Improving Construction Productivity: Implications of Even Flow production principles

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Abstract

Subcontracting has been widely used in order to address the high level of variability and associated risks in the complex configuration of residential construction production systems. However, the explosion of subcontracting and the parade of trades have made the construction operations very fragmented, leading to lack of predictability and adequate control on schedules and quality. The present paper proposes a set of system configurations for residential construction. On this basis, after an extensive review of the efforts to model construction production problems, several discrete event simulation models have been developed so as to assess tangible performance measures. Comparing and contrasting the results, two attributes of the system were found to be critical to yield better performance measures. In the proposed flexible system design, fewer cross-trained subcontractors undertake integrated work processes. Also, the number of houses under construction does not grow infinitely and is proportional to the system capacity.

Keywords: Australian residential construction, even flow production planning, resource queue, specialized trade contractors, Work-in-process inventory

1. Introduction

To manage a construction system effectively, it is necessary to understand its configuration first. Residential construction is a sector with many similarities to manufacturing (Bashford, Walsh & Sawhney 2003). In other words, it is possible to look at residential construction as a production line, both sharing similar production problems. For example, in boom periods when the demand for building houses peaks, production homebuilding is flooded by large numbers of houses under construction. This increased level of work-in-process inventory (WIP) will lengthen the cycle time (CT), which is the average time between the start and end of construction operations. This is due to limited capacity of the construction systems.

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Furthermore, Events such as worker fatigue or illness, equipment breakdown and shortage of material supply may impose delays or interruptions on individual processes (micro level). Also, exogenous events of inclement weather conditions, inefficient construction management decisions and industrial actions may affect the operations at the macro level (Damrianant & Wakefield 2000). These reduce the output rate or throughput (TH) of the system.

To address the high level of variability and resulted risks, subcontracting has been widely used in the complex configuration of residential construction production systems. Homebuilders, who generally act as the construction manager, subcontract all of the production processes. In the most common scenario in the Australian residential construction, around 50 trade contractors are in charge of more than 100 building processes in order to build typical detached onsite houses. In this way, the risk of delays and late completion is generally avoided by the builder and is transferred to other stakeholders (Arashpour & Arashpour 2012). In fact, subcontractors are only paid upon the completion of a given activity. The explosion of subcontracting and the parade of trades have made the construction operations very fragmented, leading to a lack of predictability and adequate control on schedules and quality (Dalton, Wakefield & Horne 2011). The result is significant holding cost for capital that is generally borne by homebuyers due to extended cycle times.

Using the current system configuration, one solution, for instance, would be to pay attention to selecting the right subcontractor for the right activity. For example, Doloi, Iyer and Sawhney (2011), have linked contractors' performance on a project to a set of qualification criteria. However, although many attempts have been made by construction management professionals to improve the situation within the present system configuration, little attention has been paid to reconfigure the system, inspired by the principles of even flow production that have been successfully utilised in manufacturing for decades. Even flow production known as workflow-levelling strategy aims to decrease variability in the workflow for trade contractors.

On this basis, we analyse the implications of two even flow production principles: Maintaining a constant number of houses under construction (Constant work-in-process inventory (CONWIP)), and adding flexibility to movement of jobs (hand-offs) by means of integrating work processes and cross-training trade contractors. To achieve the aim, after an extensive review of the efforts to model construction production problems, several discrete event simulation models are designed and run in order to compare and contrast results and investigate significant changes in production parameters.

2. Review of efforts to model production problems

Construction production systems face several problems that directly affect their tangible performance measures. These problems include but are not limited to: Excessive work-in-process inventory (Love et al. 2002), lost throughput rate (AbouRizk, Knowles & Herman 2001), insufficient use of resources (Sacks et al. 2010), long cycle times (Bashford, Walsh & Sawhney 2003), interruptions and delays (Damrianant & Wakefield 2000) and inflexible production processes (Dalton, Wakefield & Horne 2011). To address these issues several

modelling initiatives have been developed in the construction literature that can be categorized into three main groups. Planning, monitoring and controlling of construction projects are facilitated by means of these models. Figure 1, illustrates a map of the construction management literature with regard to production problems and the modelling efforts to address them.

