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Quantitative analysis of rate-driven and due-date-driven construction: Production efficiency, supervision and controllability in residential projects

Mehrdad Arashpour, M.ASCE¹; Ron Wakefield, M.ASCE²; Nick Blismas³; and BabakAbbasi⁴

Abstract

Concerns about production efficiency, quality and affordability in the residential construction indicate there may be benefits in adopting alternative production control strategies to those traditionally used. Reducing adverse effects of exogenous variability in demand and endogenous variability in process are the ultimate goals of production control strategies. For residential construction this means controlling the number of houses under construction and controlling the start rate of new house constructions. The aim of this investigation is to compare and contrast the outcomes of these two production management strategies. Production data of two volume house builders in Victoria and Queensland, Australia, were collected. Tangible performance metrics of builders were analyzed and compared using principles of the queuing theory. Then numerous simulation experiments were designed and run in order to analyze different what-if scenarios in the building environment. A special purpose simulation template was developed in order to define a cap for production and limit the number of houses under construction based on actual demand and available capacity. The findings reveal that rate-driven construction outperforms due- date-driven construction in terms of three studied performance measures. This investigation adopts an original and quantitative approach towards three production aspects of efficiency, supervision and controllability. Therefore it contributes to the body-of-knowledge by developing an in-depth insight into superior performance of the rate-driven control strategy with the

intention of improving production output and long term sustainability of residential and other sub-sectors of the construction industry.

CE Database subject headings: Engineering productivity; Lean construction; Modeling, Project workflows; Work process simulation

Keywords: Computer simulation; Critical Path Method (CPM); Due-date-driven construction; Efficiency; First-in-first-out (FIFO); Project management; Rate-driven construction; Residential projects; Resource utilization; Queuing theory; Sensitivity analysis

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Introduction

House building is an important sector of the construction industry that heavily relies on subcontracting (Sawhney, Walsh et al. 2009). Evidence of shortage in supplying new housing has been recognized by government and industry bodies. As an example in Australia, the National Housing Supply Council (NHSC) and Housing Industry Association (HIA) estimate a shortage of 466000 houses by 2020.

In order to improve the situation, principles of production management have been borrowed from manufacturing to enhance traditional methods of construction project management. For example, resource driven scheduling or Critical Chain Project Management (CCPM), which is based on the theory of constraints (Goldratt and Cox 2005), adds more accuracy to the Critical Path Method (De la Garza and Kyunghwan 2009). Furthermore, lean construction (Sacks, Treckmann et al. 2009) and even flow production (Bashford, Sawhney et al. 2003) are being increasingly cited in the construction management literature as means of optimizing performance measures such as lead time, profit, output/throughput (TH), and service level.

The objective of workflow management or even flow production (EFP) is to ensure a smooth work flow among several interacting trade contractors by means of reducing the variability in their workload caused by fluctuating sales rates. In construction, using EFP was first proposed in studying homebuilding projects in Phoenix Arizona (Bashford, Sawhney et al. 2003). They reported on the superiority of EFP in terms of minimizing house completion times, workflow variability, and management efforts. There are two distinguished strategies for system loading in resource-constrained networks of production homebuilding, each with unique effects on performance measures (Bashford, Walsh et al. 2005).

The first, and traditional, method to manage system loading in the volume homebuilding is due date driven in which builders schedule/push new jobs into the network so as to match the sales rate. This strategy fails to maintain house completion times at a reasonable level and also creates an unsustainable production flow especially during boom periods, when demand for building new houses increases substantially and therefore resource constrained trades are not able keep up (Lu and Lam 2008, Dalton, Wakefield et al. 2011). The second production control strategy is called rate driven production. This strategy does not authorize a new construction start unless a completed job leaves the network (Gurevich and Sacks 2014). Improvements made by a rate-driven environment can be extended by controlling the number of houses under construction or work-in-process (*WIP*). Maintaining a constant work-in-process (*CONWIP*) has positive effects on tangible performance metrics of production homebuilders (Liu 2010, Arashpour and Arashpour 2015). In fact, this workflow control protocol turns the network of trades into a closed queuing system where unauthorized jobs from outside cannot enter. Despite the wealth of research on alternative project planning and control strategies, further quantitative productivity studies are required to evaluate the performance of such strategies and propose a continuous productivity improvement process (Lucko, Alves et al. 2014). Furthermore, theoretical reasons behind the superiority of these alternative strategies and the resultant practical issues need more investigation (Gouett, Haas et al. 2011).

