, work in progress, and throughput could be calculated for residential construction at the level of the individual house. However, it was not possible to drill down to the level of the individual trades involved. Understanding the response of the trade contractor to workload increases would seem, however, to be a key to understanding the production capacity increases which lead to buffer unloading, and thereby to the development of predictive ability for residential cycle times.

The trade contractor level seems to be a critical piece of the puzzle for at least two reasons. First and most obviously from the previous description, the trade contractors are responsible for crew management and daily work assignment. In theory, this work assignment is completed in response to builder requests based on their monitoring of progress at their subdivisions. In practice, however, many trade contractors find these requests to be so unreliable that they employ their own personnel to search subdivisions for which they are contracted to locate work ready-to-conduct (Walsh et al., 2003b).

Furthermore, Joines (1999) studied trade contractor crewing strategies in residential construction. He found that trade contractors have the ability to absorb dramatic fluctuations in workload – on the order of 300% -- which ability they develop largely through network crewing. Residential trade contractors reported employing directly a relatively small number of crews, appropriate to about their lowest workload for the year. As workload increases, they can activate additional crews. First, they have part-time crews, composed often of past full-time employees. Next, they have a network of piecework crews with which they have experience. Finally, when the backlog gets very large, they rely on an extended network of friends of employees, recommendations by word of mouth, etc., to obtain additional production capacity. Because trade contractors have responsibility for the management of production and the deployment of variable production units, it seems logical to consider measures of their production.

The second reason is somewhat more subtle. It was previously pointed out that Little's Law was not practical for application to the entire house, because the period of variation in sales was substantially less than the cycle time to construct a housing unit. The work of any given trade contractor has, of course, a substantially shorter cycle time than the entire unit. Accordingly, it seems promising to consider measures at the trade contractor level in order to achieve a better match between Little's Law and actual production.

In this paper, building permit data including code compliance inspection dates were used to evaluate the applicability of Little's Law at a finer level of detail. Since code compliance data included dates of inspections and re-inspections, code compliance inspection failure rates were intrinsically available from the same data set. Code compliance failure rates were found to be surprisingly high, and variable, which impacts the ability of Little's Law to predict cycle time. One aspect of the flexible crewing strategy previously described is that the additional production capacity represented by the additional crews comes with ever less direct knowledge of the ability or quality control of these short-term production assets. In essence, the residential construction market represents an n-machine space, in which additional production assets can be brought on-line, each with less confidence in the quality of the output. In light of this conceptual model of a trade contractor in the residential "factory", it was hypothesized that increased workload would be reflected in variable quality, and thus in higher failure rates of code compliance inspections. The implicit presumption in this hypothesis is that code compliance inspections are related to quality.

BUILDING PERMIT DATA

The Development Services Department of the City of San Diego, California, provided data from residential building permits in the City covering the period January 1999 to July 2003. Only new units which both started and finished sometime in that period were included. The data were extracted from the Department's database, and consisted of the fields indicated in Table 1. The Inspection Type was taken from a list of inspections conducted during residential construction in San Diego, and so gave an indication of the status of work at that time. The Inspection Status was recorded as either P ("pass") or F ("fail"). In the case of failures, no indication as to the reason for the failure is archived. The data provided included a record for each inspection conducted, with the identifying and structure information repeated. A total of 160,995 records were provided.

Table 1: Building Permit Data Fields Provided by San Diego Development Services Department

Category	Relevant Fields
Identifying Information	Permit Number, Permit Application Date, Permit Date, Permit Final Date, Applicant Name
Structure Information	Building Area, Floor Area, Habitable Area
Inspection Information	Inspection Type, Inspection Scheduled Date, Inspection Completion Date, Inspection Status

By counting the number of unique permit numbers associated with a particular applicant name, the high-volume builders were revealed. The vast majority of the records arose from applicants with over 100 permit numbers in the City of San Diego, comprising 138,646 records out of the 160,995 provided. These records relate to a total of 7,818 separate homes.

