Lean Management Model for Construction of High-Rise Apartment Buildings

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Abstract: Execution of the finishing works in high-rise apartment buildings is made complex by the need to customize apartments to the varying requirements and designs of individual clients. The conventional construction planning practice of progressing upward from floor to floor breaks down in the face of the arbitrary sequence in which clients finalize their decisions. The results are long cycle times for delivery of completed apartments and corollary high levels of work in progress, budget and schedule overruns, and general dissatisfaction with the process on the part of the developer, contractor, subcontractors, and the clients. Application of lean construction principles to this problem has led to development of a management model that adopts pull scheduling, reduced batch sizes, and a degree of multiskilling. The main benefits expected are an enhanced ability to provide customized apartments, improved cash flow, and reduced apartment delivery cycle times. The model was first formulated in theory, then tested using a management simulation game and computer simulation, and subsequently, developed for practical application. This paper presents an analysis of conventional practice, the theoretical background to the lean approach, and the specific management changes proposed.

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Introduction

In most first-world free-market economies, residential real estate developers face lively competition. Potential apartment buyers demand good service and a customized product, making the ability to tailor the interior design of an apartment to individual demands a valuable asset. Customization demands the ability to respond rapidly to late changes in design, because home-owners' design decisions are only made relatively late in the production process, always after the apartment is sold.

The disruptive influence of customization on production flow in residential construction has been recognized by construction companies for decades. Wherever customization could be avoided (where demand outstripped supply), such as at Levittown, where "The homes were . . . monuments to standardization" (Levitt 2006), it was. Where it could not, strategies, such as the conscious use of time buffers, were developed as early as the late 1950s (Horman et al. 1997). Time-gating (buffering) strategies, with highly-specialized subcontractor teams, are common in large volume U.S. home building (Bashford et al. 2003). Gann (1996) compared industrialized housing with car manufacture in Japan, highlighting similarities and differences in production and supply chain strategies. Naim and Barlow (2003) proposed the application of lean and agile approaches to housing construction in the United Kingdom, but focused on supply chains and did not tackle the fundamental construction planning and control practices. Ballard (2001) suggested multiskilled teams, as a key factor, in achieving even-flow production for reducing cycle times, and enhancing stability for construction of single-family houses.

Most of the research activity in this field has focused on single-family dwellings. In the majority of housing construction projects other than single-family dwellings, and particularly in high-rise construction, construction is usually commenced before the last apartment is sold. Conventional practice is to perform the finishing activities in a building in the same sequence as the structure itself is erected—from the ground floor up. However, apartments are not sold in the same sequence. As a result, the construction team must deal with design changes well into the construction process. In many cases, this requires demolishing work already completed in order to accommodate the desired adaptations. Change orders have been shown to have a strong negative impact on labor productivity (Moselhi et al. 2005); other researchers have shown that the later a change order is introduced, the greater its negative impact on labor productivity (Hanna et al. 1999; Rosenfeld and Paciuk 2000). Frustration for all involved is common, with high rates of litigation resulting. The conflict between the need for customized products and rigid approaches to production planning, with resulting inherent waste, is reminiscent of the problems faced by many manufacturing industries that have adopted lean production (Womack and Jones 2003).

Residential construction is a prime candidate for lean construction research, both theoretical and applied, for a number of reasons. First, it forms a major part of the construction industry in

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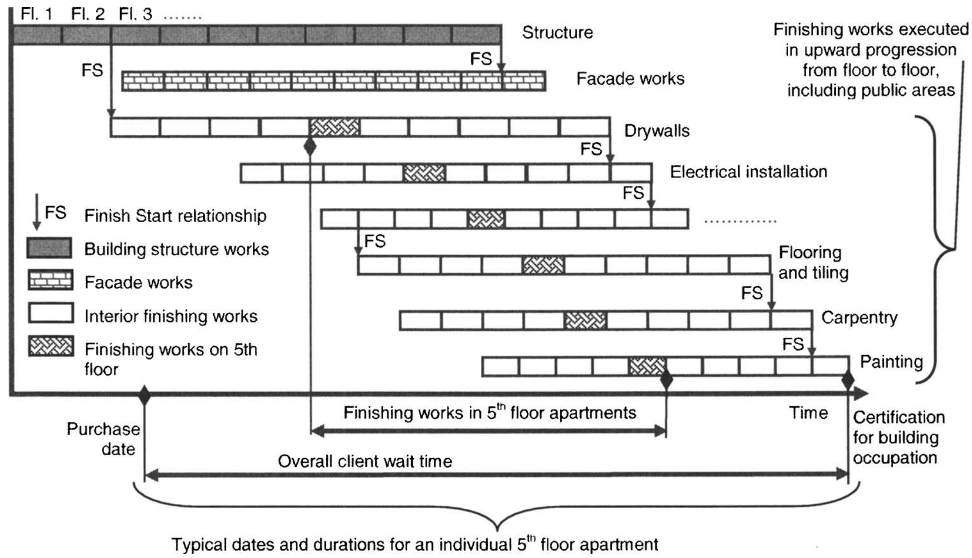

Fig. 1. Conventional management model—schematic Gantt chart for an eight-story residential building

most countries (approximately 47% in the United States) (United States Census 2004). Second, cost and schedule overruns and rework are common (Josephson and Hammarlund 1999; Koushki et al. 2005). Third, construction management practices in residential construction are largely conventional, and traditional critical path scheduling and work structuring practices are relatively inflexible (Ballard and Howell 2003). Predetermined and optimized construction schedules and centralized control structures result in significant and inevitable waste in projects where dynamic change is prevalent. For example, Bashford et al. (2003) examined the impact of time-gating strategies, adopted by U.S. housing developers, exposing very long cycle times and large inventories of work in progress (WIP) that resulted from extreme optimization of the individual activities for single-family houses. The relationship between cycle time and WIP, predicted by Little's Law (Hopp and Spearman 1996), was shown to hold at a macroproject level.

High-rise residential construction is typically characterized by repetitive cycles of activities performed consecutively on each floor. The line-of-balance method (Carr and Meyer 1974; Peer 1974) has traditionally been considered applicable, because it ensures continuity of work for teams, but it is not in common use. The more recent focus on "location-based" planning using dedicated line-of-balance software (Seppanen and Aalto 2005), is likely to facilitate its use. However, where thorough customization of apartments is necessary and information is delivered late in the process, neither the sequence of locations nor all of the construction methods are known completely *a priori*, making the use of the method difficult, because the nature and size of many work packages cannot be predicted.