In order to bridge this gap, this paper quantitatively analyzes the performance of homebuilders that use due-date driven strategy with those who take the alternative approach of rate-driven production. Volume house building sector with its data rich environment is a suitable domain for the purpose of this study. First, mathematical models of open and closed queues for individual trades were built and analyzed. Since construction production networks are too complex to be

solved analytically, in the next step simulation model of the whole trade contractor network was built and run in order to analyze and compare the collected data. Efficiency, coordination and supervisory requirements, and controllability are three areas under investigation in the current study. This paper suggests that rate driven production and its workflow leveling approach can improve both the economic sustainability and production efficiency of the homebuilding sector. Improvements in the house building sector from the use of rate driven production are likely to be generalizable to other sub-sectors of the construction industry due to their similarities.

Production efficiency in construction projects

Underperformance in the construction industry is a problem that is closely related to low productivity levels (Peña-Mora, Han et al. 2008, Skibniewski and Ghosh 2009, Arashpour and Arashpour 2010, Moselhi and Khan 2012). Using an appropriate production control strategy can improve performance metrics in different sectors of the industry, including residential construction. Due-date-driven and rate-driven construction are two production control strategies within the interconnected network of trade contractors in house building. Each strategy has unique effects on performance metrics.

Production data of two case studies were collected and utilized to validate the results of analytical and simulation modeling of house building networks driven by two control strategies of due-date-driven and rate-driven production. Selection of a major house building company with headquarters in Queensland and Victoria, Australia, enabled the authors to compare the performance of two similar building systems in terms of construction methods and processes. The major difference between Victorian and Queensland builders are the workflow control strategies they use. While Victorian builder uses a rate-driven production strategy, the mining boom in Queensland and the need to build more houses to accommodate workers, has

encouraged the other builder to use a due-date-driven strategy where new jobs are scheduled/pushed into the network so as to match the sales rate.

Production rate of the builders were computed by recording the number of houses started and completed each month. Furthermore, the degree of workflow stability was calculated by recording the standard deviation of time between completions. Several site observations and documentary analysis were conducted in order to collect the required data. The notation and symbols used for the modeling purpose are listed in the appendix of this manuscript.

One of the builders, coded as builder A in the current study, tries to match the production with sales with the intention of meeting the agreed completion times. In other words, the level of work-in-process (*WIP*) or number houses under construction varies at times based on sales, which is represented by the contractors' production output. In this way, *WIP* acts as a function of output/throughput i.e. $WIP = f(TH)$. Throughput defines the rate at which jobs pass through processes. This behavior closely represents due-date-driven production (Sacks and Goldin 2007, Arashpour 2014). Fig. 1 shows a schematic illustration of the production workflow and control in the due-date-driven construction.

Fig.1. Schematic flow of work and production control within the due-date-driven network

Fig. 1 illustrates due-date-driven construction, which is an open queuing network and jobs can freely enter the network Based on forecast demand. As can be seen, new jobs are scheduled/pushed into the network of trade contractors in a due-date-driven construction and the main focus of production control system is on start and finish of assigned tasks to specialty trades.

However, the second builder, coded as builder B, starts a new house only after a completed house exits production. In fact, the start rate to build new houses varies at times based on the trade performance and output/throughput rate is a function of *WIP* inventory, i.e. $TH = f(WIP)$. This strategy represents rate-driven production, where a new job is pulled into the network upon the completion of one job by the very last processor. Fig. 2 shows the flow of work in the rate-driven network.

Fig.2. Flow of work within the trade network in rate-driven production

Fig. 2 illustrates rate-driven production, which creates a closed queuing network with a maximum production bound. The stability of workflow in the rate-driven environment enables the network of trade contractors to accommodate an expected level of demand easily. In order to compare the efficiency of due-date-driven and rate-driven construction, processes of individual trades were first modeled analytically and tangible performance measures were compared quantitatively. Then, simulation models of the whole production network were built and run in order to analyze different what-if scenarios in the real-life construction environment. Two selected production builders use similar construction methods and processes. Behaviors of two production networks in building 1000 detached suburban houses were analyzed and compared in the two production networks.