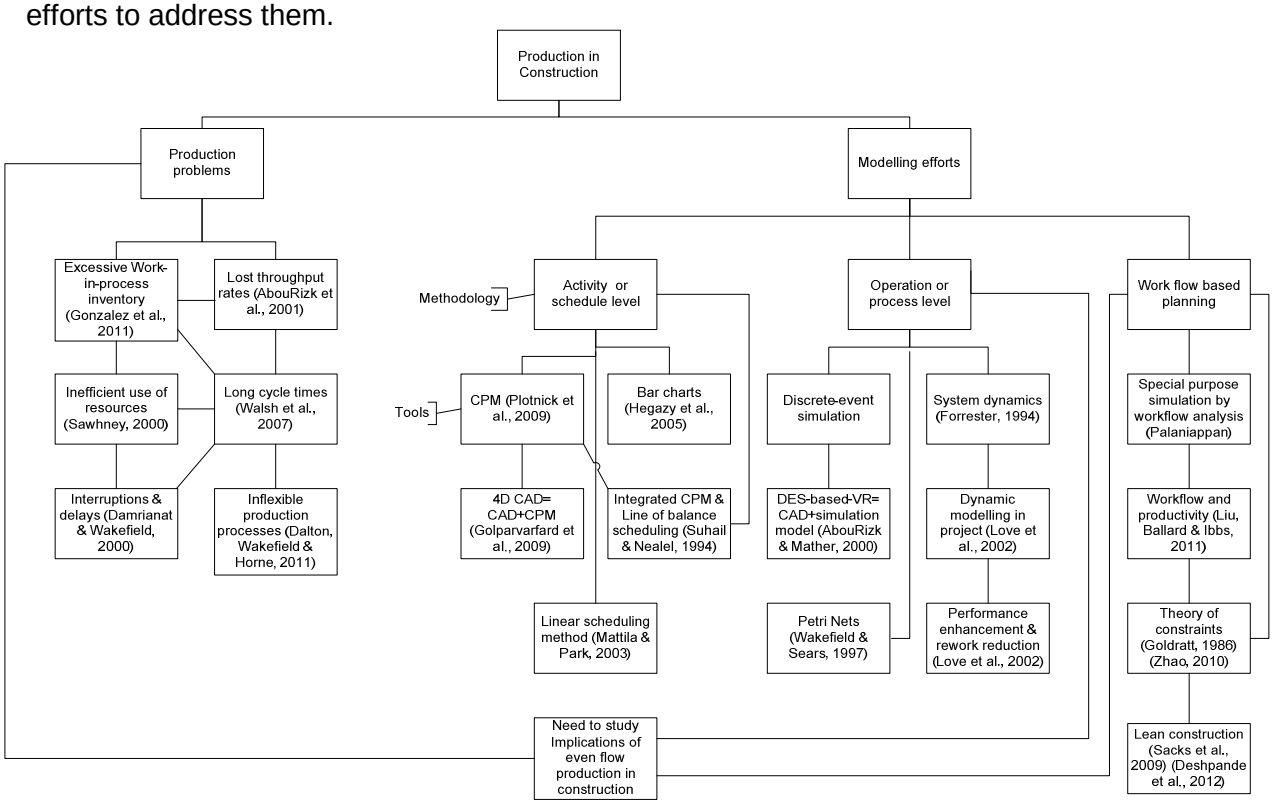

Figure 1: literature map on production problems and modelling efforts

2.1 Activity or schedule level modelling

The aim here is to analyse discretely evolving construction product and describe what is built where and when in order to study spatial and temporal interferences and optimal activity sequence (Kamat et al. 2011). Activity level visualization combines activity-based construction schedules, such as critical path method (CPM) or bar charts, and 3D computer-aided design (CAD) models of facilities in order to create four-dimensional (4D) CAD.

Four dimensional models in the augmented reality (4D AR) integrate as planned (expected) and as built (actual) visualizations to monitor and control construction performance using building information models (BIM). These models combine BIM, which represents the as-planned status of a project, and daily photographs taken in the site, which represent the as-built status of a project in order to track the physical progress of the project (AbouRizk, Knowles & Herman 2001). In this fashion, expected (as-planned) and actual (as-built) performance are compared in order to show what is expected to be built where and when, and the interactions among personnel, equipment and material. Using colour gradient spectra, the project performance measures such as Schedule Progress Index (SPI) and Cost Progress Index (CPI) can be visualised (Golparvar-Fard & Peña-Mora 2007). Also the construction sequences can be communicated. In this level of planning, BIM, which is typically used at design and preconstruction stages, is extended to the construction phase to

compare and contrast as-planned and as-built performances. This facilitates remote construction control decision making and also reduces the wasted time in contractor coordination meetings by cutting travel cost and time for project participants.