In this research, a lean construction management strategy, based on pull flow scheduling, was developed for high-rise customized apartment buildings. The research method comprised five basic components: Observation, data collection, and analysis of current practice; formulation of a theoretical alternative management strategy; laboratory testing of the strategy using simulation; development of a practical implementation strategy in collaboration with a task group of a large high-rise construction company; and implementation in a pilot project and monitoring of results. This paper focuses exclusively on the current state and formulation of the alternative management approach; brief summaries of the early simulations and the approach to trial implementation are provided to complete the picture. Detailed descriptions of the simulations are reported separately (Sacks et al. 2007); the implementation strategy developed by the task group for the pilot project will be reported in future work.

Analysis of Existing Practice

For purposes of this discussion, we define the "conventional approach" to planning construction of high-rise apartment buildings to mean the practice of scheduling construction activities to be performed starting from the lowest floor and then continued on floors above in simple upward progression. Consecutive technologically constrained activities follow one another in the same upward progression, until the building is completed. Each work team can begin its activity on a floor when the previous team vacates it, and so, in theory, work teams can follow one another in simple linear fashion without interruption. Scheduling in this manner aims to fulfill the management objective of least duration; from the perspective of each floor, it is always occupied, and so work on it is continuous.

Fig. 1 illustrates the conventional approach using a Gantt chart. The activities shown in the upper row of the figure represent erection of the building's structure. The structure is naturally constrained to be built from the ground up, floor by floor. The activities shown in lower rows represent the finishing works (drywalls, flooring, plumbing, electrical installations, tiling, painting, carpentry, etc.) that complete the building. The first finishing activity is scheduled to begin as soon as the preceding structural activity vacates each floor, and so on, as shown. Note, while structural activities have a technological constraint, that they cannot precede structural activities on lower floors, no such constraint exists in the case of finishing activities. Nevertheless, the default convention is to simply continue the same ordered sequence as was used for the structure, because in the absence of any design changes, this provides the shortest overall duration.

Schedule plan and control data retrieved from the archives of a major construction company were studied in order to assess the impact of the mismatch between theoretical plan and construction

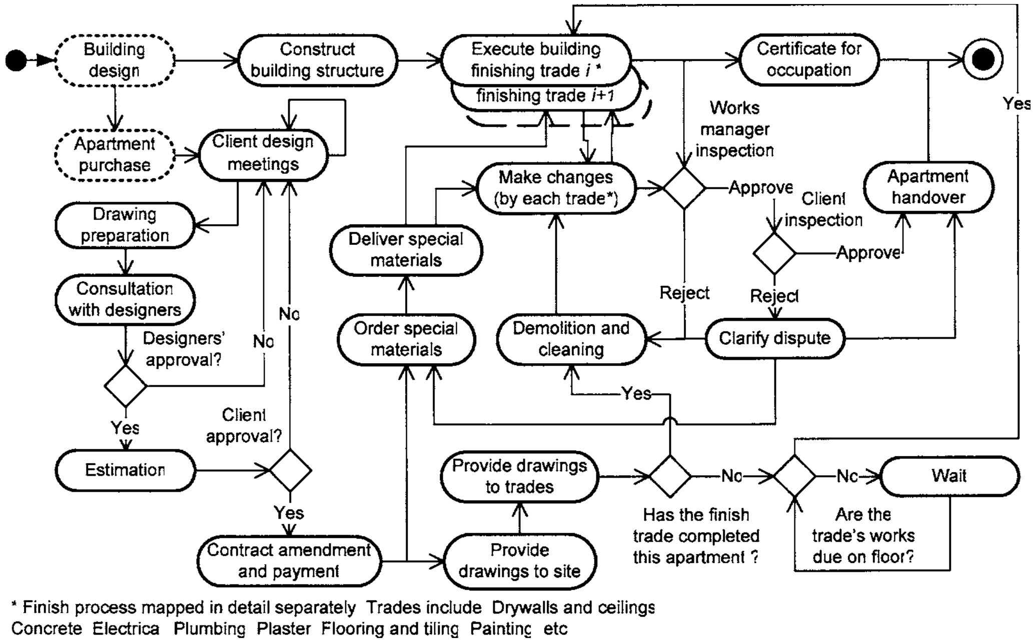

Fig. 2. Information and workflow process map of traditional management model

reality. The company builds approximately 2,300 apartments annually, all in medium to high-rise buildings of reinforced cast-in-place concrete, some of them with precast facades. Three projects (276 apartments) were analyzed in detail. The projects were assessed in terms of lean metrics, such as waste, batch size, cycle time, and WIP. The findings, based on the data, were augmented with the experience shared during 24 weekly meetings of a joint academia-industry task group (consisting of the authors, a senior executive of the company, a head engineer, two project managers, a construction engineer, a site supervisor, a construction planner–scheduler, and two representatives of the client service department), which was formed to research and develop new management procedures. Standard practice of the construction planning department of this company is to schedule construction floor by floor as defined above, although no effort is made to achieve equivalent production rates for work teams.

The value stream for a typical customized apartment was mapped at two distinct levels of detail: The information and work flow through the process, and the detailed finishing activities. In the information and workflow process map, shown in Fig. 2, the need for rework resulting from late changes is shown explicitly by the demolition activity, while accumulation of WIP is shown by the "wait" activity. These wastes are derived from the fact that the overall building design and construction stream (shown along the top of the fig.) is planned and pursued without consideration of the impact of the information processes of the individual apartments. The map of the detailed finishing trade activities included 56 distinct on-site activities, executed by 18 separate work teams, with 54 handovers between teams. At each handover, the work completed was checked for quality by the general contractor's site supervisor with extensive checklists.

The first observation was that all of the forms of waste classified in lean thinking (Womack and Jones 2003) occur; examples are listed in Table 1. Second, it was noted that the batch sizes invariably comprised all the apartments on a typical floor, usually four to six. WIP, counted as the number of apartments in which work was performed simultaneously, rose rapidly at the start of each project, reaching the full complement of apartments in each building, and remained at that level for the duration of the project (as can be seen in Fig. 5). The ratio between the total WIP and the number of apartments worked in on any given day averaged 4.4 (calculated for each apartment as the total duration from start to finish divided by the actual number of days on which work was performed in the apartment). The high WIP level can be inferred from Fig. 3, which shows a record of work performed in a typical apartment; the gaps between periods of activity represent days the apartment spent in queues waiting for subsequent activities.