Open and closed queuing networks

In this investigation, the construction processes in both due-date-driven and rate-driven environments are subcontracted to up to 50 trade contractors. Construction methods and process times are similar for specialized trades in the two house building networks and the output of a trade is always required by the successors in order to perform their tasks. It is assumed that there

is sufficient external demand for both production environments. The decision variable for the due-date-driven builder is selecting the start rate of new houses. The trade network in this case acts as an open queuing network where freely fluctuating *WIP* is observed and the rate of new construction starts is controlled. Queues for houses waiting to be processed by trade contractors can be modeled using queuing theory principles for first-in-first-out (FIFO) queues. According to Kendall's notation (Kendall 1953), the most general form of queue for our case can be represented by $G/G/1$, in which a Generally distributed demand rate is processed by a trade in a Generally distributed process time, one by one. This queue can realistically represent unsteady-state construction processes because simplifying assumptions such as normal process times are not required (Walsh, Sawhney et al. 2007).

Adopting a due-date-driven workflow, the expected number of jobs in the queue to be processed by a trade (WIP_q) can be modelled in a similar approach to Spearman and Zazanis (1992) as Eq. (1).

$$WIP = f(TH) \xrightarrow{yields} WIP_q = \frac{TH}{1 - TH} \quad (1)$$

In Eq. 1, TH is the throughput rate of the trade. Understandably, TH is equal to the rate of new construction starts (r_a) when there is not re-entrant flow or rework (Brodetskaia, Sacks et al. 2013). This assumption will be relaxed in the simulation modeling and analysis in the next section. Since N trades are interacting in the network, the total work-in-process inventory can be approximated by Eq. (2).

$$WIP_{total} = \sum_{q=1}^{q=N} WIP_q \quad (2)$$

In order to model the rate-driven production strategy, a cap should be defined on the inventory of work-in-process or number of houses under construction. In this scenario, random external demand is not released to the trade network directly. For example, as suggested by González, Alarcón et al. (2011), a work-in-process buffer can be placed in front of the first trade in order to dampen the effects of demand variability. Consequently, the trade network acts as a closed queuing network where *WIP* is closely controlled and the rate of new construction starts is observed. In this production setting, throughput is a function of *WIP* and can be modeled in a similar approach to Arashpour, Wakefield et al. (2013a) as Eq. (3).

$$TH = f(WIP) = \frac{WIP}{WIP + N - 1} \quad (3)$$

In Eq. 3, *N* is the number of processors (trade contractors). It is worth mentioning that Eq. 2 and Eq. 3 are simplified models that partially reflect the interaction of specialty trades and impacts on the productivity of one another. More sophisticated models are required to capture the impact of site congestion and the need for using on-demand resources such as tower cranes.

In order to make a fair comparison between efficiency of the due-date-driven and rate-driven production, the required work-in-process inventory to achieve same levels of throughput rate should be compared in both environments. Towards this aim, *WIP* is let to build up in the rate-driven network and resultant throughput rate is computed using Eq. (3). Then, exactly same throughput rates are inserted into the Eq. (1) and (2) in order to compute the required *WIP* inventory in the due-date-driven production network. The surface chart in Fig.3 shows the work-in-process inventory versus achieved throughput rate in the due-date-driven and rate-driven production environments.

Fig.3 Higher levels of work-in-process inventory in due-date-driven than rate-driven production in order to achieve the same throughput rate

As can be seen in Fig.3 and as a result of setting a cap for the number of jobs under construction, the rate-driven production network needs a smaller work-in-process inventory compared to the due-date-driven production network. In other words, rate driven construction can achieve same rates of throughput with less *WIP* and consequently is more efficient. It is worth mentioning that in manufacturing, Kanban squares intend to pull the workflow from every upstream processor. However, the proposed control protocol of constant work-in-process aims to limit the number of jobs in the whole system and only pulls from the very end of the production network. It has also the flexibility of pulling from the bottleneck and start of a new job can be authorized when bottleneck finishes the work on an in-process job. This original perspective makes the rate-driven method flexible and applicable to many construction networks even those using more complex production strategies than the traditional subcontracting system.