2.2 Operation or process level modelling

On the other hand, simulation modelling represents a framework to design, analyse and improve construction operations and processes. Dynamic operation level planning is rooted in discrete event simulation (DES) and combines operation planning tools (i.e. simulation models) and CAD models of static and dynamic entities . Here, the focus is to analyse interaction between resources, machines and materials in order to communicate not only what, where and when of the construction product but also who builds it and how. It depicts the continuous evolving products and processes (Kamat et al. 2011).

Designing construction processes is about comparing alternative construction methods, equipment, labour levels, temporary structures, and operating strategies to undertake the planned operations. Visualizing construction operations, project participants can graphically see (on the computer) the processes that would be done in the real site by conducting virtual walkthroughs. Virtual reality is a computer-generated environment that is sensory-immersive and responds to the user. Discrete event simulation and virtual reality can be combined to form what is called DES-based-VR. In the virtual reality environment, the logic of DES model can be validated and decision makers can provide feedback on the model.

Discrete-event simulation systems are characterized by their application breadth (general purpose or special purpose), flexibility (being programmable) and simulation paradigm, which can be either Process Interaction (PI) or Activity Scanning (AS). AS-based discrete-event simulation take the advantage of Activity Cycle Diagrams (ACD), to simulate complex construction operations (Martinez & Ioannou 1999). The logic behind this paradigm is that in manufacturing systems, materials arrive and undergo a fixed processing pattern; however, construction operations capture many interacting resources. Many construction simulation languages have been developed such as MicroCYCLONE, COOPS, CIPROS, and STROBOSCOPE.

However, construction operations can also be precisely modelled by means of other graphical and mathematical models. For example Damrianant and Wakefield (2000) used Petri nets to simulate and model construction systems. In this fashion, the user enjoys the flexibility in using both simulation-modelling constructs and user-written codes by general-purpose procedural languages (Arashpour, Wakefield & Blismas 2013).

2.3 Workflow based modelling

Flow variability in production systems can be the result of management decisions or randomness in process and demand. Subcontracting construction processes to several trade contractors makes the management of job movements (hand-offs) difficult. Several influences of workflow variability on project performance have been investigated in the construction management (CM) literature. For instance, Arashpour and Arashpour (2011)

and Liu, Ballard and Ibbs (2011) showed how labour productivity is directly correlated with some measures of workflow variability.

Other applications of workflow planning have been used to develop lean construction models. For example, Sacks et al. (2010) developed a framework to integrate lean management and building information modelling.

3. Research design

The purpose of this paper is to investigate the effects of two even flow production principles on production parameters in volume homebuilding sector. These two principles are using fewer but cross-trained subcontractors and limiting the number of houses under construction (work-in-process inventory). The positive effects of these principles have already been proved in manufacturing (Hopp & Spearman 2008). However, their impact on production construction has not been investigated yet. This investigation was conducted in order to bridge this gap.

Volume homebuilding in Australia was selected as the scope of this work. We designed four experiments by varying process times and their distribution, number of trade contractors, and rate of starting new homes. Care was taken to realistically model major production homebuilding elements. The experiments were simulated over 1000 working days using ARENA in order to compare and contrast associated performance measures. Figure 2 shows the base case involving 20 specialised subcontractors.

