IMPLEMENTATION OF PULL CONTROL IN FINISHING WORKS WITH RE-ENTRANT FLOW

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ABSTRACT

Construction project activities exhibit high degrees of variation, especially during finishing works, as a result of uncertainty in supply chains, variations in work quantities, client changes and lack of predictability of the production capacity of subcontracting trades. Decisions must constantly be made concerning effective utilization of available resources. Re-entrant workflow patterns, where a trade crew returns twice or more to the same space, make production control even more difficult. We present a method for pull flow control at the operational level, even where re-entrant flow occurs. Pull of works is achieved through real-time prioritization of pending work-packages and daily regulation of trades' production capacity. Application of various heuristics was evaluated and examined using discrete-event simulation of a representative construction project. Experimental results show how careful production system design, with daily evaluation and adjustments using heuristic production control rules, can improve flows that include re-entrant loops.

KEY WORDS

Production system design, production control, pull, simulation, re-entrant flow.

INTRODUCTION

The finishing works of construction projects often have highly variable production rates. The sources of variation in cycle times for building spaces can be classified as production system, inherent work content, and external. Insufficient materials, overcrowding of work areas, lack of information, inappropriate equipment, inconsistent deliveries, low levels of control on availability of subcontracting teams, etc. are the main sources of production system variation. Additionally, there is inherent variability of workflow throughput even when methods and technology are fixed. Inherent variability arises because each building space has particular finishing requirements and different volumes of each work type, so that different work packages require different resource inputs. Changing client requirements are the most common external source of variation (Sacks and Goldin 2007).

According to lean production principles, managing variation requires three approaches: 1) prediction of the factors that may disturb continuous workflow and taking action to overcome them through production system design; 2) maintenance of *pull* flow conditions by assigning work to trade teams on the basis of work-readiness and the readiness of the subsequent trades to accommodate the work, rather than on pre-determined planning imperatives; and 3) careful treatment and continuous

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improvement of individual activities to reduce 'micro-variation' in their production rates and reliability.

The Last Planner System™ (Ballard 2000) plays a significant role in managing variability. It provides constraints analysis on different levels of a project hierarchy, filtering tasks to workable backlog, thereby supporting stabilization of flow in terms of its predictability and reliability of planning. However, it has no mechanism to analyze the project flow progress in order to prioritize or authorize backlog tasks for execution regarding stability and continuity of workflow forward.

Implementation of pull flow control has some obstacles and constraints when the production system has processes that have production units with re-entrant flow patterns. In construction, re-entrant flow occurs when one trade team is required to return to the same work space multiple times for different process stages. This imposes an interesting and important challenge in allocating resources: in order to prevent starvation of the other subsequent trades, the crews of a trade with re-entrant workflows should be effectively shared between operations that 'open up' new spaces for work and operations that 'close out' other spaces.

Re-entrant flow patterns are common in traditional construction processes and especially typical for finishing trades (Brodetskaia and Sacks 2007). Drywall, plumbing, electricity and other crews return multiple times to the same apartment at different stages as works progress. A value stream map for a typical residential apartment revealed as many as 44 handovers from one team to another (Sacks and Goldin 2007) with only 18 trades, reflecting multiple cycles of re-entrant flow. If it were possible to re-align the construction methods so that sequential packages could each be performed by a multi-skilled team (production cell) that does not return to the same space, then re-entrant flow could be avoided. However, given the high degree of trade specialization, and the nature of common construction methods, it is extremely difficult to remove all re-entrant flow cycles.

GOALS AND METHOD

Although re-entrant flow appears to be an unavoidable feature of many construction methods, particularly in the execution of finishing works, it has not been studied, and the impact on flows of work and trade crews in construction is not well understood. This research explored the nature of these flows and to test the following hypothesis:

> *Work flow and product flow can be improved by developing, calibrating and applying heuristic rules at the operational level in construction finishing works, even where re-entrant flow occurs.*