In the next step, computer simulation was used to model production processes of the trade contractor network in order to extend comparisons on efficiency under the two production control strategies.

Simulation experimental framework

The interconnected networks of trade contractors in the construction production are too complex to be solved analytically (AbouRizk, Knowles et al. 2001, Halpin 2010). In such networks, resource delays often result in formation of queues or waiting lines. Among other methodologies to model construction queues, discrete event simulation (DES) is the most common used (Farid and Koning 1994, Martinez 2010). In simulation of construction queuing systems, providing

timely and proper input data with high temporal and spatial accuracy enhances the reliability of decisions making based upon the simulation output (Akhavian and Behzadan 2014).

In this study, simulation experiments were designed and run in order to analyze real-life what-if scenarios in the construction production. Stochastic variables of construction production were analyzed using ARENA discrete event simulator. Performance metrics of the due-date-driven and rate-driven production networks were measured by running the simulation experiments for a long production period (16 months).

Nonlinear random demand rates and process times were accommodated into the model. In a similar approach to Lee, Fung et al. (2013) and Chan, Yuen et al. (2015) demand rates and process times were not fit to the theoretical statistical distributions such as exponential or triangular, in order to increase the modeling precision. Instead, ARENA input analyzer was used to divide the actual data into groups and calculate the proportion in each group. In this way, accurate empirical distributions were formed for both demand and processes. On-site process times of trade contractors were observed and recorded in order to ensure simulation models can realistically represent operations of the two builders. Finally, models were verified and validated by applying modifications recommended by the project and site managers.

Care should be taken in using empirical distributions in simulation of construction processes. Although empirical distributions are more accurate than theoretical distributions because they are built using the actual data, there are two major limitations in using them. First, a high quality sampling with large numbers of data points is required to form an empirical distribution function (EDF) without undesirable irregularities. Second, using the empirical distribution in simulation of construction processes is more plausible when probability of occurring extreme events is low.

This study, for example, uses empirical distributions to represent the repetitive operations in residential construction as the probability of occurring a process with extremely short or long durations lends itself to estimation and therefore realistic lower and upper bounds for EDF are known.

The main challenge in modeling the rate-driven production was to set a desired cap for the number of houses under construction. This production strategy cannot be precisely modeled using ready-to-use constructs in most simulation systems (AbouRizk, Halpin et al. 2011). A special purpose code in SIMAN simulation language was written that prevents the very first trade contractor from starting a new house until a house completion by the very last trade contractor. Towards this aim the cap for maximum number of jobs under construction was defined using a variable named CONWIP (constant work-in-process). This variable is decremented when a new job enters the construction network and incremented when a completed job leaves the network. Authorization for starting a new job is only granted if the variable is greater than zero. The simulation module for enforcing a rate-driven production is shown in Fig.4.

Fig. 4. Defining the control protocol in the simulation model for rate-driven production

The simulation construct in Fig.4, ensures that the number of jobs in the construction network never grows beyond the predefined cap. Interested readers can refer to Arashpour, Wakefield et al. (2014a) for a more detailed treatment of the modeling approach. Due-date-driven production network does not limit the number of houses under construction and new job starts are scheduled (not authorized). The results of running simulation experiments for the due-date-driven and rate-driven production are shown in Fig 5.

Fig. 5. Work-in-process (WIP) levels under the two production control strategies

Based on the simulation results in Fig. 5, the number of houses under construction for both systems grows until two production networks are loaded up to their production capacity by month 4. Then, rate-driven production manages to set the cap for the number of houses under construction and *WIP* inventory never grows beyond this level. However, house completions in the due-date-driven production fall behind the number of starts and *WIP* inventory continues to grow, reaching a peak of 582 at the end of the simulation period.

This continuous ingrowth of *WIP* reflects congestion in the due-date-driven production network and not surprisingly, this congestion inflates the house completion times. Based on the simulation results, number of house completions in the house building network with a cap on *WIP* level surpasses the network without this workflow control strategy. This fact is evident in the surface chart illustrated in Fig. 6.