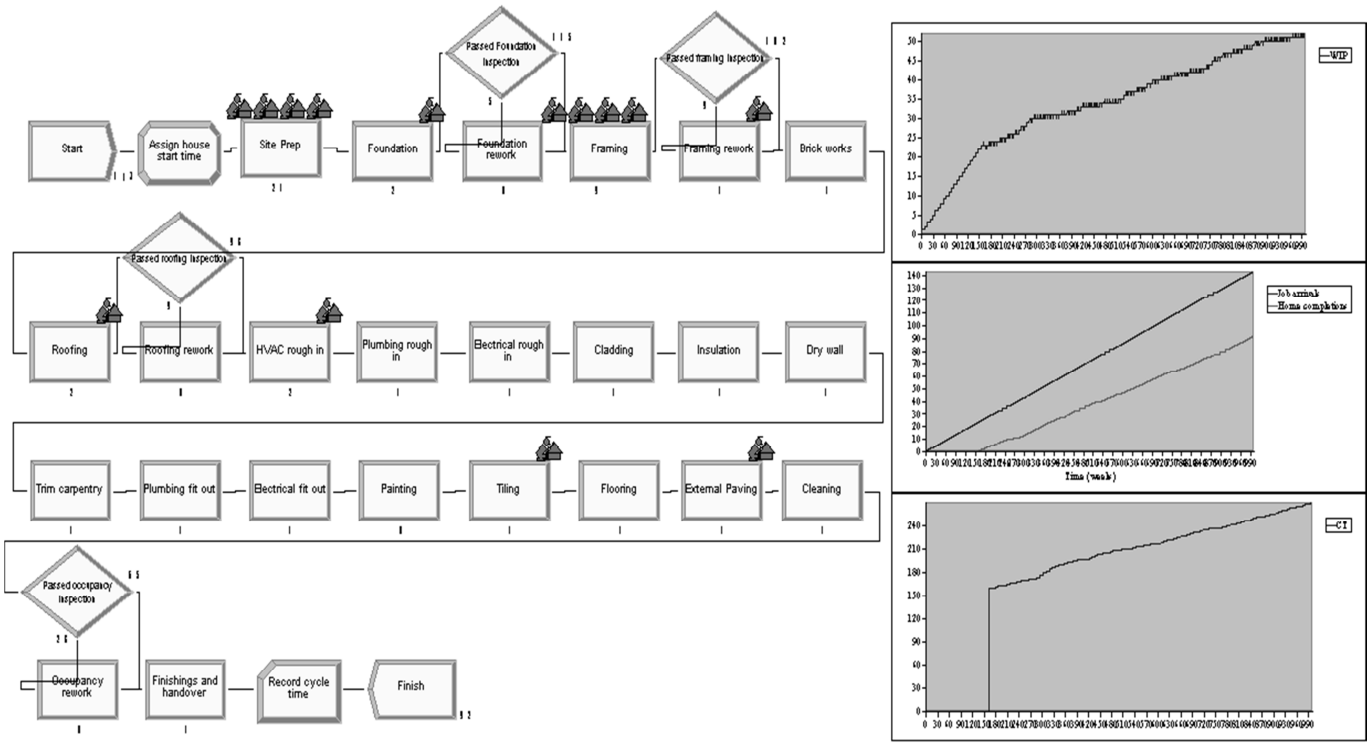

Figure 2: Interacting specialized trade contractors to build detached Australian houses

This simplified model of production homebuilding, which is similar to that of Bashford, Walsh and Sawhney (2003), was developed in order to demonstrate movement of jobs (workflow) among trade contractors and interaction of resources. These 20 major elements are similar to those of level 1 in the work breakdown structure (WBS).

The first simulation experiment, which served as our base case, involves deterministic process times for all processes. In experiment 2, new constructions are started without considering production limitations, which is a typical practice in push production. Therefore, probabilistic sales rates determine the start pace of new constructions. In contrast, the rate of starting new homes is controlled in experiment 3. That is, work-in-process inventory are constant (CONWIP) and stand at about 20 homes at all times. In experiment 4, 20 specialised trade contractors are replaced by 10 cross-trained contractors in order to explore whether or not this strategy would smoothen movements of jobs (hand-offs) among trade contractors.

4. Results and analysis

4.1 Deterministic process times- Base case performance

Having deterministic process times without any variability, the first experiment demonstrates the best case performance. Each of the 20 trade contractors in figure 2 need exactly seven working days to complete their processes and act as bottlenecks. Therefore, the throughput rate of the bottleneck (r_b) is 1/7 (house/day). Raw process time (T_0) is the average time that a single house takes to traverse the construction production line and is equal to 140 days in this case.

Production parameters can be computed by Little's law (Little 1961), which is a basic equation used in manufacturing:

$$TH = WIP / CT \qquad (1)$$

In equation 1, TH= output rate (throughput); WIP= number of houses under construction (work-in-process inventory); and CT= house completion time, respectively.

