EVALUATION OF LEAN IMPROVEMENTS IN RESIDENTIAL CONSTRUCTION USING COMPUTER SIMULATION

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ABSTRACT

Changes to apartment designs initiated by clients are an inherent part of residential construction. Competition for customers where supply exceeds demand, and increasingly sophisticated consumers, have forced construction companies to accept the phenomenon. However, client changes delivered during construction adversely affect the stability and flow of work at the construction site. To cope with this challenge, three main changes were suggested to the traditional approach of construction of high-rise residential buildings: reduce the batch size to single apartments, work with multi-skilled teams and schedule work with a pull controlled system. To evaluate these three changes, Sacks and Goldin developed a management simulation game, called 'LEAPCON™', which simulates the construction process of an eight story building with 32 apartments using Lego® pieces. Repeated executions of the live game indicated reduced cycle times, cash flow and levels of work in progress, and improved throughput. However, investigation of the separate and combined influences of each intervention could not be measured, nor could the performance indicators be monitored through time. Thus computerized discrete event simulation was needed for more complete evaluation of the three lean management changes. Twelve computerized simulations were built using the Stroboscope® program. It was found that each one of the interventions improved one or more of the parameters of interest, while different combinations of them also improved some of the results. Reduced batch size improved cash flow and work in progress; multi-skilled teams improved labour utilization rates, and pull flow enabled execution of all client changes. However, application of all three interventions in unison was essential for achieving the anticipated results simultaneously.

KEYWORDS

High-rise apartment construction, production system design, computer simulation.

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INTRODUCTION

Competition due to supply exceeding demand and increasingly sophisticated clients force property developers and construction companies to offer clients the possibility of customizing the interior layouts and finishing designs of their apartments. Apartment buildings must then be built as customized products. Implementing client changes affects the productivity, stability and flow of the construction project (Sacks et al. 2005a).

The principal problem is that the timing of client decisions, in most cases, does not match traditional construction schedules. Project managers must decide whether to start finishing works in an apartment when called for by their schedules, or to wait until the decision are made and definitive information is available. If a project manager decides to begin work according to schedule, he or she assumes a risk that demolition may become necessary to suit clients' needs; on the other hand, if the project manager decides to wait until decisions are made, the pre-determined work flow is disrupted. Therefore it is common for the company to fail to meet the client's demands. Most construction companies price client changes at a premium above regular works (Rosenfeld and Paciuk 2000), due to the waste of increased management costs and the need for rework to effect changes after finishing works have already progressed.

Traditional construction of high-rise apartment buildings includes:

a) Large batches (commonly whole floors) and large buffers between work teams (subcontractors want to be sure that they have sufficient work ahead to maintain productivity).

b) Finishing works are scheduled to be executed sequentially from the bottom to the top using critical path tools, because it gives the shortest possible theoretical schedule (when there are no design changes or rework). This implies working with a push flow system.

c) Work is performed by highly specialized subcontractors, who each execute a specific part of the work.

In small projects such a traditional construction management system can be used without too much harm (Koskela and Howell 2005), but in large and medium scale projects, the traditional approach breaks down. Tommelein (1998) claimed that the models used in the industry do not properly describe real construction processes where instability and uncertainty are common. In this context, three principal changes in the construction management system were proposed (Sacks and Goldin 2005):

1. Reduce the batch size to the minimum, usually a single apartment.
2. Employ multi-skilled teams that are capable of performing as much as possible of the finishing trades in an apartment.
3. Implement a pull flow system.

Sacks et al. (2005b) proposed a role play game, called LEAPCON™(LEAPCON 2005), to examine the influences of the changes to the construction management system. However, live executions of the game enable only relatively superficial examination of the impacts of the three changes proposed and suffer significant drawbacks in terms of accuracy and comparability:

- Players are human – although there are very clear rules, players can make independent decisions that change the results (Lucas 2004);
- Quantity of runs is severely limited by the availability and stamina of players;
- Only a limited set of parameters can be measured and these only at specific times.

For these reasons, computer simulation was adopted to explore their individual and combined impacts, and to track the results through time. Computerized simulation has long been recognized to be an efficient way to examine process improvements in construction management (Halpin 1977). Despite its potential, its use has remained restricted to academia and very large-scale projects (Hajjar and AbouRizk 2002)

THE LEAPCON GAME

The LEAPCON™ game was developed as a part of a large scale investigation to develop a lean approach to construction management of high-rise apartment buildings (Sacks et al. 2005b). Ten players adopt the roles of the project manager and management team, four subcontractors, and client representatives. The goal of the game is to execute the finishing works for 32 apartments in an eight story building with four apartments on each story. The apartments are built of Lego® parts.