Fig. 6. Number of house completions (due-date-driven vs. rate-driven construction)

Comparison of Fig. 5 and Fig. 6 reveals that although there are more houses under construction in the due-date-driven network (Fig. 5), the output is less than the rate-driven network (Fig. 6). This proves the fact that the rate-driven production is more efficient than due-date-driven because a higher output level is achieved by having smaller levels of work-in-process inventory. This is consistent with findings of Gurevich and Sacks (2014), indicating that defining a cap on the work-in-process level can improve the efficiency in the construction production and enable builders to operate their trade contractor network in a more cost-effective way. Furthermore, the simulation results are in line with those obtained by analytical results in the previous section and provide a measure of validation.

Supervisory and coordination requirements in the due-date-driven and rate-driven construction

There is a high level of variability in both process times and demand rates within the construction and particularly the house building sector. Variability in the construction process is caused by many factors such as accidents on worksites(De la Garza, Hancher et al. 2000), worker fatigue and illness(Arashpour, Shabanikia et al. 2012), shortage in material supply(Castro-Lacouture, Süer et al. 2009, Hwang, Park et al. 2012), and management-related issues (Cheng, Huang et al. 2013). Furthermore, periods of boom and bust cause variable demand rates for the construction of new houses.

When all the house building processes are subcontracted to trades, the builder is solely in charge of sales, marketing and construction management. The major difficulty for the builder is to manage the flow of work or ‘hand-offs’ among trade contractors(Walsh, Bashford et al. 2004). This complex coordination task is undertaken by building supervisors. In the common practice in the Australian house building, a supervisor usually coordinates construction processes of about 15 houses. This makes supervisors a valuable and highly utilized resource in the production house building (Dalton, Wakefield et al. 2011, Arashpour, Wakefield et al. 2015a). The objective of this section of the study is to explore possible effects of due-date-driven and rate-driven production on the supervisor workload.

Analytical model

Both due-date-driven and rate-driven production environments heavily rely on their building supervisors in order to coordinate the flow of work within the network of trade contractors. In order to develop a special model for comparing the supervisory conditions in the two production environments, the annual target of building 1000 houses was converted it to 83 houses per month and almost three houses per day. Due-date-driven production exposes the trade network to a

random external demand with the mean value of three in order to fulfill the set objective. The capacity of resources involving trade contractors and building supervisors are set to keep up with this average demand. In particular, enough supervisors need to be hired to coordinate the construction processes. In modeling of construction processes, the random variable of demand is traditionally represented by a Poisson process with exponentially distributed process times and in the current case: ($Demand \sim Poisson (\lambda = 3)$). In a similar approach to Hopp and Spearman (2011), the probability mass function (PMF) can be used in order to compute the likelihood of having different levels of demand.

$$P(d) = \sum_{d=0}^{\infty} \frac{e^{-\lambda} \lambda^d}{d!} \quad (4)$$

In Eq. (4), $P(d)$ is the probability of having a given level of demand and λ is the mean value for the demand rate. Understandably, the expected number of days having a certain demand level can be calculated using Eq. 5.

$$E(d) = n \times p(d) \quad (5)$$

In Eq. 5, n is the duration of observation for our set objective. In the current analysis, there have been 365 working days and 115 nonworking days during the study period (16 calendar months), therefore $n = 365$.

It is worth mentioning that sales rates and consequently job arrivals to the network are random. After setting the throughput rate in the due-date-driven production, there exist periods when supervisors are not busy. The probability of having no demand for constructing new houses is $P(d = 0) = e^{-3} \approx 5\%$. Furthermore, the number of idle days for a supervisor can be computed by Eq. 5 and is equal to $E(d = 0) = 365e^{-3} = 18$ days.

During construction boom periods, it is also likely that sales rates are greater than the initial estimation of the due-date-driven builder. The proportion of time when production is not able to keep up with constraints in the capacity of trade contractors and supervisors can be calculated as,

$$P(d > 3) = 1 - P(d \leq 3) = 1 - \sum_{d=0}^3 \frac{e^{-\lambda} \lambda^d}{d!} = 1 - \left(e^{-3} + \frac{3e^{-3}}{1!} + \frac{9e^{-3}}{2!} + \frac{27e^{-3}}{3!} \right) \approx 35\%$$

This indicates that over a long period of time (127 days in a working year) the due-date-driven production experiences a slowdown, which is caused by trade contractor and supervisor overload. This fact has also been illustrated in Fig.7. The shaded area shows the likelihood of having greater demand than three houses per day.