Cycle times for finishing apartments are relatively long. Table 2 lists the average cycle times measured for different phases of apartment construction, together with the standard deviations for each. The net duration required for execution of the finishing works averaged 10 work weeks. If cycle times could be reduced, the quantity of WIP required would also be reduced. Application of Little's Law (Hopp and Spearman 1996) suggests that if cycle time could be reduced to 15 weeks (50% more than the net working time), WIP could be reduced to 30% of current levels without changing project durations.

One apparent cause of high WIP is that subcontractors, who are employed on unit price contracts, selectively assign their labor to work packages with high rates of productivity (Sacks 2004; Sacks and Harel 2006). Project managers reported that the subcontractors tended to redirect their efforts to those apartments in which larger quantities of work were available, leaving many minor details unfinished in incomplete apartments. Apartments with little work left were simply not completed, thus, remaining as WIP. Push scheduling was another cause of high WIP, since work was begun in apartments that either had not been sold or where client changes had not been confirmed, with the result that stoppages in their execution were inevitable.

Allocation of labor to each project by specialty contractors was not stable. Fig. 4 shows the number of workers on site for 10 specialty contractors, over a one month period, at the early stages of a building with 48 apartments. The fluctuations in their numbers may be the result and/or the cause of instability in a project. Thomas et al. (2003) have shown that unstable flows of labor reduce labor productivity, and that variability in labor

Table 1. Waste in High-Rise Residential Projects

Waste	Observations
Undesired products	Apartments built to standard designs are less attractive to potential buyers.
Rework	Client changes performed as change orders require demolition of work completed earlier; management effort is required to coordinate late change orders and to control their execution; repair of damage done by successive subcontractors to work performed earlier.
Inventories	Inventories of completed (but not yet purchased) apartments are accumulated; finish materials are delivered in batches from each supplier, not per apartment, and stored until used; work in progress encompasses 100% of apartments.
Unnecessary activities	Unfinished apartments must be cleaned and repaired after periods during which they are not worked on; temporary measures are taken to protect work partially completed, such as security doors installed to lock incomplete apartments.
Unnecessary movement of workers and/or materials	Work stoppages are frequent when apartments are sold during finishing, to allow time for clients to reach design decisions—specialty contractors are forced to move to other apartments and then back again later; small sections of work left incomplete when information is lacking requires return of numerous contractors to the same apartment.
Waiting for materials or information	Delays due to unavailable information reduce productivity; materials that wait to be delivered in batches delay potential work.
Products that do not meet clients' needs	Apartments built to standard designs do not fully meet the clients' needs; clients often forego customization where the cost of change orders is considered prohibitive.

productivity adversely affects project outcomes (Thomas et al. 2002).

An extensive survey conducted among a random sample of 248 clients from the contracting company's previous projects revealed that the existing process did not provide maximum *value* (Danya-Cebus 2004). The range of changes was restricted, prices for changes were considered by clients to be exorbitant, decisions were demanded too early, multiple design consultations were required at different physical locations, design choices and changes were not accurately executed, and handover dates were unreliable if changes were made. From the point of view of project developers (the company's immediate clients), value was delivered when the design decisions for unsold apartments were delayed as far as possible, extending the time during which they could sell apartments, and offer maximum customization flexibility to potential buyers.

The flow of design information (plans and specifications) from clients to the construction process did not match the flow of work performed. The Gantt chart of Fig. 5 shows the finishing works performed in 24 representative apartments of a 15-story building, with four apartments on each floor. Each cluster of four solid lines represents the work on each floor. The work start is the same for each whole floor, with sequential dates for each floor moving up the building. The timing of the information flows from client

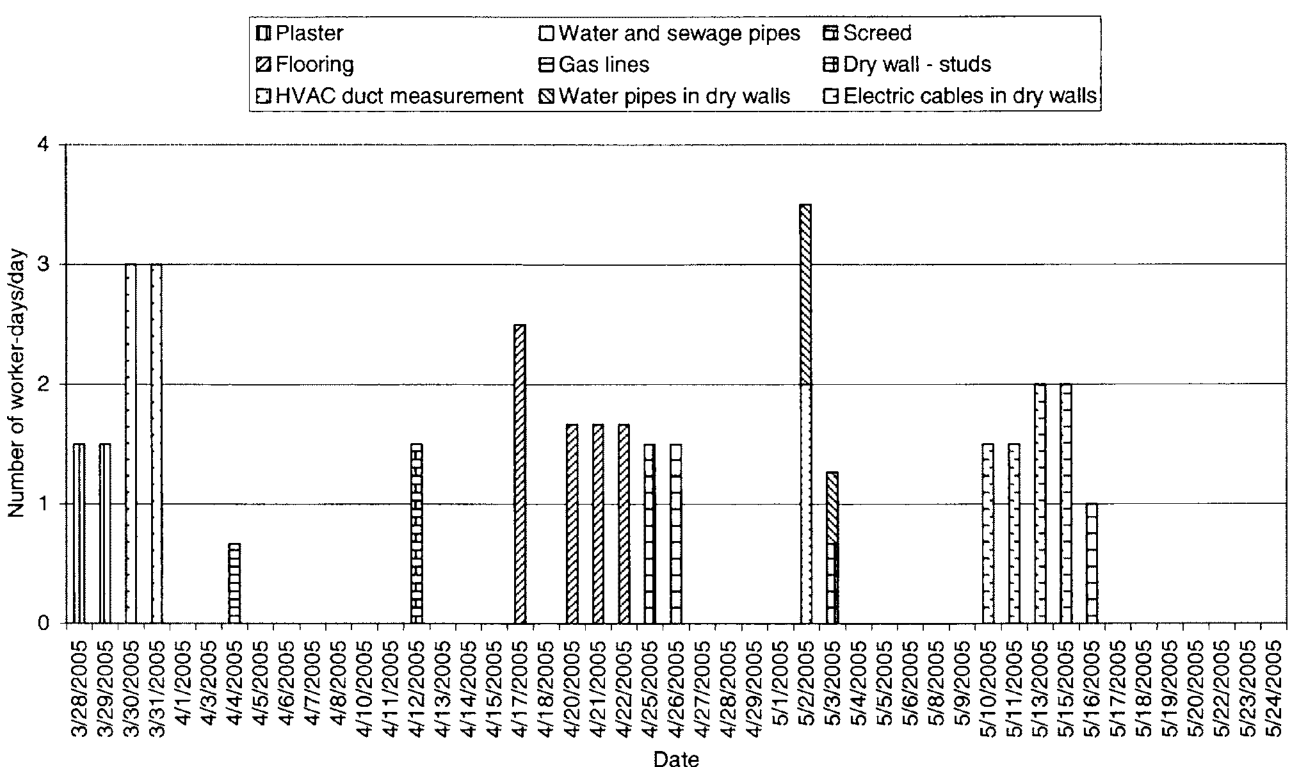

Fig. 3. A typical record of days worked in an apartment through part of its production cycle