Unfortunately, it is extremely difficult to explore the nature of the flows and develop the rules in real conditions. Construction projects are not effective laboratories where multiple alternative production control policies must be developed, tested and fine-tuned. Medium to large construction projects, such as high-rise residential projects, involve dozens of suppliers and subcontractors (Brodetskaia and Sacks 2007; Sacks and Goldin 2007) and have long durations. Thus, discrete event simulation was employed for examination of the proposed hypotheses. This is a tried and tested method in operations research in general and in lean construction research in particular (Alves and Tommelein 2004; Sacks et al. 2007; Tommelein 1998)

EXPERIMENTAL CONSTRUCTION PROJECT SIMULATOR

An simplified representative project was developed for simulation and examination of different policies of real-time allocation of available resources. The project has 20

typical floors with six apartments on each floor. All of the apartments on the typical floor have unique configurations and internal designs, and thus have different work quantities for each activity. The apartments are assumed to be sold in random order at an average rate of five apartments every two weeks.

The project supposes performance of seven finishing activities, as presented in Table 8, in the optimal sequence of their execution within an apartment. The seven activities are performed by five trades. Finishing works within an apartment may only start once the structural works and the exterior curtain wall façade on its floor of the building have been completed. The average handover rate is assumed to be one floor per week, with six apartments per floor.

Table 8: The finishing activities composing the experimental project sorted according to the optimal sequence of performance within an apartment

Performance Sequence	Activity	Crew Type
1	Installation of drywall framing and the first side (Side A) of the walls	Drywall trade
2	Installation of plumbing	Plumbers
3	Electrical conduits	Electricians
4	HVAC ducts	HVAC trade
5	Closure of the second side (Side B) of drywall walls	Drywall trade
6	Building of suspended drywall ceiling	
7	Tiling of all the floors (other than the bathrooms)	Tilers

This sequence of activities represents the range of complexity in the flow of finishing activities. It was specifically designed to enable modeling and further examination of the primary factors affecting the stability of flow of in-door finishing activities, such as re-entrance of trade workflows, interference between trades' workflows, and variability of supply chains of raw materials and of prefabricated elements.

Finishing works start with installation of framing and one side of the drywalls ('Drywall Side A' works). The same trade returns to each apartment for the second side ('Drywall Side B' works) and to install the ceilings after the in-wall systems have been installed, thus exhibiting re-entrant production flow. The three systems installation flows (electrical, plumbing, and HVAC) are enclosed within the loop of the re-entrant process and their stability depends on the crew dispatching policy used for the drywall crews. Thus, the behavior of the re-entrant workflow under different crew dispatching policies, and the effect of re-entrance on the stability of flows that are 'enclosed' in the re-entrant loop, can be simulated. Similarly, the behavior of activities following re-entrant loops (tiling in this case) can be simulated and studied.

The model includes three different types of common construction material supply chains (O'Brien et al. 2008): 1) made-to-stock (standard materials for plumbing, drywall and electricity works); 2) made-to-order (such as floor tiles, which are uniquely supplied for any given apartment or room); and 3) engineered-to-order (HVAC duct parts prefabricated off-site, with unstable and uncertain delivery rates).

A project workflow simulator was developed to simulate the experimental construction project described above, in order to examine the flow characteristics and to evaluate different daily resource allocation policies. The model was built using

ProModel^{TM} simulation software (ProModel 1996-2010), and it provides a simulation of production flow at the resolution of individual operations.

The model contains procedures for *daily* or, if necessary, ***real-time*** allocation of the available crews. Allocations are made according to sets of rules. For example, a crew will always continue the work it began on the previous day if it has not completed that work (the crew is assigned to the same apartment). All the other rules governing labor allocation policy can be set parametrically to implement different policies; some of these are described below, in the context of the policies examined.

The model considers variation of trades' production capacity by modeling the behavior of subcontractors who mobilize and withdraw crews according to the amount of work available. The work available is the so called 'upstream buffer' – the number of apartments pending for a trade subcontractor's crews. The subcontractors' behavior is described by the following rules:

- If the workable backlog is less than one apartment for each crew available, the number of trade crews is reduced. The crew demobilization time is one workday.
- If the workable backlog is greater than three for each crew available, an appropriate number of crews is mobilized to the project. Mobilization time for each crew (i.e. the time required from the moment the decision is made until the crew is available for work on site) is defined as a triangular distribution with minimum one day, most likely three days, and maximum seven days TRIA(1, 3, 7).