A study of the inspection types included in the database reveals that there are a number of pathways through the building code compliance process. For example, in some cases each service rough-in receives a separate inspection, while in other cases there is an "all rough-ins" inspection. Depending on the features of the home, some inspections will not always occur; for example, the stucco and lath inspection is not always performed, presumably because some other siding has been used. In another example, some homes have inspections of the natural gas connections; others are not located in areas served by natural gas and no such inspection takes place. In addition, the work of some trades is not inspected at all; there is no cabinet inspection, for example. As a consequence of these difficulties, it was necessary to identify a few inspections that always occurred in some form, and to use those as break points between different phases of the home (Figure 1).

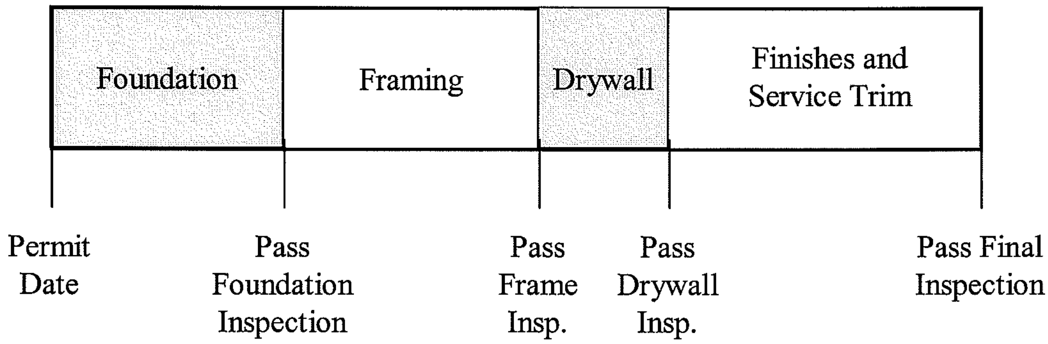

Figure 1: Phases of Construction and Important Dates from Database

Further investigation revealed that the framing and drywall phases are poorly defined in the database. This is because in some cases, the framing inspection is completed at the end of framing but before any service rough-ins (mechanical-electrical-plumbing), and in other cases the frame and the rough-ins are inspected at the same time. This significantly influences the usefulness of the database in regards to the framing inspection because it is not possible to tell what is actually being inspected during this inspection. The result is that the cycle time of the framing and drywall phases cannot be accurately assessed (nor can the various service trades). During the finish and service trim phases, inspections are too infrequent to be applied to any individual trade. As a consequence, even though higher failure rates are attributed to the framing inspection, the foundation phase is the best opportunity to identify an individual trade's production metrics.

PRODUCTION MEASURES FOR FOUNDATION CONSTRUCTION

The foundation process was deemed to begin as of the Permit Date in the database. The permit application date was also provided, but this date is often well in advance of the start of construction. In fact, in many cases this date is years in advance of the start of construction, as builders often submit applications for all the lots in the subdivision at one time, early in the development process. Builders typically release homes to sales in phases, a few at a time, with phases separated by several weeks to several months, so the lag between the permit application date and the start of construction can be very large, especially for the later phases in the subdivision. The permit date reflects the date on which the permit is issued, which is commonly very close to the intended start of construction.

The foundation is typically installed by a concrete contractor. Post-tensioned slabs constructed on-grade are common, with waste plumbing installed under the ground floor. All other services are installed in the walls or ceilings. This means that the foundation phase does include some plumbing work, but the plumbing activity represents a comparatively minor fraction of the total effort in the foundation phase.

The permit date and the successful foundation inspection provide start and end dates for the foundation phase. The difference between these dates is the foundation cycle time (calendar days). All active foundations in a given month are counted as WIP for that month (units), and all foundations finished in a given month are throughput (units/month). Using these definitions, the CT, WIP, and TH for the foundation phase – largely the concrete construction trade contractors – in San Diego could be calculated. Using Equation 1, a theoretical WIP could be computed from Little's Law for comparison to the actual WIP. The results are shown on Figure 2.