Also, the critical work in process inventory (W_0), which is the optimum number of houses under construction that yields the maximum throughput rate and minimum cycle time, will be:

$$WIP_{critical} = W_0 = r_b * T_0 \qquad (2)$$

$WIP_{critical}$ also results in the optimum utilisation of resources, which are trade contractors in our case.

An inventory of 20 houses under construction in the first experiment builds up no queues and results in the most efficient behaviour of the system.

4.2 Uncontrolled number of houses under construction (push production)

During construction boom periods, when demand for building new houses peaks, construction production systems are flooded by large number of houses under construction (work-in-process inventories). The intuition behind setting high levels of WIP is to increase resource utilisation and achieve throughput close to capacity. However, this approach will cause cycle times to grow infinitely because of the limited production capacity. Although adding resources may improve the performance measures of the system (Arashpour & Arashpour 2010), it would not financially or spatially be feasible in all cases.

Several real world production detractors are present in construction sites such as worker fatigue or illness, equipment breakdown, shortage of material supply and inclement weather conditions. To impose maximum randomness to production homebuilding, the process times were considered random and occurred according to exponential probability distribution. Having a mean value of seven days, the probability that a process can be done is proportional to the time. For example, there is about 35% chance for a given process to be done under three days: $F(3/7) = 1 - e^{-3/7} \approx 0.35$

Similarly, the probability that a process will take more than 14 days is:

$1 - F(14/7) = 1 - F(2) = e^{-2} \approx 0.14$

Considering exponentially process times, a given house to be processed by a subcontractor expects (WIP -1) / N other houses in the queue. Number of subcontractors (N) is equal to 20 in the present case.

In experiment 2, demand rates were considered random and occurred according to exponential probability distribution. In contrast to the previous case, new jobs are pushed into the system regardless of the current system state or WIP inventory level. The average level of WIP inventory reached a peak of 39 in the current case. Due to finite capacity of the system, the completion time of houses increased dramatically.

4.3 Constant level of work-in-process (CONWIP)

In designing experiment 3, care has been taken to maintain the constant number of houses under construction at all times. That is, new constructions are not started unless a completed house left the production line. In this event, T_i is the average time that each contractor takes to complete their construction process and will be,

$$T_i = t + \frac{WIP-1}{N} * t \qquad (3)$$

In equation 3, t= subcontractor processing time; and $\frac{WIP-1}{N}$ = queue time, respectively.

$$\text{And, } CT = \sum_{i=1}^{N} Ti \qquad (4)$$

In this experiment, the throughput rate is more than push production in experiment 2. Also the average completion time for a house stood at 273 days, which is considerably less than 395 days in experiment 3. Figure 3 compares the levels of WIP versus throughput in these experiments.

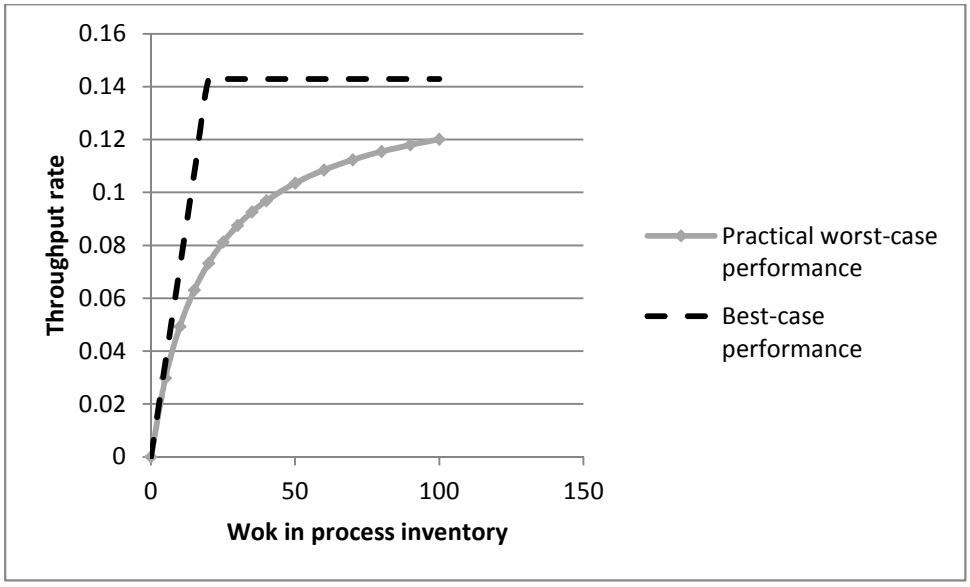

Figure 3: Work-in-process inventory versus throughput- Base case vs. push production

Based on the measurements, controlling number of houses under construction (work-in-process inventory) showed to have significant positive effects on production parameters in volume homebuilding sector.