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Table 2. Cycle Times Recorded for Finishing Works in Apartments

Cycle-time measure	Average (weeks)	Standard deviation (weeks)
Start of finishing works to handover	49.1	8.4
First client change meeting to handover	50.4	12.0
Last client change meeting to handover	24.9	15.4
Duration of change definition process—first to last client change meetings	25.5	17.5

decisions (shown as vertically hatched bars) is random, showing no relationship to the progression of work.

Attempts to deal with these problems commonly include efforts to bring the sources of instability under tighter control. Clauses are written into contracts with suppliers and specialty contractors to enable project managers to enforce schedule compliance. The most difficult problem, however, is to control the flow of information from clients. How can clients be coerced into making design decisions at specific times so as to conform to prescriptive construction schedules? Two methods encountered were: (a) High unit prices for late (postexecution) design changes, and (b) financial and other incentives to clients to make design decisions and material selections according to a predetermined set of due dates. Despite these practices, construction management personnel at all levels felt that dealing with client changes remained one of the more difficult and time-consuming of their tasks. In summary, the existing process exhibited various forms of waste, large batch sizes, long cycle times and high levels of WIP, a lengthy and complex work structure, unstable work rates, disjointed information and construction flows, and dissatisfied clients.

Lean Management Model

In reality, the basic assumption underlying the conventional approach, i.e., that the inputs and durations for each activity can be set and controlled deterministically by management, does not hold true. The availability of labor and equipment is not constant; work rates are not static, due to learning curve, human and environmental impacts; the sizes of work packages vary from apartment to apartment, subject to client design choices; material delivery times fluctuate; and most significantly, the flow of information—a critical resource—does not conform to the idealized sequence of work envisaged.

In response to the findings, the authors proposed and developed a lean management model. The broad goals for production system design were expressed as: (1) improve the value stream and remove obstacles to flow of apartments through the process: Identify and remove superfluous activities and interfaces between teams; (2) Increase the flow stability of work, work teams, and information; and (3) Reduce quantities of WIP (the quantity of apartments worked on simultaneously).

In the conventional approach, the general contractor views the project as delivery of the entire building. The change in thinking from the conventional approach to the lean approach in this context is to reconsider the nature of the project in terms of its products and their value to the clients. The whole building can be considered to be composed of one public project (the grounds, lobby, hallways on each floor, roof, etc.) and multiple private projects. Each client places value in the public project and one private project. Clients desire short apartment delivery cycle times (from submission of design changes to handover) and maximum flexibility in design changes, with minimal cost. Property developers desire client satisfaction, short cycle times, and low