Stable production flow supposes both stable ***product flow*** and continuous and effective ***flow of trade crews*** through the project. Stable product flow means predictable flow, with predictable activity durations. The parameters defined for comparison between the different labor dispatching policies that were examined cover both of these aspects, as detailed in Table 10.

PRODUCTION CONTROL STRATEGIES TESTED

The problem of daily effective resource utilization is similar to the Job Shop Scheduling problem discussed in factory production systems (Askin and Goldberg 2002; Baker 1974; Gershwin et al. 2003). Systems with re-entrant workflow are typical in semiconductor manufacturing. The study of the semiconductors manufacturing experience (Gupta and Sivakumar 2004) showed that the most effective solution found is implementation of different heuristic rules to dispatching the queue of jobs pending for execution on any particular workstation. 'Dispatching jobs' in the context of construction works corresponds to: 1) setting relative priorities for all pending work-packages for each trade crew type according to a chosen heuristic rule; and then 2) assigning the work packages with the highest priorities to the next available crew for each trade.

There are some important differences between factory production systems and construction projects that prevent direct application of the well-known heuristics that have been developed for job shops. For example, in construction, the product (apartment) can be worked on by more than one crew at a time, which is analogous to splitting a product to be worked on at two different workstations simultaneously. Similarly, a work crew can be split up temporarily, corresponding to batching in a job shop. Different approaches to these factors and their effect on the stability of product and process flows were examined in the research, but this discussion is out of scope for this paper.

The system also enables modeling of the positive effects of filtering work for readiness, as is done in the Last Planner System™, but this too is outside of the

current scope. Instead, we assume filtering to be done for all the tests (i.e. LPS is applied) and focus on aspects of heuristic approaches to production control that go beyond reduction of variation and shielding from uncertainty. Specifically, we assume in all of the experiments discussed in this paper that the preconditions of information, materials, spaces and preceding works are ensured through filtering before work packages are assigned.

The discussion in this paper is restricted to four cases. Two of these concern implementation of 'pull' flow control. Table 9 summarizes the main parameters of the experiments that were performed in order to explore the main changes in dispatching policy from one experiment to the next (policies and parameters are explained below).

Table 9: Dispatching rule parameters for the experiments

Experiment Parameters / Dispatching Rules		Exp#1	Exp#2	Exp#3	Exp#4
Sequencing Rules for…	Drywall Side A	Structure Progress	Design Completion Sequence		
	Plumbing	Maximum Available Work	Earliest Apartment Performance Start Date		
	Electricity				
	HVAC				
	Drywall Side B & Ceiling				
	Tiling				
Priority to the Side B drywall works over the Side A		Always	Always	For the first 3 crews only	
Downstream Buffer		---	---	≤3 work packages for each available crew	
Maximum Trade Production Capacity	Drywall	≤5	≤5	≤5	≤5
	Plumbing /Electricity/Tiling				≤3
	HVAC				≤1

STANDARD (BASIC) SITUATION (EXPERIMENT #1)

The first experiment generates a baseline control by simulating the traditional situation observed on sites, but with some well understood lean improvements. The modes of dispatching trade crews to finishing works in traditionally managed construction projects, observed in multiple cases (Brodetskaia and Sacks 2007; Sacks and Goldin 2007), include 'pushing' crews to begin work in apartments immediately on completion of the structure, frequently even when the prerequisites are only partly fulfilled (fractional information, partly available materials, not fully completed preceding works, etc.). The lean improvement included in this experiment is that all the 'pending' works are filtered according to their readiness before crews are assigned to them, as would be done with the LPS. However, the primary policy for release of apartments for execution remains unchanged from the traditional approach: finishing works within apartments start from the bottom of the building and progress upwards, in the same sequence as the structural frame was built. In sequencing the drywall trade backlog, the highest priority is always assigned to closure of Side B and Ceiling over the Side A works. The rule implements a commonly observed managerial approach to WIP control. The other crews were allowed to select the largest available

work packages, simulating their observed behavior of attempting to maximize short-term throughput.