Fig. 7. Probability distribution plot for the number of new construction starts (due-date-driven production)

It should be taken into consideration that sales and marketing strategies can play a major role in any residential development project. In the current investigation, such strategies are very similar as the builders are two regional branches of a major house building company in Australia. Understandably, a more detailed treatment of the sales/marketing strategies requires a more advanced modeling approach.

Overall, the results of this part of the study indicate that due-date-driven production faces difficulties to create a smooth workflow for building supervisors, who experience periods of idleness followed by periods of overload. In other words, supervision and coordination of construction processes is difficult to plan in the due-date-driven production.

In the next step, simulation experiments were designed in order to investigate the behavior of both due-date-driven and rate-driven production strategies with regard to building supervision and coordination.

Simulation experiments

The house building processes in the rate-driven production environment were simulated. Frequency statistics were collected in order to observe the daily status of supervisors (idle or busy). In a similar approach to Arashpour, Wakefield et al. (2013b), a special purpose code in SIMAN was developed to report on the resource status. The simulation models were run for 100 times in order to obtain the desired confidence interval of 99%. Comparison of results for the due-date-driven and rate-driven production is shown in table 1.

Table 1. Summary of frequency statistics (working status of building supervisors)

As can be seen in the rate-driven production, there are only 20 observations when supervisors experience an excessive workload (supervision of more than 15 houses). More importantly, there was a far more balanced utilization level for the rate-driven than due-date-driven building supervisors, 54% versus 22% over the simulation period. It is worth mentioning that in real-life construction, resources are not dedicated to a single project and when their workflow is unstable, they might engage in another project. Rate-driven construction can stabilize the workflow in the network and therefore maximize availability of resources when they are needed.

Other resources in the construction network have a similar situation to what is shown in table 1. For example, roofing contractor had the highest long-term utilization level and was the bottleneck in the network. By defining a realistic cap for the production and limiting the number of houses under construction in the rate-driven network, roofing contractor and other trades were able to stabilize their workflow. This stability in rate-driven production is characterized by reduced average standard deviation of time between activity completions. Actual production data from the two cases such as process times were fed into the simulation model in order to compare

production rate (average time between completions) and workflow stability (standard deviation of time between activity completions) for 10 major house building processes.

Table 2. Production rate and workflow stability in the two house building scenarios

These results extend those of Halbach and Halme (2013) and Arashpour, Wakefield et al. (2015b), indicating that adopting the rate-driven production strategy together with limiting the number of houses under construction can alleviate the variation in the building supervisor workload and increase the coordination level of the construction processes.

Controllability

In order to compare the controllability of production for the two production control strategies, two issues of practical implementation and robustness in dealing with control errors were investigated.

Practical implementation

Throughput rate (the number of houses that pass through processes) is set based on the capacity estimations, which can only be done based on detailed information about work efficiency, construction process times, rework and interruptions in the worksites (Sawhney, Walsh et al. 2009). Based on an estimation of the true capacity of the trade network in the due-date-driven house building, throughput is set to the rate of new construction starts (r_a), assuming that there is no re-entrant flow or rework involved. Upper bound of the throughput rate is limited by the performance of the trade network and is beyond the builder's control. In this way the function of TH can be stated as:

$$TH = \begin{cases} \text{Start rate } (r_a) & \text{if: } r_a < \text{capacity} \\ \text{Capacity} & \text{Otherwise} \end{cases}$$

Commonly, an overestimation of the capacity leads the due-date-driven production strategy to allow for excessive number of construction starts by the trade network and consequently the number of houses under construction will grow rapidly. This is particularly true during construction boom periods when a higher numbers of house completions than normal are desired. This fact makes the implementation of the due-date-driven production strategy very risky.

Another issue regarding the practical implementation of due-date-driven is the utilization rate of trade contractors. Results from running the simulation experiments showed that 50 trade contractors in the due-date-driven production network experience high levels of variations in the flow of work and frequent periods of idleness. This variable workload is difficult and expensive for the trade contractors to accommodate (Bashford, Sawhney et al. 2003, Arashpour and Arashpour 2012). As can be seen in Fig.8, utilization rates (the proportion of time that a trade is busy) fluctuate between 62 and 99 per cent in the due-date-driven homebuilding network.