The players try to build as many apartments as they can in an eleven minute period. There are eight different apartment designs, representing the standard default model (A) and seven variations (B to H). After one minute of play, the client representatives begin to draw random pairs of design codes and apartment numbers from a hat, modelling the client design decision delivery process. This operation is repeated each 15 seconds until all apartments are 'designed'. The goal of the general contracting team is to earn as much money as possible: each apartment begun requires an up front investment of $1,000, while delivery of a finished apartment without defect and according to the design changes required earns $1,500.

The game is played in two rounds. The first simulates the traditional construction management system and the second simulates the lean management system, incorporating all three changes described above and detailed in Table 1.

Table 1: Characteristics of each of the two rounds of the LEAPCON™ game.

Characteristic	Round one (Traditional management system)	Round two (LEAN construction system)
Game time	11 minutes	11 minutes
Batch Size	Entire Floor (4 apartments)	A single apartment
Flow system	**Push**, the goal of the contractors is to build as many apartments as they can	**Pull**, the flow of contractors is controlled by availability of design information
Work Groups	Specialized teams	Multi-skilled teams

Over a span of just over one year the game was played 16 times by a variety of teams ranging from undergraduate and graduate students to subcontractors and executives of three large construction companies in Israel and other countries. Table 2 provides a summary of the results.

Table 2: Summary of live round results of the LEAPCON™ game after 11 minutes.

Round		Work in Progress (units)	Apartments Delivered (units)	Cash Flow ($)
Traditional (Round 1)	Average	14.1	8.5	-$9,136
	Std Dev	4.5	3.4	$5,427
Lean (Round 2)	Average	2	16.3	$6,136
	Std Dev	1.1	2.1	$1,645

COMPUTERIZED SIMULATION

The results of the live game show improvement in every one of the parameters, but do not provide any information about how each lean intervention works, what its impacts are, how they develop as the production system becomes 'primed' with work and WIP rises, which must be implemented in full and/or can be implemented in part, how they cope with changes, etc. The computerized simulation was designed to provide answers to these questions, so as to deepen the understanding of how lean production system design changes function in a construction context.

The Stroboscope simulation software (Martinez and Ioannou 1999) was selected among other possible systems because it allows resources to be characterized (to have a unique identity). Twelve simulations were programmed, each one with different characteristics that make possible the examination of the impact of every one of the changes in the construction management system separately and together. Table 3 lists the simulations with their characteristics and their tag letter.

Table 3: The different simulations.

		Push system flow		Pull system flow	
		Specialized contractors	**Multi-skilled teams**	**Specialized contractors**	**Multi-skilled teams**
Without client changes	**Batch size 1**	c	d	e	f
	Batch size 4	a	b		
With client changes	**Batch size 1**	C	D	E	F
	Batch size 4	A	B		

The characteristics of simulation E, for example, are: with client changes, batch size of 1 apartment, specialized contractors and pull system flow. Simulation A simulates the traditional construction management system and simulation F simulates the lean construction management system. Pull flow with batch sizes greater than one were not modelled.

Preparation of the simulations required input data for all possible permutations of individual activities that might be encountered in the LEAPCON™ game (e.g. 'change an apartment from design A to design H after the wiring has been completed'). A team of undergraduate students performed each of these according to a matrix of activities. Each was repeated 50 times in different sequences, durations were recorded and the average and standard deviations calculated from the samples were then input to the system to define normal distribution functions, which are recommended in situations where the sample size is relatively small (Lu and AbouRizk 2000).

The required quantity of simulation runs for each situation was established by experimentation to achieve reliable precision of two decimal places for average duration of the process. It was found that after ~780 repetitions the results converge on the desired precision; for sake of simplicity the number of runs for every simulation was set at 1000.

The simulations were also checked for compatibility by comparing the results of runs cases A and F after 11 minutes with those recorded for the live runs of the game. The intrinsic limitations of the live game (very small number of repetitions, incomplete runs and human influences and error, learning curve between rounds) meant that close numerical matches were not expected. However, the same trends were expected and indeed found, as shown in Table 4.

Table 4. Quantitative and qualitative comparison between the live rounds and the computerized simulations.