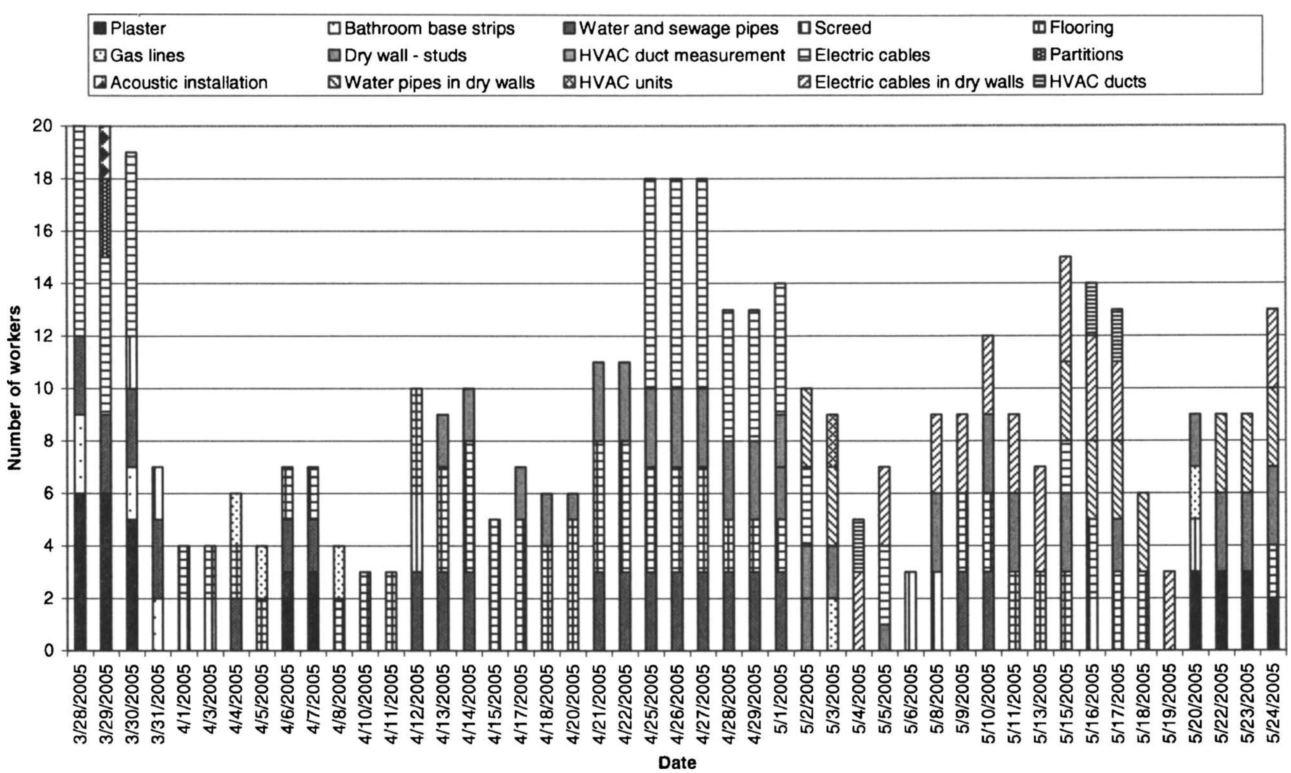

Fig. 4. Allocation of workers by specialty contractors

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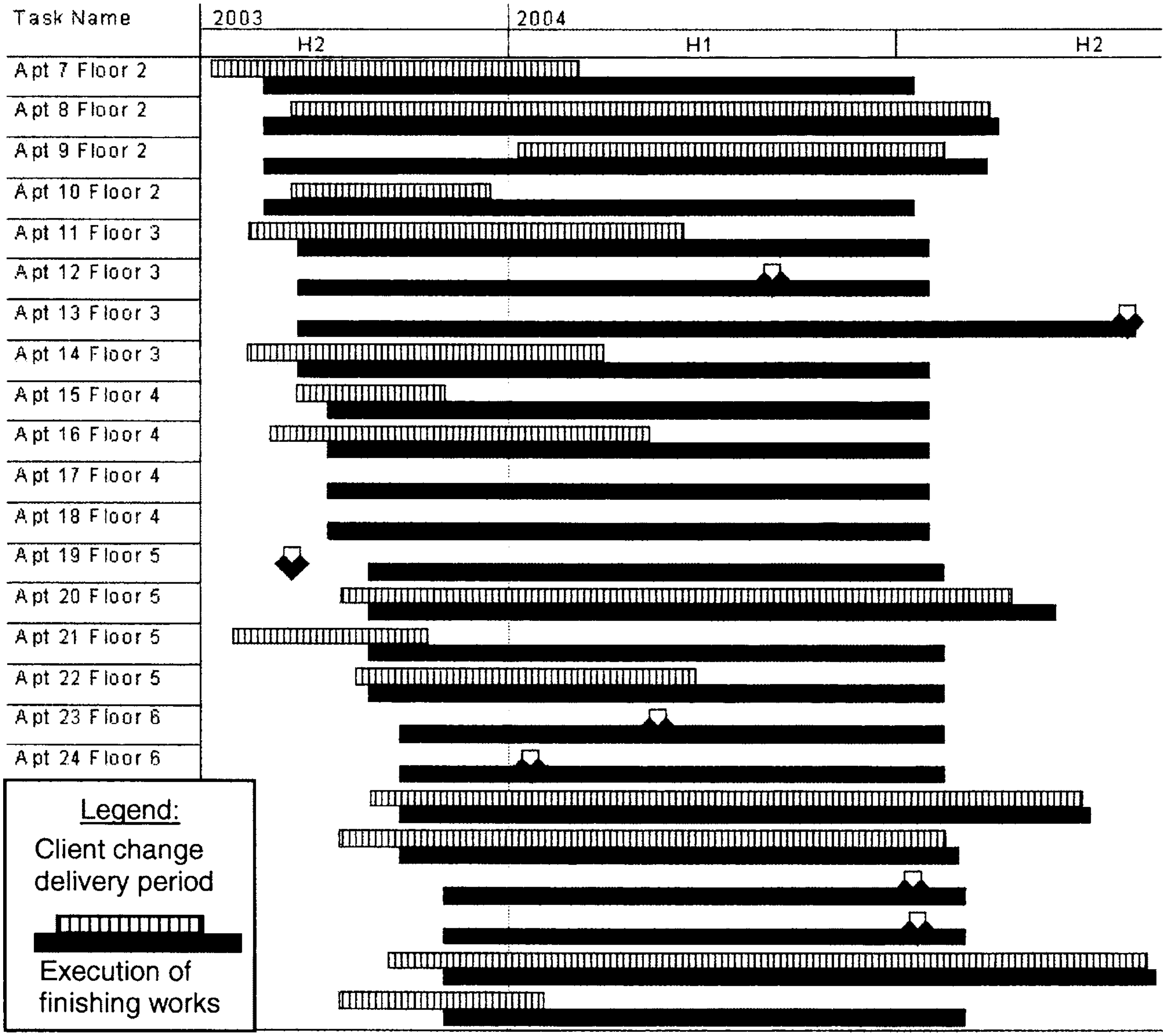

Fig. 5. Finishing works and delivery of client change orders

cost design changes to encourage sales. Construction companies desire reduction of management overheads, positive cash flow, lower direct costs, and high client satisfaction.

The important distinction between the public and private areas, for the purpose of production system design, is that the public areas of the building are stable in terms of their design information, while the apartments are unstable, because the timing and nature of their design information is subject to the clients' changes. Therefore, the main features of the lean model relate primarily to the interior finishing works of the apartments. The model has four main features: Reduction of batch sizes, use of pull flow, work restructuring, and process improvement with multitasking. Each is presented with discussion of its expected impact and considerations for implementation below.

Batch Size

The first change proposed is to reduce the batch size from full building floors (four to six apartments) to a single apartment, thus, achieving single piece flow. This change has the potential to reduce cycle times and WIP and improve the project cash flow, but it is also the basis for enabling a sequence of execution of individual apartments, that is not constrained to progress from floor to floor. It both allows and requires finer-grained planning than floor by floor execution.

An important consequence of the reduced batch size, and the possibility that workflow will move between floors more frequently, is that where heavy equipment is required, it will need to be transported, resulting in nonvalue producing movement and setup activities. Fortunately, the majority of interior finishing trades require no heavy equipment. Exceptional trades, such as wet application of stucco plaster to ceilings that requires scaffolding to provide access to the ceilings, can be replaced with alternative trades, such as drywall or acoustic false ceilings.

