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Off-site construction optimization: Sequencing multiple job classes with time constraints

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ABSTRACT

Off-site construction is a unique hybrid of manufacturing operations and on-site construction activities. Maximizing the production output has long been the main challenge for off-site manufacturers. Among other responses to this challenge, the use of multi-task shared resources has proved its effectiveness in improving tangible performance measures of production. However, multi-skilled resources often become bottlenecks (overloaded) when producing multiple classes of products and prevent the production network from meeting due dates. This paper analytically models the problem of defining the optimal product sequencing using optimization-based metaheuristics with the aim of minimizing changeover time, which is wasted switching from a product class to another. Production data of two Australian off-site manufacturers are used in the subsequent empirical analysis resulting in advancement of five research propositions. This research contributes to the scheduling theory by expanding the insight into dynamics of resource sharing and job sequencing. The developed models and propositions are of practical value for off-site manufacturers of building elements to maximize their production output.

1. Introduction

Off-site construction has long been regarded as beneficial to all stakeholders in the construction process [1–3]. It has also been recognized as the key vehicle for driving innovation and improvement within the industry [4,5]. Its numerous advantages include but are not limited to reducing the number of on-site trade contractors and coordination efforts [6], producing high-quality building elements in the controlled environment of factories [7], reducing construction time and cost [8], minimization of construction waste [9], and improving workflow continuity [10].

Off-site construction has consistently achieved higher productivity growth comparing to site-built construction [11]. The reason behind this, is the flexibility to adopt manufacturing principles common to other industries and produce high-volume and high-quality products [12]. Among other manufacturing principles, resource sharing and multitasking have significant impacts on improving production performance [13]. Multi-skilled resource utilization changes the fragmented approach of assigning tasks to specialty resources and enables the production network to respond dynamically to variable product demand and resource availability [14]. Use of multi-skilled resources also increases the output rate by reducing handoffs among production resources [15].

Despite the evidence of positive impacts of multitasking on productivity and efficiency, its complexity and potential side effects in off-site construction are generally poorly understood [16]. Under such arrangements, scheduling the production process will be complicated especially when multiple classes of products are manufactured [17,18]. In almost all off-site construction plants the authors have visited, there are significant changeover/preparation times when switching from one product class to another, which adds to the scheduling complexity. Even by using the simplifying assumption of sufficient existing capacity to meet periodic demands, it will remain a nontrivial task to find the optimal number and order of jobs in each product class to be worked on by the shared resources.

The necessity to find the optimal product sequence in off-site construction of multiple classes of jobs with time constraints is addressed in this research. To this end, relevant literature is reviewed first and

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the gaps resulting in the current research are identified. Next, the optimal sequencing in off-site construction is modeled as an optimization problem. Then, real-world data from ongoing production processes in two Australian off-site manufacturers are used in empirical analysis of sequencing and cross-validation of analytical results. Finally, the findings are discussed and translated into five propositions of this research.

An important contribution of this paper is to scheduling theory as it expands the insight into dynamics of job sequencing using shared resources in off-site construction. By carefully considering all influential variables in defining the optimal production sequence, off-site manufacturers of building elements can quote due dates that are both responsive to on-site construction needs and feasible in terms of manufacturing capacity.

2. Research background

Despite well-documented benefits of prefabricating building components in improving productivity and efficiency [19–21], the uptake of off-site construction has been limited [22,23]. Recent studies have traced root causes including longer lead times due to a lack of coordination between on-site demand and off-site production [24], higher costs for end users caused by low utilization of expensive manufacturing resources [25], and inconsistent quality due to high variety of customized products and inefficient shop floor control [26].

Previous research has shown the effectiveness of using multi-skilled resources to improve the production performance [27,28]. Multitasking and process integration are not limited to only off-site processes and can be undertaken beyond manufacturing settings and equipment. Adopting a hybrid process integration architecture, multi-skilled workforce is used in both on-site and off-site production environments [29]. Such architectures have significant potential to reduce rework and enhance quality [30], and improve coordination between on-site and off-site production [31,32]. Furthermore, multi-skilling is beneficial in production of multiple classes of building elements by minimizing the probability of resources sitting idle [33,34].