Measured parameters		Live Traditional	Live Lean	Direction of the change	Computer Traditional	Computer Lean	Direction of the change
Accepted Apartments (units)	Average	8.5	16.3	⇧	6.8	21	⇧
	s	3.4	2.1	⇩	3.8	1.3	⇩
Work in Progress (units)	Average	14.1	2	⇩	22.8	5.2	⇩
	s	4.5	1.1	⇩	4.7	0.7	⇩
Cash Flow ($)	Average	-$9,136	$6,316	⇧	-$19,501	$4,999	⇧
	s	$5,427	$1,645	⇩	$6364	$1535	⇩

RESULTS AND ANALYSIS

Three comparisons were drawn: a) between the basic simulation A and simulations B, C and D in turn, to establish the impact of each intervention alone; b) between the lean simulation F and simulations D and E in turn, to establish the marginal contribution of each intervention and the combined contributions of the case where two of three interventions were applied, and finally, c) between A and F, to consider the overall impact.

IMPACT OF REDUCED BATCH SIZE

The batch size is a basic parameter that every project manager must decide on at the beginning of a construction project. In residential construction projects of the type investigated, it is usual to determine the batch size as a complete floor, to try to avoid interference between subcontractors. Comparison of simulation A (traditional) and simulation C (traditional with reduced batch size) showed that the reduction of the batch size improved the execution time by 13%, reduced the cycle time 78% (from 7:30 minutes to 1:40 minutes) and improved the cash flow: in Figure 1, it can be seen that in the traditional simulation it took 960 seconds to cross the break-even point, as opposed to 550 seconds only with the reduced batch size. The minimum cash flow, or maximum capital requirement, is another interesting parameter that can be seen in the cash flow graph. Reduced batch size reduces it from $19,191 to $4,317. Reduced cash flow requirements allow developers or contractors to operate more projects, reduce their debt and so to increase the return on their investments.

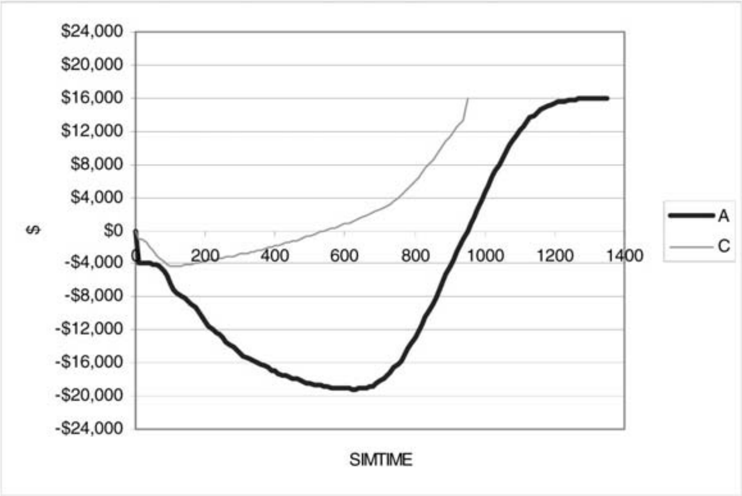

Figure 1. Cash flows of the traditional simulation (A) and the simulation with reduced batch size only (C).

However, the shortened execution time makes it more difficult to fulfill clients' change orders. In many cases changes do not arrive before the completed apartment is delivered with the standard design. The quantity of apartments delivered according to clients' change orders was reduced from 91% to 74% (see Table 5).

The combination of pull flow with multi-skilled teams, without reduced batch size, was not tested, because pull flow in this context implies full information for a whole floor. It was therefore not possible to evaluate the marginal contribution of reduced batch size to the overall lean solution.

Table 5. Simulation results for selected parameters (Average and standard deviation shown in each cell).

Measured parameters	**A Traditional**	**B Multi-skilled teams only**	**C Reduced batch size only**	**D Reduced batch size and multi-skilled teams**	**E Reduced batch size and pull flow**	**F Reduced batch size, multi-skilled teams and pull flow**
Execution Time (minutes)	18.01 *1.27*	14.64 *0.95*	15.82 *1.05*	12.69 *0.47*	18.09 *1.11*	13.85 *0.48*
Cycle Time (minutes)	7.50 *2.13*	5.08 *1.04*	1.66 *0.06*	1.63 *0.29*	1.67 *0.28*	2.68 *0.27*
Maximum WIP	22.7 *3.8*	23.2 *2.4*	7.7 *2.11*	6.5 *0.6*	4.0 *0.67*	5.4 *0.64*
Apartments delivered according to client order (%)	91% *5%*	85% *6%*	75% *6%*	72% *6%*	100% *0%*	100% *0%*
Ratio of Working time to Total time on site (%)	68%	91%	67%	93%	60%	93%