Figure 6 reflects a typical simulation run. It shows a line-of-balance progress chart of performance of 120 apartments, with time on the X axis, apartments on the Y axis (ordered according to the start date of the finishing works), and trade crew activities shown color-coded. The parameter results are collected in Table 9.
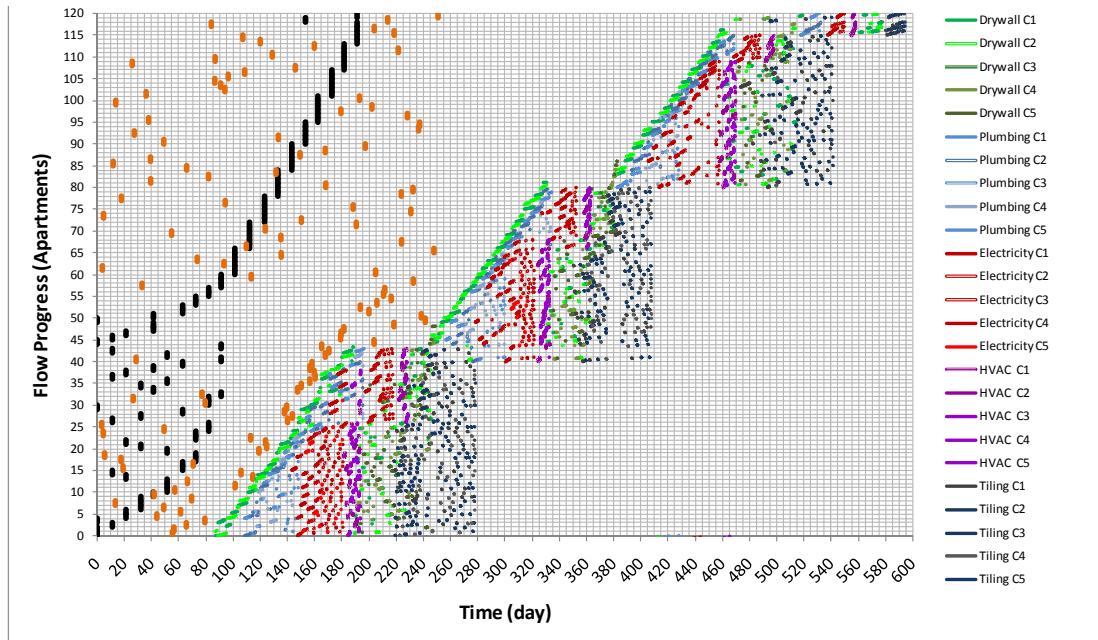

Figure 6: Flow of trades through performance of 120 apartments, presented as flowchart with apartments (axis Y) sorted according to sequence in which works began.

The most striking feature of the chart is that the project flow is split into distinct 'blocks'. This is a direct result of the re-entrance of the drywall trade flow coupled with high priority given to the Side B works in the CONWIP policy. Once Side B work packages become available, the drywall crews begin to work on Side B and Ceilings, no longer opening up Side A works, thereby causing 'starvation' of the other trades and interruption of their flows. Lack of guidance of crews between apartments extends activity cycle times unnecessarily and increases variability. Moreover, in contrast to what might be expected, this behavior does not increase the average trade productivity and utilization through the whole project run, but only increases the flow disruptions, forces the crews to leave the site and return later, and increases the total set-up times that occur with each mobilization. This is an important result, because it shows how the best intentions of application of a controlled WIP policy, giving priority to closing out apartments, with LPS style filtering, can lead to major flow disruptions where some flows are re-entrant.

EXPERIMENTS WITH PULL FLOW CONTROL (EXPERIMENTS #2 TO #4)

Two steps are required to achieve pull flow of apartment finishing works:

1. Enable pull of products by clients, which means releasing apartments in the order in which their interior designs are completed (modeled as the random sequence of sales).
2. Apply pull production flow control techniques once work on apartments has begun.

Step 1: Pull products (Experiment #2). To pull a product through a production system, the product required first should be processed first. In terms of job shop scheduling heuristics, this policy may be implemented through the First-In-First-Served (FIFS) rule. Apartments should be released for execution according to the internal design completion sequence. Thus in the simulator, the pending (ready) Side A works were sequenced according to design completion dates.