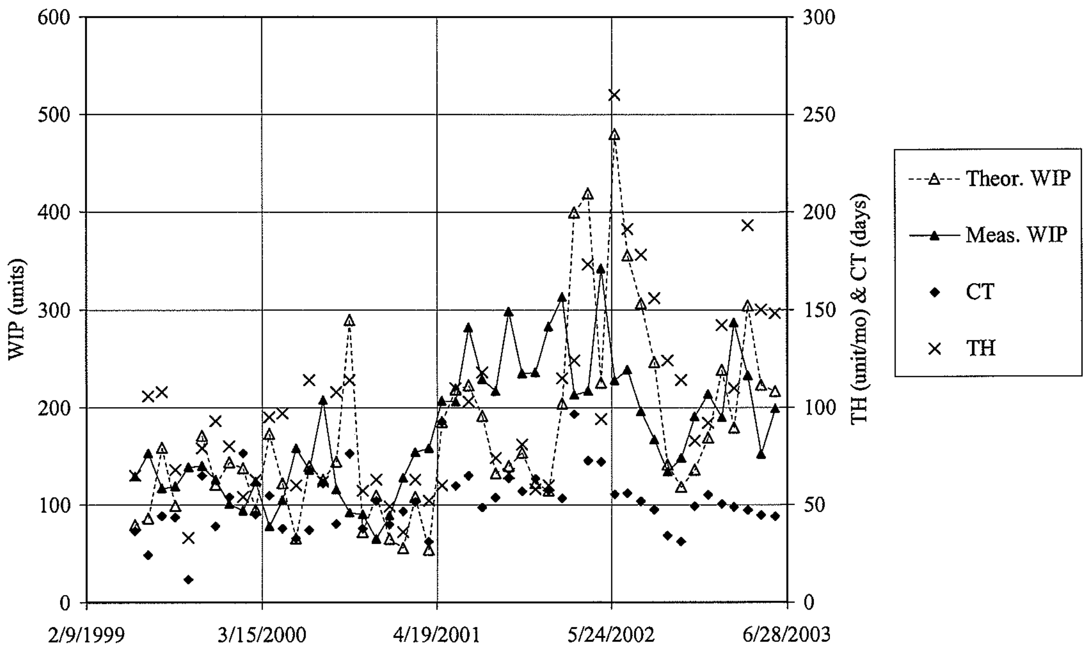

Figure 2: Time History of Cycle Time (CT), Throughput (TH), and WIP (measured and theoretical) for the Foundation Phase based on 1999 to 2003 Residential Building Permit Data for High-Volume Builders

The measured and theoretical WIP are in reasonable agreement, although some periods of buffer loading and unloading are apparent in 2001 and 2002. Further, the theoretical WIP seems to be slightly out of phase with the measured WIP over most of the time scale, which may be an artifact of the counting rules.

INSPECTION PASS-FAIL RESULTS

The observation that buffer loading and unloading are occurring when there are substantial differences between measured and theoretical WIP is explained in some detail by Bashford et al. (2004). The observation itself does not explain the reason for the change in buffer size, of course. One explanation is a run up in sales, which would pump more houses into the queue of buildable work. In fact, the database reveals that such an increase in sales (measured by starts) does occur in late 2001 and early 2002, leading to a need for increased capacity. There is some delay, apparently, in activating increased production assets, which results in a steady increase in WIP and CT over that time period. A sharp increase in TH in early- to mid-2002 indicates that additional production assets have been deployed by that time.

Based on the previous discussion of crewing strategies, this deployment of more extended production assets might reasonably be expected to be accompanied by a decrease in production quality. Unfortunately, there is little data upon which to base a production quality measurement. The best measure might be the performance of the particular system of interest for the appropriate permit numbers, but this does not work in practical terms because such data are not available. There is no central repository of such information, and even if there were, problems might not reveal themselves for some substantial time after completion of the home (especially for foundation performance).

Building code compliance inspection results are archived, however. The database used for this study contained information about the pass/fail status for each inspection conducted on the homes. Examination of these data reveals that failure rates are extremely high. Table 2 presents failure rates for the four inspections represented on Figure 1. Note that these inspections place the project on hold – no other production can take place until these inspections have passed.

Table 2: Average Building Code Compliance Failure Rates for Four Inspection Types in San Diego, California, 1999 to 2003

Inspection Type	Average Failure Rate		
	1st Inspection	1st Re-Insp.	2nd Re-Insp.
Foundation	24%	21%	20%
Framing	54%	49%	48%
Drywall	34%	26%	25%
Final	48%	33%	33%

The maximum number of re-inspections in the database was 8, which occurred for framing, drywall, and final inspections. Considering the whole day incremental scheduling method, a day is required to conduct each inspection, at least a day to coordinate a return by the relevant trade contractor, at least a day to attempt repairs, and then another day for re-inspection. This means that each failure adds a substantial delay to the affected house. It is tempting, of course, to ascribe these high failure rates to the peculiarities of construction in California, which is often regarded as a relatively unfriendly building environment. However, similar rates have been noted in a companion study in the Phoenix, Arizona, municipal area.