4.4 Flexible system design with integrated work processes using cross-trained contractors

Excessive number of trade contractors in the system makes it difficult to manage handoffs among predecessors and successors. A solution would be to collapse work processes by using cross-trained processors (Arashpour, Shabanikia & Arashpour 2012). In other words, replacing single specialised trade contractors with parallel cross-trained contractors with the same capacity can improve performance. Such system designs used to be the common practice in the residential construction industry in the past, when a sole builder was in charge of all processes and was responsible towards the homebuyer.

In this scenario, 20 work processes were collapsed to create 10 integrated processes. The design is similar to that of Bashford, Walsh and Sawhney (2003). The process times were exponentially distributed and took twice longer than those in the previous case. That is, the first contractor, for instance, was in charge of site preparation and concreting the foundation slab. Therefore, instead of using two specialized contractors to cover site preparation and foundation processes, two cross-trained contractors that are able to cover both processes were employed. It was assumed that process times are twice longer than other experiments in order to have a fair cross-experiment comparison: t = EXP (7) + EXP (7)

As can be seen in table 1, number of completions in experiment four is almost the same to our base case. This indicates that reducing the number of interacting trade contractors along with controlling number of houses under construction can reduce the workflow variability and improves tangible performance measures volume homebuilding.

5. Discussion

Data obtained in previous studies indicated that workflow-levelling methodology known as even flow production can improve production efficiencies considerably. According to Bashford, Walsh and Sawhney (2003), even flow strategies affect both completion time and management efforts. In our study, a series of simulation experiments were used to implement two initiatives of constant level of work-in-process (CONWIP) and also integrated work processes. Table 1 shows the results obtained from production homebuilding simulation over 1000 working days.

Table 1: System description and tangible performance measures

Parameters	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Process time distribution	deterministic	Probabilistic	Probabilistic	Probabilistic
Production line status	Balanced	Balanced	Balanced	Balanced
System description	Best performance	Push system	CONWIP	Integrated process+ CONWIP
Raw process time (T_0)	140	alters	alters	alters
WIP_0	20	20	20	20 (jobs)
Average WIP inventory	20	39	20	19
Avg. subcontractors' time	7	20.6	13.65	7 (days)
Completion time (CT)	140	395	273	127 (days)
Job completion intervals	7	15.4	13.7	7.14 (days)
Throughput rate	0.14	0.065	0.073	0.128 (job/week)
Number of completions	124	65	111	123
Number of system states	1	$9.4 * 10^{14}$	$6.9 * 10^{10}$	10^{7}

As can be seen, the first experiment yielded the best throughput rate because there was no variability in process times. This best case performance served as the benchmark in order to evaluate production parameters in other experiments.

The push production approach used in experiment 2 downgraded all tangible performance measures in volume homebuilding. The average process time for each subcontractor reached a peak of 20.6 days resulting an average completion time of 395 days for a house. In fact, increasing the number of houses under construction in resource constrained scenarios causes long delays and less output rate.

Controlling number of houses under construction (constant work-in-process inventory) resulted in close to ideal number of 111 completions. This is consistent with results obtained in previous studies (Bashford, Walsh & Sawhney 2003). Furthermore, a dramatic improvement in production parameters was observed when integrated work processes were used together with CONWIP strategy in experiment 4. Completion intervals, for example, were shortened considerably. Using cross-trained contractors decreased the complexity of the system by means of reducing the number of system states. Information about the number of jobs, which are being processed or are in a queue to be processed by trade

contractors, can be stated in matrices called system states. Table 2 illustrates possible system states for 10 contractors working on a constant level of 20 houses under construction.