A complication arises in allocating work to subsequent trades because, due to the requirement that tasks be filtered for maturity, the actual sequence of the start of finishing works within apartments is not identical to the initial sequence of apartment sales and design completion. There are therefore two ways to sequence the work pending for the subsequent trades:

1. Sequence them in the same order of apartment sales, which should minimize apartment delivery cycle times.

2. Sequence them in the order of the actual starts of finishing works in apartments, which should shorten apartment execution cycle times.

Both alternatives were examined. The first alternative showed the relatively longer activity cycle times with higher rates of variation in trades' production capacities. As a result, due to the increased movement of crews and the penalty of mobilization times, the actual apartment delivery cycle times increased. Thus, in further simulation runs, the second approach was used for dispatching a backlog of all the activities beside the Side A works (as presented in Table 9).

The experimental results, collected in Table 10, show improvement of all product and process parameters when compared with Experiment #1: reduction of the durations of typical activities, shortening of apartment delivery and apartment performance cycle times, and finally shortening of overall project duration. The trades' workflow parameters are also improved for almost all trades. But maybe the most important result is the reduction of the variation rates for all the average durations that indicates improved flow stability and predictability.

The improvement is concluded also from Figure 7, which presents the resulting project workflow. In comparison with the standard situation (Figure 6), the band of flow lines is narrower, indicating reduction of the performance WIP accumulated through the project run. However, the same blocks of apartments noted previously may also be distinguished here by the waves of the tiling trade flow. The blocks indicate interruption of the flow of all the trades enclosed in the loop of the drywall works due to starvation, again resulting from the WIP reduction policy (implemented by preferring the closing drywall work activities over the opening activity). The block disruption appears exactly when the Side B closure stage begins. The tiling trade absorbs all the uncertainty and variability accumulated by all the supply chain trades, which is apparent in its low productivity and utilization rate (Table 10).
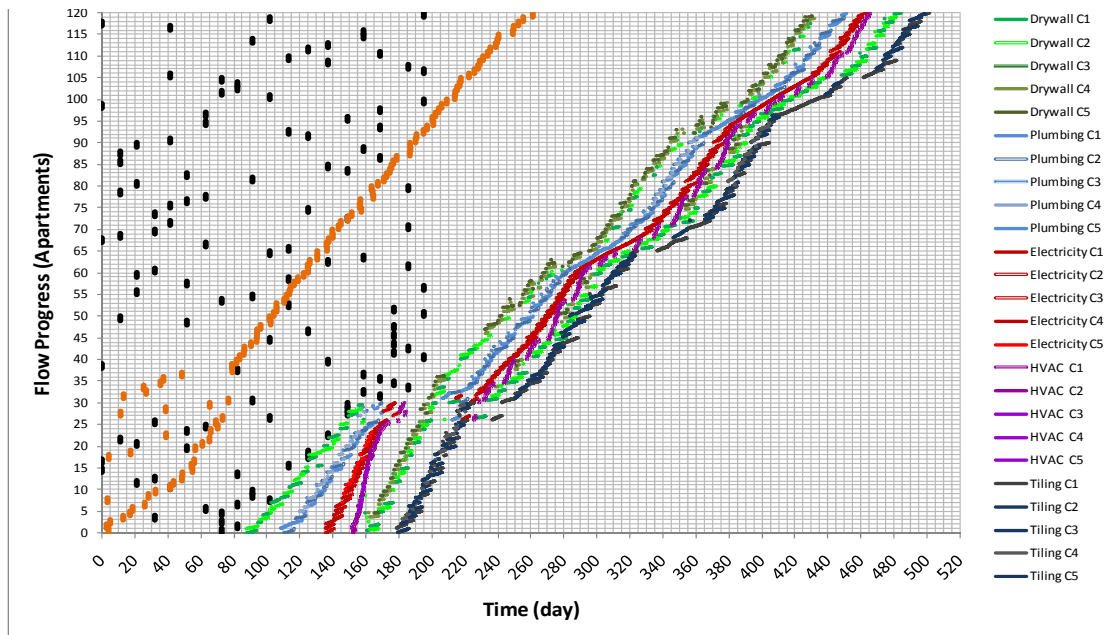
Figure 7: Trades workflow (Exp#2)

Clearly, the drywall trade production capacity should be optimally shared between 'opening' and 'closing' activities. It should be dynamically regulated according to the current state of the flow using pull flow control techniques.