Pull Flow

The second change is to replace the fixed activity network schedule for the execution of finishing works with a dynamic method of pulling apartments through the finishing process, according to the maturity of the clients' design changes. The floor-by-floor sequence of work is replaced with a sequence dictated by the avail-

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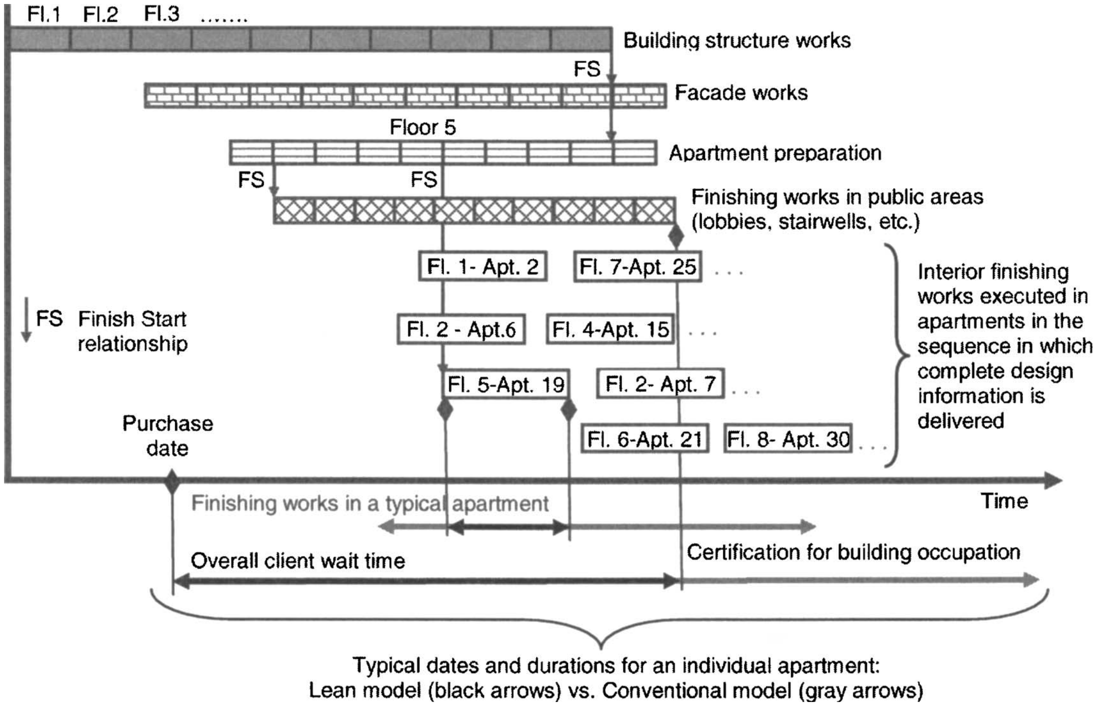

Fig. 6. Proposed lean management model—schematic Gantt chart

ability of stable design information. The client change representative assesses the design maturity of each apartment, and releases information to the site according to a continuously updated ranked list of apartment files. Ideally, apartments are not introduced into the process unless all the conditions for their completion have been completely fulfilled (e.g., design documents are finalized, work teams, equipment, and materials are available).

Pull scheduling with single piece flow has two important potential benefits:

- The waste of rework is essentially eliminated. Finishing works are not executed according to standard designs before changes can be delivered, but are instead always executed according to the clients' design requirements.
- WIP is controlled. The desired level can be determined roughly by multiplying the required throughput rate (with respect to the overall project schedule) by the practical cycle time required for continuous execution of the finishing works in each apartment. In general, WIP will be equivalent to the number of work teams plus a controlled buffer.

In practice, each customized apartment requires a unique sequence of activities, each with varying durations and often with diverse trades. The rate of introduction of "mature" apartments into the system depends on sales and the clients' decision making and may therefore also be irregular. These sources of variation can be coped with in a number of ways: (1) by planning buffers of stable work; (2) with flexible labor capacity strategies; (3) by relaxing the degree of design maturity required from time to time; and/or (4) by allowing long time buffers between trades. The latter two are undesirable (they are part of the original problem), but cannot be avoided entirely. Instead, they should be used in limited fashion and with care. The maturity of apartment design choices can be prioritized for release not only in terms of completion, but also in terms of the *probability* of completion of specific milestone design decisions before those milestones are likely to be reached. In this way, apartments with less than 100% design information can be released when absolutely necessary. Time buffers between trades should be monitored and reduced to the minimum necessary to avoid unacceptable reduction in productivity (Sakamoto et al. 2002).

Public areas, on the other hand, provide a ready buffer of stable work packages that can be introduced as and when needed, in order to compensate for periods in which insufficient mature apartments are available for the start of work. This can help avoid introducing "immature" apartments, although it is limited to the earlier stages of a project, because completion of the public areas themselves determines the cycle time for the first apartments. A degree of flexibility in labor capacity is therefore necessary, primarily because of the diversity of trades and the wide disparities in their production rates. Multiskilling, as discussed below, ameliorates the problem, but cannot solve it entirely.

Unlike a linear production line, pull flow from one "workstation" (work team) to the next using "Kanban" style flow control (Ohno 1988) is not applicable. Pull signals are not visible in construction in the way that they are in manufacturing, because the "products" do not move along a production line, but rather the work teams move from product to product. Not only must the amount of WIP between any two work teams be communicated to the teams explicitly, but also its *location*. Instead, a controlled WIP (CONWIP) system is used, in which mature apartments are released for execution at a rate set according to the desired takt time for the system (Hopp and Spearman 1996), and trades are pulled from apartment to apartment using administrative directives. Work teams must be prevented from progressing to apartments not yet released for execution. The directives must be communicated and the system's state should be made visible to all participants. This can be achieved with frequently updated notice boards on site, or better by using online information technologies.

Work Restructuring

The third change is to restructure the work itself to enhance stability and reduce cycle times. Since the goal is defined as the

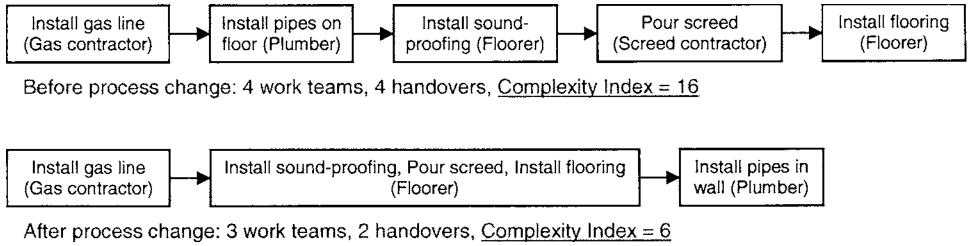

Fig. 7. Construction process complexity index

reduction of cycle time from client changes to handover, any work that can be performed independently of client decisions should be performed ahead of time. The dichotomy of the two products, public and private, identified above, implies that the building "platform" (the building structure, envelope and public areas), which is not subject to change, should be separated technically from the apartment interior finishing works, which are subject to change. Removing client-dependent features from the building structure and public areas is essential.