In terms of the time history of the failures, once again the foundation inspection was used to investigate relationships to production metrics. Figure 3 shows the time history of measured WIP together with the time history of the average failure rate for the building code compliance inspection for the foundation. Note that the trends are very similar, although once again there seems to be a lag between the two curves. Bashford, et al. (2004) comment extensively on the difficulties inherent in direct analysis of regression coefficients of such a relationship. Still, there is little question that failure rates are higher when WIP is higher, which also is the time when additional production assets in the form of temporary crews will be brought to bear. This increase in failure rates artificially increases CT even above what might be expected due to queuing in larger buffers.

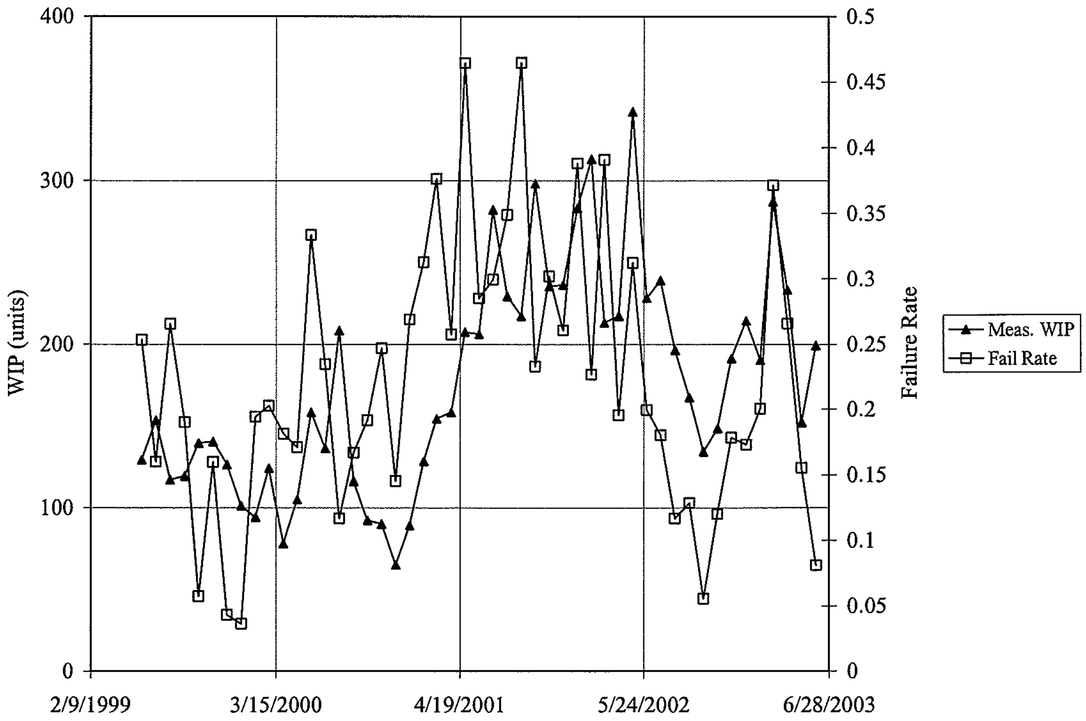

Figure 3: Time History of Measured WIP and Foundation Inspection Failure Rate for the Foundation Phase based on 1999 to 2003 Residential Building Permit Data for High-Volume Builders

CONCLUDING THOUGHTS

Homebuilding companies have been focusing on increasing the quality of their homes for many years. For example, the JD Powers ratings, the National Association of Home Builders Research Center quality program, various "zero defects at closing" programs, and Shephard (2001) all describe programs that have been or are being used by homebuilders in their search for quality. Often overlooked are the basic elements of complying with the building code. Even if there are zero defects at closing, the results of inspections made by building inspectors during construction indicate there may be other issues. Most municipalities require inspections during residential construction as part of the code compliance process. Inspections are typically made to verify code compliance of the foundation slab, footings, strap and shear, framework, heating ventilation and air conditioning (HVAC), plumbing, electrical work, gas piping, drywall, lath and the completed house. These inspections impact the construction industry and their consumers. The results presented in this paper indicate that substantial delays in production are associated with high building code compliance inspection failure rates, especially given the very large number of re-inspections required for successful completion. Given very high real estate costs, the value of time to closing is very high, implying that there is a substantial financial implication also.