Step 2: Pull process control (Experiment #3). In the conventional implementation of pull flow control in the Toyota Production System, KANBAN cards are posted by the client to the final activity, from the final activity to its predecessor, and so on to the beginning of the production chain, thereby producing pull of the product with minimal inventory accumulated between the workstations. The most important place to implement pull flow is upstream of the bottleneck process.

In the project modeled here, the drywall trade is the bottleneck resource. Thus, the 'pull' of apartments should be initiated by the drywall crews, specifically by the Side B and Ceiling Closure activities, which are closer to the final activity.

The model supposes only five drywall crews to be available each workday. In order to balance and optimize the sharing of production capacity between 'opening' and 'closing' activities, it was decided to limit the maximum number of the crews that may be assigned to the Side B and Ceiling works to just three.

The pull flow control was implemented through dynamic regulation of the trades' production capacity (and consequently of the trades' throughput) according to the capability of the *downstream* trade to accommodate the work stream, i.e. without increasing the buffer of pending jobs between the trades. Figure 8 shows the flow of decision about required production capacity of the preceding trade according to the size of the subsequent trade's backlog (so-called *downstream buffer size*). If the number of jobs pending for Side B and Ceiling activities (HVAC downstream buffer) is greater than three for each available drywall crew, then the HVAC trade production capacity should be reduced. If not, the HVAC crews are behaving according to their workable backlog scope, as discussed before. Thus, the number of crews on site is determined by both the crews' behavior according to the *upstream* buffer size and from the managerial top-down instruction according to the *downstream* buffer size.
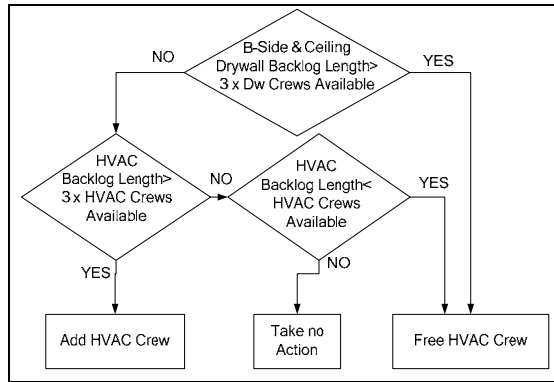
Figure 8: Flowchart for Setting Trade Production Capacity in the 'Pull' Flow Control System for the HVAC Trade

The experiment results, collected in Table 10, show insignificant change of overall project duration and apartment delivery and performance cycle times from Experiment #2 to Experiment #3. They even show an increase in the average and maximal values of the WIP accumulated through the project run. The Side B and Ceiling drywall activity also shows an increase in instability, because priority is no longer given to this activity over its partner, Side A drywall activity. However, the overall effect on the drywall trade is positive because the Side A activity is made much more stable, which improves the stability of the system as a whole. The blocks of apartments worked-on (batches), which were observed in the simulation of the standard situation, almost disappear in Experiment #3, and the same is true for leaps in the apartment completion rates,.

As the production system parameters are refined from the standard (Experiment #1) to a pull flow policy (Experiment #3), the trend for all trades is toward decreased cycle times, increasingly stable production, and higher crew utilization (Table 10).

The improvement trend concerns plumbing and electricity trades, which are enclosed within the re-entrant loop, and the tiling trade that follows the loop. The only exception to the trend is in the case of the stability of the HVAC trade, whose work becomes progressively less stable through Experiments #1 to #3 (SD 62%, 79%, and 84%, respectively). The reason for this is that the production rate capacity of a single HVAC team is greater than the average production rates of the other teams. This leads to a sustained high rate of mobilization and demobilization of HVAC teams according to the generic strategies employed. The low value for the HVAC trade productivity in Experiment #3 reflects this waste. This behavior emphasizes the need to strive for balanced production rates, particularly within re-entrant loops.