Many opportunities arise for achieving this by making design decisions or by selecting appropriate construction methods, or both. For example, all electrical wiring, piping and heating, ventilation, and air-conditioning (HVAC) ducting must be designed to be installed in partitions or ceilings during finishing works, instead of within reinforced concrete members during the erection of the structure. An open channel can be designed in reinforced concrete floors, from end to end of each apartment, to allow flexibility in routing wastewater pipes that restrict placement of bathrooms. Where this cannot be achieved entirely, multiple alternative routes can be prepared, rather than demanding precise information early in the process. The impact of these changes is to delay the point in time at which the client must commit to design changes, thus reducing the effective cycle time. The corollary impact is that they allow as much work as possible to proceed predictably, shielded from the instability introduced by late design changes.

The potential of technological changes to increase flexibility, through delayed dependence of the production process on information, can be measured with a simple "rigidity index" (RI). The index is calculated using the formula:

$$RI = \sum_{i=1}^{n} (N - j_i) D_i \tag{1}$$

where i=client design decision index; n=number of client design decisions; j_i=serial number of work package by which design decision i must be made; N=total number of work packages; D_i=relative impact of design decision i. A reduction of the index indicates that a process has been made more flexible. A hypothetical process with maximum flexibility (i.e., all design decisions can be made at the time of the last finishing work package) would have $RI=0$; a process that demanded all design decisions before its start would have $RI=\sum_{i=1}^{n} ND_i$.

The result of the first three changes is a work sequence similar to that shown schematically in Fig. 6. Interior finishing of apartments is begun in the sequence in which information is delivered. The reduced cycle time for a typical apartment is shown as a full line superimposed on a dashed line that represents the cycle time for the same apartment in current practice. Independent work packages, such as structure, facade, stairwells, and lobbies are shown separated from the apartment finishing work packages. Apartments can be delivered to clients when two conditions are fulfilled: The building, as a whole, receives certification for occupation, and the individual apartment is complete. For most apartments, the first condition precedes the second, but for some, occupation may be delayed while the public areas are completed.

Process Improvement with Multiskilling

The work process can be improved by recognizing that fewer work teams, each performing larger packages of continuous work,

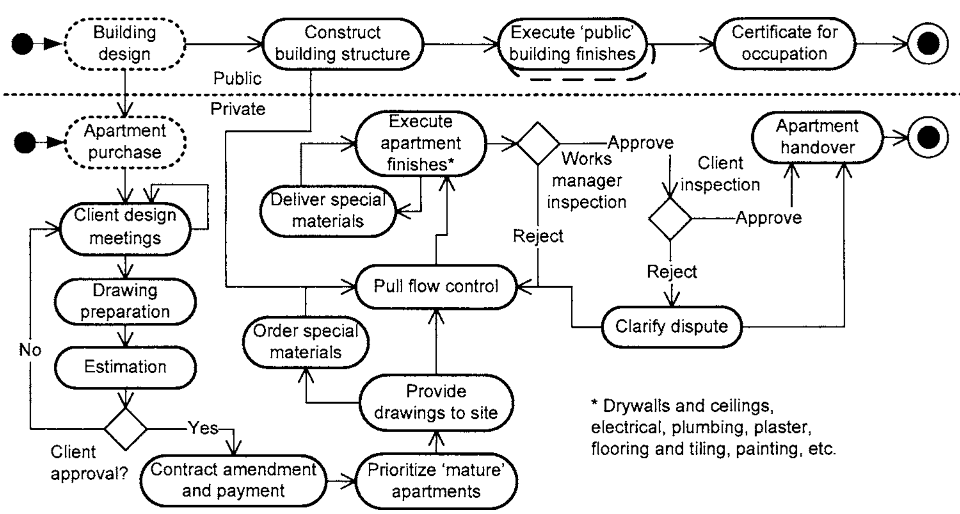

Fig. 8. Information and workflow process map of the lean management model

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Table 3. Lean Apartment Simulation Game Results for 11 Repetitions (Sacks et al. 2005)

Round		Apartments completed	Defective apartments	Time to deliver first apartment (min:s)	WIP	Throughput (units/min)	Cash flow	Cycle time (min:s)
Round Number 1 (conventional)	Average	8.5	1.2	5:45	14.1	1.3	($9,136)	5:26
	Standard deviation	3.4	1.8	1:42	4.5	0.5	$5,427	1:00
Round Number 25 (lean)	Average	16.3	0.0	1:34	2.0	2.0	$6,136	2:18
	Standard deviation	2.1	0.0	0:36	1.1	0.3	$1,645	0:41

implies fewer interfaces and thus a more stable process with lower management overheads. Longer periods of continuous work and fewer interruptions between work packages should also contribute to reducing cycle time and WIP. This can be more clearly understood by considering an extreme case, where all of the work in an apartment is performed by a single multiskilled team, in a single continuous activity; the WIP level is then restricted to be equal to or less than the number of teams.

A quick measure of the complexity of the work process can be obtained by multiplying the number of work teams by the number of handovers between them. The lower the value, the more streamlined the workflow. For example, the standard process mapped for one of the buildings included in this study required 18 separate work teams, with 54 handovers between them; the corresponding "complexity index" was 972. The relative improvement of any specific process change can be compared by recalculating the resulting complexity index. Fig. 7 illustrates the concept with a simple example extracted from a full construction process analysis, in which two alternatives for the process of flooring are compared.

Multiskilling has a corollary beneficial effect of increasing the number of work teams that can work in parallel rather than in series. This is similar to replacing two different machines that operate in series in a production line with two identical alternative versatile machines that operate in parallel. The change reduces queuing times by providing two parallel routes (Hopp and Spearman 1996). The impact of multitasking in production cells has been shown to be significant in precast concrete fabrication (Ballard et al. 2003).

The resulting high-level process map is shown in Fig. 8. The distinction between the public and private areas is reflected by the lack of information or work flow crossing the imaginary boundary between them.

Management Simulation Experiment

A management simulation game was devised to investigate the effect of the changes proposed in a "laboratory" setting before proceeding to explore implementation in a pilot project. It was first implemented using live participants, and subsequently using computerized discrete event simulation, which allowed the thorough exploration of the distinct impacts of each change in isolation and in different combinations. Called the LEAPCON (lean apartment construction) simulation game, it simulates construction of an eight-story building with four apartments on each floor. Although a complete discussion of the experimental method and results is beyond the scope of this paper, a brief description of the experiment and its results are pertinent in helping gauge the scale of change that might be achieved. Full details can be found in (Sacks et al. 2007).