The time and cost associated with inspection failures are incurred by builders, municipalities, and consumers. The builder loses time, money, and momentum due to inspections and re-inspections of failed inspections, especially repeated re-inspections. The municipality must staff appropriately to provide the required re-inspections, which creates a direct personnel cost. Ultimately, increased costs of construction are passed on to consumers, and it is worth noting that every increase in cost prevents some families from qualifying and ties up a larger fraction of family income for those who do qualify.

In terms of the direct impact on the production process, a failed inspection extends the construction cycle time of the house. Why do inspections fail, especially at such high rates? With highly specialized crews performing each activity of the construction, it intuitively seems that inspections should rarely fail. What are the relationships between failed inspections and quality of homes? The failure rate for certain inspections is extremely high. Homebuilders often criticize the inspectors, calling into question the expertise and motivation of the inspectors themselves. They frequently point to inconsistencies between the results of inspections made by different inspectors. Inspectors maintain that inspections fail because of shoddy workmanship, or because of poor management techniques which lead them to be called to inspect homes not yet ready for inspection. Whatever the reasons, it is clear that the time and rework caused by failed inspections represents waste, and the quantity is not insignificant. It is also clear that for the data set used in this study, inspection failure rates significantly increase during times when temporary crews are pressed into service. Thus, the concept of building efficiency into the process by relying on specialized trade contractors is working less well than one might hope.

Because the data set is limited to one city, the authors are hesitant to make broad conclusions about the use of specialized trade contractors for residential construction. However, in this instance, it is clear that the specialized trade contractors have significant difficulty in complying with the code, which must be considered the lowest common denominator in terms of quality.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Development Services Department of the City of San Diego, California, and in particular Mr. Joseph Compton, for making available the data referenced in this work. The study was supported in part by the National Science Foundation through Grant Number PFI 0090559. Opinions expressed are those of the authors and not necessarily those of the Foundation. The authors also express appreciation to the reviewers of this paper, who spent significant time and provided suggestions that substantially improved this paper.

REFERENCES

Bashford, H.H., Sawhney, A., Mund, A., and Walsh, K.D. (2002), "Process Mapping of Residential Foundation Slab Construction," *Proceedings*, Winter Simulation Conference, San Diego, CA, Dec. 8-11, 2002, 1752 – 1760.

Bashford, H.H., Walsh, K.D., and Sawhney, A. (2003), "Production System Loading – Cycle Time Relationship in Residential Construction," ASCE, *J. of Constr. Engrg. and Mgmt.*, accepted.

Hopp, W.J. and Spearmann, M.L. (2001), *Factory Physics: Foundations of Manufacturing Management*, 2nd Edition, Irwin/McGraw Hill, New York, NY.

Joines, J. (1999), "Work Flow Variability," MS Thesis, Arizona State Univ., Tempe, AZ.

Mayo, R.E., and Bashford, H.H. (1993), "Building Inspector Productivity Rates," Report to the City of Tempe Building Department, unpublished.

Shephard, J. (2001). "Evaluation of a Process Improvement System within the Residential Construction Industry", MS Thesis, Construction, Arizona State Univ., Tempe. AZ.

Walsh, K.D., Sawhney, A., and Bashford, H.H. (2003a), "Cycle-Time Contributions of Hyper-Specialization and Time-Gating Strategies in US Residential Construction," *Proceedings*, 11th Annual Conference on Lean Construction, Blacksburg, Virginia, USA, July 22-24, 390-397.

Walsh, K.D., Sawhney, A., and Bashford, H.H. (2003b), "A Case for the Utility of Agent-Based Simulation in Construction," *Proceedings*, 4th Workshop on Agent-Based Simulation, Montpellier, France, April 28-30, 2003, 173-179.