Fig.8. Utilization rates for 50 trade contractors (Simulation results for due-date-driven and rate-driven production)

As it is evident in Fig. 8, in the rate-driven house building network, where the number of houses under construction is bounded, trade contractors are more evenly utilized. Here the rates only vary between 80 and 99 per cent and therefore trade contractors can be confident that they will have a continuous flow of work.

While achieving a true capacity estimations and balanced utilization of trade contractors is difficult in the due-date-driven production environment, rate-driven production directly observes

the number of houses under construction. This is consistent with findings of Ballard (2000) and Koskela, Sacks et al. (2012) indicating that the rate-driven production is a more practical strategy in order to control the flow of work and utilization within the trade networks.

Model validity

Throughout this paper, analytical models have been developed to model system performance measures in the residential construction context. Despite the use of simplifying assumptions/approximations, the conjecture is that developed models are still reasonable representations of the real system. Cross-comparison of simulation and analytical results has been used to support this conjecture throughout the paper.

Furthermore, simulation results were validated using a systematic approach similar to Cates (2004) and Mielczarek (2013). In the first step, case study participants were briefed about the methodology used to develop the model and the way actual data were used to determine empirical distributions. A total of 25 professionals were approached, six construction engineers, four architects, 12 subcontractors, and three construction managers. Comments and final agreement of case study participants on the model resulted in a high level of face validity.

Simulation models were expected to achieve a high face validity because in this study, existing construction production networks were modelled. Furthermore, since empirical distributions have been primarily used in this study, project participants were able to recognize data and relate them to actual production. As a result, participants were inclined to accept the modelling assumptions and simulation logic as the model reasonably represented the existing production network and yielded the same output as the actual system. Achieving a high face validity is a very important step in checking the model credibility as project participants have the deepest understanding and insight into the ongoing production scenarios (Fellows and Liu 2008).

In the second step and in order to validate the process of input–output transformation in the simulation model, regular daily production processes of the two cases were modeled and run 500 times. Average time between activity completions (mean value and standard deviation) was checked against the actual data collected from February to October 2014. The real-world production data and simulation results were almost identical, with errors within the range of 0.3%. Table 3 shows the comparison between the results of the discrete event simulation model and observed completion intervals.

Table 3. Validation of simulation results against actual completion intervals

In the third and final step, a sensitivity analysis was conducted by slightly manipulating input variables to the model and this caused no extreme variation in model outputs. As an example, the start rate of new houses were increased in the simulation model (1% growth in r_a). This caused only 0.5% increase in the number of houses under construction (WIP), which is acceptable as WIP is also dependent to other variables such as house completion times (CT). By completion of the three steps of model validation process, results of simulation were considered valid and reasonably robust.

Robustness

In order to compare the robustness of the two production strategies in dealing with control errors, the optimization problem of balancing the cost of excessive number of houses under construction and the cost of missed sales opportunities was considered. An excessive work-in-process results in direct and indirect costs such as on-going site establishment costs and overheads. The optimization problem, attempts to maximize the builder profit by finding a balance between

throughput and work-in-process levels. The profit function of the production can be formulated as Eq. (6).

$$Profit = \alpha_1 \times TH - \alpha_2 \times WIP \quad (6)$$

In Eq. (6), α_1 is the builder profit for signing a new house contract and α_2 is the total cost associated with an uncompleted house in the builder's production network such as on-going worksite establishment costs and late completion penalties. Let the profit of a new construction start to be much higher than costs of having an uncompleted house in the production network ($\alpha_1 = 1000\alpha_2$). That is, any house going through the homebuilding processes has the potential to generate 1000 units of profit and to incur only one unit of cost. Understandably, assuming a high profit/cost ratio, changes cost efficiencies in favor of the due-date-driven production. This encourages the start of more new houses, even if production resources for on time completion of those houses in the specialty trade network are currently unavailable. In the rate-driven production, however, the main idea is to start a certain number of houses that can be completed on time based on the available capacity (production resources).