IMPACT OF MULTI-SKILLED WORK TEAMS

In the traditional construction management system numerous different contractors work in every apartment. Handover of apartments between the different contractors is a weak point that brings different problems: transfer of responsibility, wasted time, damage and difficulty in identifying existing defects, and lack of flexibility in application of labour to reduce unbalanced production durations are some examples of the problems encountered.

Multi-skilled teams resolve many of these problems and improve important system parameters. Table 5 shows the changes in the parameters between the traditional simulation (A) and the simulation with multi-skilled teams only (B). Labour productivity is a critical measure for both subcontractors and the lead contractor. In Table 5 it can be seen that in the traditional system only 68% of the total workers time on site is spent in actual work, whereas the multi-skilled teams work 91% of their time on site. However, when applied alone, multi-skilled teams appear to reduce the capacity of the system to cope with change (fewer apartments delivered according to change orders) and reduce project duration only a small amount.

The marginal contribution of multi-skilled teams is apparent in the comparison between simulations E and F. The main contributions of multi-skilling are to significantly reduce project completion duration (from 18.09 to 13.85) and to reduce the wasted waiting time of some of the work teams (utilization rose from 60% to 93%).

The contribution of the combination of reduced batch size and pull system flow is also given by simulation E. In Figure 2 it can be seen that this combination dramatically reduces work in progress (WIP) from 22.7 apartments with significant instability (for the traditional case, A) to a stable value of just 4, which gives a healthier project cash flow.

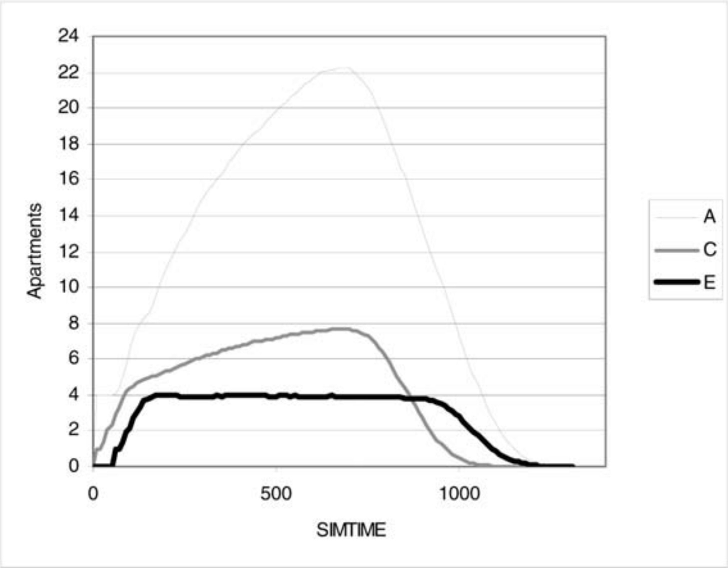

Figure 2: Comparison between the WIP of the traditional simulation against the WIP measured for both the simulation with reduced batch size and the simulation with reduced batch size and pull system flow.

IMPACT OF PULL SYSTEM FLOW

The definition of pull system flow in this case is that work on an apartment is performed at the best time for the apartment and not at the best time for the workers (as happens in the traditional system), i.e. work is only begun on an apartment once design information is complete. This should prevent accumulation of work in process inventory and make it possible to deliver all apartments exactly according to final client orders, because, by definition, the finishing works of any apartment are only begun **after** the final design option for that apartment is selected.

Pull flow with large batches is impractical and was not modelled, and so the first evaluation of the contribution of pull flow is made by comparing simulation C (reduced batch size alone) with simulation E (reduced batch size and pull flow together). The main contribution of pull flow is clearly the fact that 100% of the apartments can now be customized, whereas only 75% were customized in simulation E. Another beneficial impact is that WIP is reduced even more than reduced batch size was able to achieve, as can be seen in Figure 2, which shows that the pull system reduces and stabilizes the WIP at four apartments, instead of the WIP of eight achieved for the single-piece flow simulation (C) that worked with push system flow.