Limit production capacity (Experiment #4). In this experiment, another improvement was made. With greater stability achieved, the next step toward improvement of trades' flow stability was an attempt to adjust the production rates of all trades to match the maximum possible production rate of the system bottleneck – drywall trade. To do this, the maximum number of crews available for each work type was capped, as presented in Table 9. The results of this experiment are also presented in Table 10.

CONCLUSIONS

The basic simulation results showed how variation and uncertainty at the level of individual operations within trade team tasks (micro-variability) strongly impact the apartment cycle times and overall project duration. They also reveal an interesting phenomenon, that of blocks of work that form due to re-entrant work flow cycles. In particular, the results clearly reveal the specific behavior of the system with re-entrant flow, resulting in blocks of activities separated by breaks. This is a side-effect of the WIP control policy, implemented by preferring later activities over earlier activities for re-entrant teams; it reduces the stability of both activities enclosed in and following the re-entrant loops.

Table 10: Results

Parameter		Exp#1	Exp#2	Exp#3	Exp#4
Project Duration		595	502	482	480
Work in progress (WIP)	Max	120	90	92	91
Performance WIP (number of apartments where finishing has been started but not completed)	Max	57	31	36	37
	Av / StDev	25.2 / 57%	18.9/ 35%	19.5 / 40%	19.7 / 45%
Product Flow — Apartment Delivery[4] CT	Av / StDev	287/42%	207 / 13%	201.1/11%	208.6/10%
Apartment Performance[5] CT	Av / StDev	135/25%	66.8/ 25%	65.5/20%	72.7 / 27%
Trade Activity CT (distribution of the time spent to complete each particular type of work in each apartment) (Average / Average Std. Deviation for all apartment types)	Side A	9.8 / 88%	8.1 / 52%	6.8 / 32%	6.9/ 33%
	Plumbing	14.8 / 71%	6.6 / 56%	6.4 / 23%	6.4 / 21%
	Electricity	19.5 / 47%	5.3 / 14%	5.1 / 9%	5.3 / 17%
	HVAC	2.6 / 62%	1.5 / 79%	1.4 / 84%	1.3 / 55%
	Side B & Ceiling	19.0 / 48%	6.1 / 21%	6.4 / 32%	6.0 / 13%
	Tiling	39.1 / 26%	6.3 / 16%	6.2 / 10%	5.4 / 11%
Trades Workflow — Stability of Trades Production Capacity (number of times crews were mobilized/demobilized)	Drywall	11	19	14	10
	Plumbing	21	13	8	8
	Electricity	28	12	9	9
	HVAC	28	30	28	19
	Tiling	18	17	13	5
Average Trade Productivity (total value produced by trade crews per time unit) (units/hour)	Drywall	5.32	5.34	5.36	5.34
	Plumbing	1.51	1.62	1.65	1.66
	Electricity	1.99	2.15	2.20	2.15
	HVAC	2.36	2.46	2.41	2.72
	Tiling	1.29	1.38	1.39	1.41
Average Crews Utilization (% of production time out of the overall time crews were available)	Drywall	77%	76%	76%	76%
	Plumbing	54%	59%	60%	63%
	Electricity	67%	74%	76%	78%
	HVAC	48%	59%	34%	67%
	Tiling	69%	74%	76%	79%

The results underline the importance of dynamic control of allocation of available production resources to the *right* activities that ensure subsequent flow, not just to the mature activities. This is particularly the case with re-entrant flow patterns. The most successful policy was to balance the trade with re-entrant flows so as to ensure sufficient feeding of new work to successive crews, but without generating excessive WIP. This strategy is different from the common approach of construction supervisors or managers who instruct re-entrant teams to complete work in their earlier activities rather than in their later activities, for the purpose of opening up work for subsequent teams to avoid starving them of work.

Pull flow control may be implemented in two ways: on the *project* level, by adjusting the sequencing of the start of works to the sequence of internal design completion; and on the *operational* level, by adjusting the trade throughput to the capacity of the *downstream* trade to accommodate the work flow. Both of these are done in addition to filtering work packages through a make-ready process. This research demonstrated how they can be implemented in systems with re-entrant flow, achieving positive impact on both product and process flows.

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[4] Time from apartment sale to delivery to owner (measured to completion of tiling works).
[5] Time from the start of the finishing works (Side A drywall) to apartment completion (tiling)

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