Four participants are assigned roles in a general contractor's organization and four more are to fulfill the roles of specialty trade contractors. Their task is to carry out the interior finishing works for all 32 apartments in as short a time as possible. Execution of the finishing works is simulated by the assembly of small building models using LEGO bricks; they are assembled in four distinct steps, each performed by one of the specialty contractors. The roles of apartment clients, who select random design variations and must approve completed apartments, are played by two more participants.

The game is played over two rounds. The first round models a conventional approach to construction planning and management, in which the finishing works are executed floor by floor in vertical progression. The second round, simulates the lean apartment construction model developed in this research. Provision of customized apartments, with the delivery of design information for apartments according to an unpredictable sequence, is the key feature modeled. In each round, play is stopped after 11 min, and the team's performance is assessed, in terms of apartments delivered, quantity of WIP, cash flow, defective apartments, and the time required to deliver the first nonstandard apartment.

Results of executions of the game with 11 different teams of players are presented in Table 3. The participants from the construction industry (six of the teams), and particularly the project managers and subcontractors among them, reported that the first round faithfully simulated their day-to-day experience in projects of this kind (Sacks et al. 2007). Comparison of the average results achieved in the conventional and the lean rounds of the game showed consistent improvement in throughput (1.3 to 2.0 units/min), average cash flow (from −$9,136 to +$6,136), and average cycle time (from 5 m 26 s to 2 m 18 s). Average WIP was reduced from 14.1 to 2.0 units. The standard deviations of the number of apartments completed and of the cash flow, were greater for the conventional rounds than for the lean rounds (although their reliability is limited, because they are based on a small number of iterations). The difference between them results from the instability of the conventional model, in the face of variations, in the sequence of provision of design change information.

The game was subsequently implemented in a discrete event simulation using STROBOSCOPE software (Martinez and Ioannou 1999). The simulation was run in various configurations, with and without changes (to provide a benchmark), and with isolated and combined interventions. The results of the computer simulation were consistent with those achieved in the live game, in terms of demonstrating the relative difference between the conventional and the lean models. However, the computer simulation provided richer data. For example, the values of performance measures—such as WIP and cash flow—could be recorded through time. The contributions of each of the three interventions modeled (reduced batch size, pull flow, and multiskilling) were evaluated independently and in different combinations. The conclusions pointed to a significant contribution of reduced batch size to improved cycle times and cash flow, while pull flow was essential for customizing all of the apartments. Details of the implementation and results are reported in (Sacks et al. 2007).

Trial Implementation

The results of the live simulation experiment, together with the analysis of conventional practice, were sufficiently decisive to encourage a large construction company to implement a pilot project in a 48-unit apartment building. A task group was formed to formulate the policies and procedures for the pilot project. The task group, led by the company vice-president for control and information systems, included the authors, a senior company engineer, the head of the client change service department, a client change representative, and the pilot project site staff—project manager, construction engineer, and the senior works supervisor. The team met weekly over an extended period to propose, evaluate, and develop the implementation. It developed procedures, recommended design changes, coordinated training for personnel and specialty contractors, and specified changes to the company's scheduling and control systems. Suppliers, specialty contractors, the building's developers, and one client were consulted where needed.

At the time that the task group began its activity, detailed design of the structure was complete, and the building's structure had already reached the second floor. Finishing works had not commenced, and only 35% of the apartments had been sold, although a number of the subcontracts for finishing works had been concluded. As a result, certain aspects of the changes proposed in the lean model above were considered impractical in the short term. Multitasking was rejected, although a small number of minor activities were transferred from specialized subcontractors to the central work teams. Only minor changes to construction methods were possible. Therefore, the most significant change implemented was to replace push scheduling with single-piece pull flow control.

At the time of writing, the finishing works in the pilot project building were approximately 30% complete. Detailed data were being collected, and the implementation methods were being evaluated and improved continuously. The task group's recommendations, the IT and other tools developed, and the results of the implementation, will be reported in a following paper.

Conclusions

Lean construction begins with detailed examination of construction projects and the way they are planned and controlled. Analyzing projects from the point of view of production flow, paying attention to the stability of the process as a whole rather than to the productivity of each operation in isolation, often reveals that the production system in its entirety can be restructured and improved. The theoretical management model developed here is the result of application of this approach in a holistic manner to management of high-rise apartment building construction. Detailed project control data, collected from a leading residential construction company, were analyzed to assess cycle times, quantities of work in progress, and responsiveness to the clients' needs. Interviews with management personnel at all levels completed the picture, by shedding light on the different forms of waste that are common. Cycle times were found to be in the range of five times the net working time. Predictably, and in accordance with Little's Law, WIP levels were high, peaking at 100% in every project examined. All the forms of waste classified in lean production thinking were found to be present. The most important observation was that there is a mismatch between the flow of information defining detailed design and the sequence of execution of finishing works in conventional construction plans for this building type.

The structural changes proposed in the management model are the reduction of batch size and change to single-piece pull flow, restructuring of work packages and construction methods to decouple stable activities from those susceptible to change, and multitasking within work teams. The impact of the proposed model was investigated using a management simulation experiment, set up first as a game played by human subjects, and then implemented using discrete event simulation software. The simulation experiments indicated the significant potential of the lean management model to increase throughput, improve cash flow, and reduce apartment delivery cycle time when compared with the conventional management model.

Research into the practical aspects of implementation is ongoing. Although implementation of the method in a pilot project is under way, no quantitative conclusions can yet be drawn about the applicability of the theoretical model in real construction situations. Assuming that not all aspects of the model can be implemented in all projects, it is imperative to determine what the impacts of each aspect are, how they can be applied in each unique situation, where the pitfalls are, and what scale of improvement can be expected. What has become apparent is that implementation cannot be superficial: It requires fundamental changes in design details, forms of contract, scheduling and control software, training of personnel at all levels, and even adaptations to equipment.

The main drivers for change are the large potential for improvement, coupled with growing competition among contractors and developers in developed economies to compete not only on price, but by providing apartments customized to meet the clients' needs. The fundamental implication for developers, project managers, contractors, and subcontractors is that the potential for improvement, through application of lean construction, should not be ignored.

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