WIP is the quantity of open apartments that are in the process at any time. Large quantities of WIP demand large quantities of management resources, which reduce the attention that can be paid to each individual apartment. It also means that apartments will be open for longer periods of time without anybody working in them, which can translate into damages and theft. The main corollary benefit of reduced WIP is greatly improved cash flow, as can be seen in Figure 3.

However, due to application of pull flow, project completion time is extended (from 15.82 to 18.09) and the labour utilization rate is reduced (from 67% to 60%) (Table 5).

The marginal contribution of pull flow is observed by comparing simulations D (without pull flow) and F (with all three interventions). As expected, pull flow improves the customization rate from 72% to 100%, and reduces WIP (from 6.5 to 5.4) with the parallel improvement in cash flow.

Simulation D also allows observation of the combined influence of reduced batch size and multi-skilled teams. Project completion time was reduced by 30% (18.01 to 12.69 minutes - Table 5) by application of reduced batch size and multi-skilling together (D), which is greater than the impact of each intervention applied individually (B and C). The same phenomenon is observed in the success of the system in delivering apartments according to client change orders, although in the direction of a less desirable result. Cycle time was improved as well but apparently all of the reduction is attributable to the reduction in batch size. The improvement in cash flow appears to be mostly the result of the batch size reduction, as can be discerned in Figure 3 by comparing curves C and D.

Previously, we observed that multi-skilled teams increased the ratio of actual working time to the total time of subcontractors on site. However, the combination of multi-skilled teams and reduced batch size adversely affects this parameter – the improvement is reduced, with the ratio reducing from 91% to 87%.

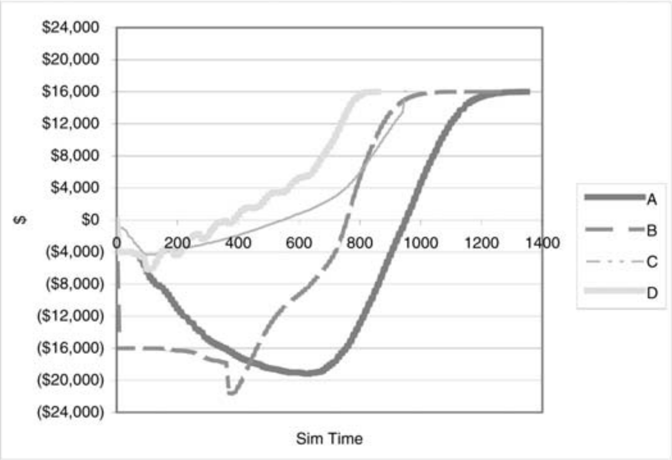

Figure 3: Comparison between the cash flows of the relevant simulations to examine the influence of the combination between reduced batch size and multi purpose groups

Combined impact of all three lean interventions

The comparison here is made between the traditional simulation (A) and the lean simulation (F). The figures in Table 5 show that not only was the number of apartments customized brought to 100% (from 91%), but also project completion time was reduced 23%, maximum work in progress was reduced from the region of 23 to approximately 5.5, with a drastic improvement in project cash flow. Figures 4 and 5 show the cash flow and WIP respectively for all the simulations, with the traditional simulation (A) and the Lean simulation (F) emphasized with thicker lines in each one of the graphs.