Values of TH and WIP were computed using Eq. 1 and 3 for the due-date-driven (open queuing network) and rate-driven (closed queuing network) respectively. The internal optimization tool in MS Excel was used to find the optimal values of TH and WIP that maximizes the builder's profit. Rate-driven production profit can reach a peak of \$13.6 M by bounding the work-in-process level to 240 houses. For the due-date-driven production, the best rate of jobs passing through the processes is three houses per day, yielding a profit of \$13.4 M. Therefore, the maximum profit level for the rate-driven production is slightly (around two per cent) more than

the due-date-driven production. Table 4 shows profit values for different *TH* and *WIP* levels in the two production environments.

Table 4 Profit values for the due-date-driven and rate-driven production

As can be seen in Table 4, profit values are not very sensitive to *WIP* levels in the rate-driven production and vary smoothly even for *WIP* levels far from the optimal. In contrast, there is a sharp fall in the due-date-driven production profit for *TH* rates far from the optimal. Periods of construction boom and tendency to build more houses generally results in excessive number of construction starts in the due-date-driven environment. As table 4 shows, having 50 per cent more *TH* than the optimum rate results in a loss for the due-date-driven production. However, the rate-driven production continues earning profits until reaching 250 per cent of the optimum number of houses under construction (600 houses).

The results show that limiting the number of houses under construction is a more observable control parameter than setting the throughput rate. This extends findings of Palaniappan, Sawhney et al. (2007) confirming that rate-driven production is a more robust strategy than due-date-driven production in terms of dealing with control errors.

Conclusions

Previous research has documented the implications of rate-driven production in construction (Bashford, Sawhney et al. 2003, Koskela, Sacks et al. 2012). The contribution of this paper to the body of knowledge can be summarized to two parts. Firstly, the proposed control protocol for maintaining a constant number of houses under construction limits the number of jobs to the capacity of the specialty trade network. This flexible approach receives available capacity signal from the production network and pulls new jobs into it. It has also the flexibility of pulling from

the bottleneck and start of a new house can be authorized when bottleneck finishes the work on an in-process job. This original perspective makes the rate-driven method flexible and applicable to many construction networks even those using more complex production strategies than the traditional subcontracting system. A special purpose simulation model has been developed in this research to implement the rate-driven production in the house building environment. Secondly, this paper addresses a gap in the construction research where quantitative performance assessment of alternative project planning and control strategies are required. This investigation analyzes the theoretical reasons behind the superiority of rate-driven production and the resultant practical issues in this environment.

Based on the results, adopting the rate-driven production control strategy along with maintaining a constant level of work-in-process can significantly improve tangible performance metrics in volume homebuilding. The findings extend those of Sacks and Goldin (2007) and Koskela (2000), confirming that direct control of the work-in-process inventory is more feasible than indirect control of throughput and capacity estimations in the due-date-driven environment. Furthermore, results of analytical models and simulation experiments produced several key observations about the superiority of rate-driven production in the real world construction, such as robustness against errors in determining the optimum number of houses under construction. In fact, optimism in estimating production capacity and the desire to yield as much throughput as possible to maximize profit are making due-date-driven production prone to errors in the control parameters. That is, overestimating the capacity of the trade contractors' network results in more construction starts and can lead to a loss of money and therefore cash flow problems for the builders.

The research reported in this paper builds up on the current body of knowledge by developing an in-depth insight into the rate-driven and due-date-driven production control strategies. Particularly, this study confirms and extends findings of Gurevich and Sacks (2014) and Arashpour, Wakefield et al. (2014b) by adopting an original approach towards three performance metrics of production efficiency, supervision and controllability.

Furthermore, residential builders can control their production network in a more cost-effective way and improve the performance by adopting a rate-driven strategy. This can address the problem of shortage in housing supply was the motivation for conducting this research. The authors are currently working on the issue of market demand in order to find optimal ways of buffering against demand variability in the rate-driven construction production. Future research should include more stochastic variables in analyzing effects of rate-driven construction on performance, productivity and process flexibility.

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Appendix. Notation and symbols

<i>WIP</i>	Work-in-process (Number of houses under construction)
<i>TH</i>	Throughput of the production network
<i>CT</i>	Completion time
<i>E(.)</i>	Expected value

560	$P(.)$	Probability of
561	$f(.)$	Function of
562	r_a	Rate of starting new houses
563	μ	Average time between completions
564	σ	Standard deviation of time between completions
565	<i>CONWIP</i>	Constant work-in-process (Number of houses under construction capped)

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