Table 2: Possible system states (10 cross-trained contractors and 20 houses under construction)

System state	Vector	System state	Vector
1	(20, 0, 0, 0, 0, 0, 0, 0, 0, 0)	101	(18, 1, 1, 0, 0, 0, 0, 0, 0, 0)
2	(0, 20, 0, 0, 0, 0, 0, 0, 0, 0)	102	(18, 1, 0, 1, 0, 0, 0, 0, 0, 0)
3	(0, 0, 20, 0, 0, 0, 0, 0, 0, 0)	103	(18, 1, 0, 0, 1, 0, 0, 0, 0, 0)
4	(0, 0, 0, 20, 0, 0, 0, 0, 0, 0)	104	(18, 1, 0, 0, 0, 1, 0, 0, 0, 0)
5	(0, 0, 0, 0, 20, 0, 0, 0, 0, 0)	105	(18, 1, 0, 0, 0, 0, 1, 0, 0, 0)
6	(0, 0, 0, 0, 0, 20, 0, 0, 0, 0)	106	(18, 1, 0, 0, 0, 0, 0, 1, 0, 0)
7	(0, 0, 0, 0, 0, 0, 20, 0, 0, 0)	107	(18, 1, 0, 0, 0, 0, 0, 0, 1, 0)
8	(0, 0, 0, 0, 0, 0, 0, 20, 0, 0)	108	(18, 1, 0, 0, 0, 0, 0, 0, 0, 1)
9	(0, 0, 0, 0, 0, 0, 0, 0, 20, 0)	109	(18, 0, 1, 1, 0, 0, 0, 0, 0, 0)
10	(0, 0, 0, 0, 0, 0, 0, 0, 0, 20)	110	(18, 0, 1, 0, 1, 0, 0, 0, 0, 0)
11	(19, 1, 0, 0, 0, 0, 0, 0, 0, 0)	111	(18, 0, 1, 0, 0, 1, 0, 0, 0, 0)
.	…	.	…
.	…	.	…
100	(18, 2, 0, 0, 0, 0, 0, 0, 0, 0)	10^7	(2, 2, 2, 2, 2, 2, 2, 2, 2, 2)

By increasing the level of subcontracting in more complex production scenarios, number of system states raise dramatically. For instance, there are 68,923,264,410 system states when 20 houses are under construction using 20 specialised trade contractors. Number of system states dramatically decreases to about 10^7 using 10 cross-trained contractors. Previous research has proved that fewer number of system states will result in shortened cycle times as all system states are not likely to happen with the same probability (Hopp & Spearman 2008). It is consistent with results obtained in the revised construction production line of experiment 4. For example, in the event that there are two houses in site preparation or foundation, it is guaranteed that both are being worked on. However, in the original arrangement of 20 subcontractors, two houses could have wound up at either site preparation or foundation processes and one always has to wait.

Overall, our results show that implementing two strategies of even flow production; namely constant level of work-in-process (CONWIP) and integrated work processes, can considerably improve tangible performance measures in production homebuilding.

6. Conclusion

Prior work has documented several problems in production construction and the efforts to model and address those. To mitigate high levels of variability and resultant risks for homebuilders, subcontracting has been widely used in the complex configuration of residential construction. While attempts have been made by construction management professionals to improve the situation within the present system configuration, little attention has been paid to reconfigure it in order to improve production parameters.

This study focused on implementing principles of even flow production in residential construction. Controlling the number of houses under construction, in accordance to system capacity, prevented long queues and work starvations within the network of trade contractors. Also, employing cross-trained contractors was found to significantly improve tangible performance measures by means of reducing the number of system states. This initiative results in better management of hand-offs among fewer trade contractors. This finding extends those of Dalton, Wakefield and Horne (2011), confirming that faster, more predictable systems tend to have more simplified configurations. Implementing such initiatives are more cost effective than adding more resources during the boom periods because efficiency is all about the how of converting WIP inventory to throughput.

Most notably, this is one of the first studies to our knowledge to investigate construction system behaviour under the principles of even flow production over the long term. Our results provide compelling evidence for the need to design simpler construction production systems and suggest that this approach appears to be effective in reducing variability that degrades performance measures. Even flow production causes significant savings in holding cost for capital that is generally borne by homebuyers due to extended house completion times.

In this investigation, the effects of controlling levels of work-in-process inventory and integrating work processes were studied. Future work could focus on other even flow strategies that can add flexibility to construction production systems.

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