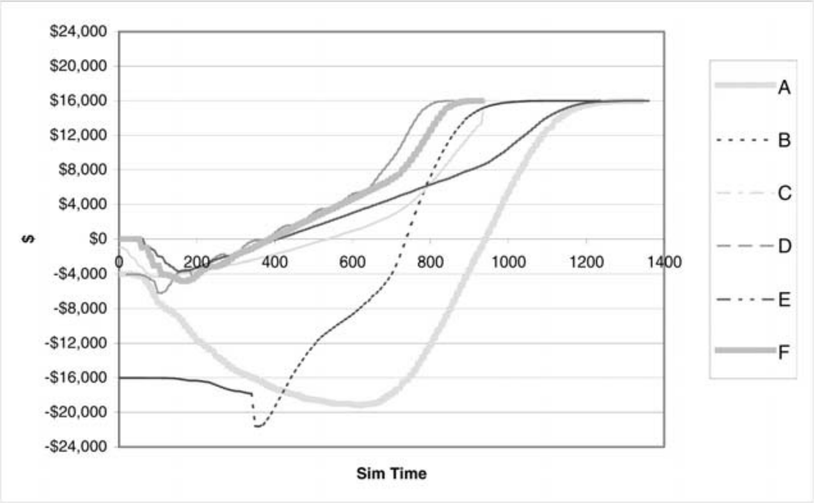

Figure 4: Cash flow of all the simulations

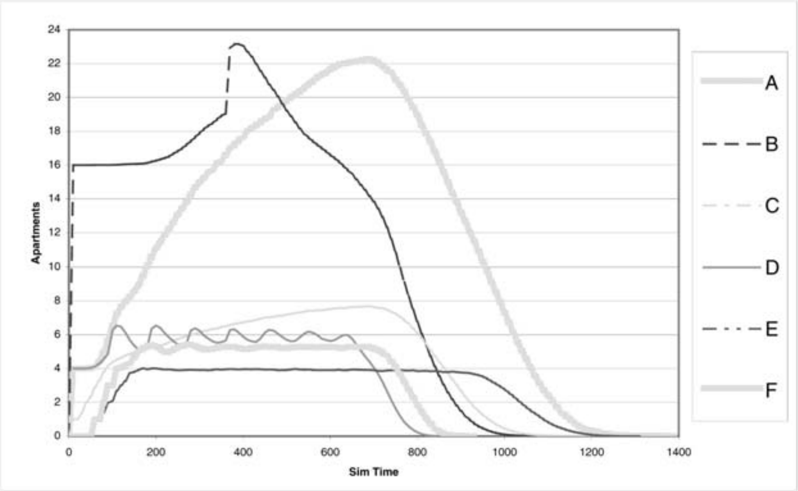

Figure 5: Work in progress of all the simulations

In all the comparisons made up to this point, there was a trade-off between shortened project completion time on the one hand, and the ability to customize apartments according to clients' changes on the other. Only when all three interventions are applied in concert is there an across the board improvement in all of the significant parameters. While the results for F are not the best achieved across all the parameters measured (with the exception of the ability to customize apartments), the difference between the best result and the result in this simulation in each and every parameter is relatively small.

CONCLUSIONS

Sacks et al. (2005a) proposed the LEAPCON™ role play simulation game to examine the influence of a lean construction management approach to the construction of high-rise apartment buildings. It simulates construction of an eight story building with four apartments on each story. The finishing works of the apartments are modelled by ten players using Lego® pieces. The three main changes to the construction management system incorporated in the game are: 1) reduced batch sizes, 2) multi-skilled teams instead of specialized contractors, and 3) transition to pull system flow instead of the traditional push system flow.

Role playing is an efficient way to examine changes to a management system, but it has limitations such as the players lacking discipline, limited time, the learning curve, measurement difficulty and others. Computerized simulation was use in order to overcome those limitations. Twelve discrete event simulations were programmed and each was run with 1,000 repetitions; this represents an equivalent of over 16 person-years of execution of the live game.

In each of the simulations, a different management intervention or combination of interventions was implemented. In this way, it was possible to evaluate the effect of each intervention when applied alone, the marginal contributions of each intervention to the full solution, and the various possible combinations of interventions. The principal parameters that were monitored were: WIP (work in progress), execution time, ability to deliver the apartment exactly as the client ordered it, cycle time, labour utilization, and cash flow.

It was found that each one of the three changes to the construction management system improved one or more of the parameters of interest. Combinations of the changes also improved the results. However, only implementation of all three of the changes simultaneously improved all of the parameters. It was also found that each change had significantly more influence on a particular parameter than the other changes, as detailed in Table 6.

Table 6: The principal factors that improve the parameters

Parameters	The changes to the construction management system with most influence on the parameter
Project completion time	Reduced batch size and multi-skilled teams
WIP and cash flow	Reduced batch size and (to a lesser extent) pull system flow
Efficient utilization of work teams time on site	Multi-skilled teams
Customization (deliver apartments exactly according to the client's order)	Pull system flow

Reduced batch size appears to be the key to improving work flow, and has a positive impact on WIP levels, cash flow and project completion time. Unfortunately, reduced completion time meant that some client changes could not be accommodated. This critical aspect, of customization of apartments according to clients' requirements delivered relatively late in the construction process, could only be addressed by using pull flow control. Multi-skilling, predictably, had most effect on improving labour utilization rates because it removed the imbalance in production rates that leads to teams being forced to wait for work to be made ready by preceding teams.

ACKNOWLEDGEMENT

The authors thank Prof. Julio Martinez for the use of the Stroboscope software and his invaluable help in revising it for this application.

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