In order to integrate production processes, specialty resources dedicated to different product classes are replaced with a multi-skilled resource that is capable of making a range of products. A number of researchers investigated the implementation of multi-skilling approach in manufacturing settings [35–38]. There have also been sparse studies that analyzed the use of multi-skilled resources in off-site construction [16,39].

Despite its benefits, multitasking substantially complicates the process of production planning and control. As a result, traditional planning techniques such as critical path method (CPM) are unable to generate optimal lead times and sequence of jobs [40,41]. In fact, the output of traditional construction planning techniques are often far from the reality on the manufacturing floor [42]. The fact that planning outputs in off-site construction is usually adjusted by in-house developed spreadsheets is an evidence for this [33]. The required changeover time for switching a shared resource from one product class to another, adds to the complexity of finding the optimal sequence of jobs.

A few researchers [43–45] have modeled the sequencing as a linear programming problem with the goal of minimizing the maximum production delay (minimax optimization). The minimax decision rule performs well when changeover times are not significantly long [46]. The effectiveness and robustness of sequencing algorithms based on minimax decline when the multi-skilled resources sit idle in the process of switching to a different product class and as a result the production network frequently misses customer due dates [47]. The difficulty of finding an optimal product sequence using a multi-skilled resource has been well-documented in the literature [48–50]. However, to the authors' best knowledge, no tailored solution in the off-site construction context has been proposed yet. An optimal product sequencing approach will enable off-site manufacturers of building products to quote due dates that are both responsive to project deadlines and feasible in terms of production capacity.

3. Optimal sequencing for multiple classes of products in off-site construction

The output rate in off-site construction can be defined as a function of average resource utilization (u) and total production time (t_p),

$$o_r = \frac{u}{t_p}. \tag{1}$$

The output rate is equal to the start rate of new jobs (s_r) given there is no production loss in the off-site construction processes. As a result, resource utilization can be defined by Eq. (2),

$$u = s_r \times t_p. \tag{2}$$

Consider an off-site construction plant in which a shared resource is used to produce different types of building elements. These elements are then transferred to construction worksites for installation. The off-site construction plant should produce with a rate (s_r) that matches the periodic construction demand. Whenever a shared resource is switched from one product to another, a product specific changeover time (t_{ci}) is required for preparation and cleanup. For multiple classes of products with changeover times on the bottleneck (shared resource),

$$u = \sum_{i=1}^{n} \frac{s_{ri}}{n_i}\left(t_{ci} + n_i t_{pi}\right) \tag{3}$$

where s_{ri} is the start rate of jobs in the ith class of products, n_i is the number of jobs in this class, t_{ci} is the changeover time on the shared resource, and t_{pi} is the processing time of a job in the ith product class. Assuming the off-site construction plant has sufficient capacity to meet the periodic demand, it is not a trivial task to find out the optimal number of jobs in a product class before switching to another class. This can be modeled as an optimization problem with the goal of minimizing the total production time,

$$\begin{cases} \textit{Minimize} & t_p \\ \textit{Subject to}: t_{ci} + n_i t_{pi} \le t_p & \text{for } i = 1, \dots, n \\ \sum_{i=1}^{n} \frac{s_{ri}}{n_i}\left(t_{ci} + n_i t_{pi}\right) = u & \end{cases} \tag{4}$$

In a similar approach to Hopp and Spearman [51], the optimal utilization level (u^*) is approximated by $\sqrt{u}$ and the constraint is used to solve the optimization problem for t_p,

$$t_p = \frac{\sum_{i=1}^{n} s_{ri} t_{ci} t_{pi}}{\sqrt{u} - u} + \overline{t_{ci}} \tag{5}$$

where $\overline{t_{ci}}$ is the mean changeover time on the shared resource in hours and s_{ri} is the start rate of jobs in the ith class of products in jobs/h. This solution balances the processing times across different product classes and synchronizes the off-site production. The optimum number of jobs in each product class is a function of t_p in Eq. (5) and can be computed as,

$$n_i^* = \frac{t_p - t_{ci}}{t_{pi}}. \tag{6}$$

As can be seen in Eq. (6), the optimal sequencing for multiple classes of products in off-site construction is dependent to two endogenous production variables of processing time (t_{pi}) and changeover time (t_{ci}).The third influencing variable is total production time (t_p) that is related to the start rate of new jobs (s_r),which has a direct relationship with the

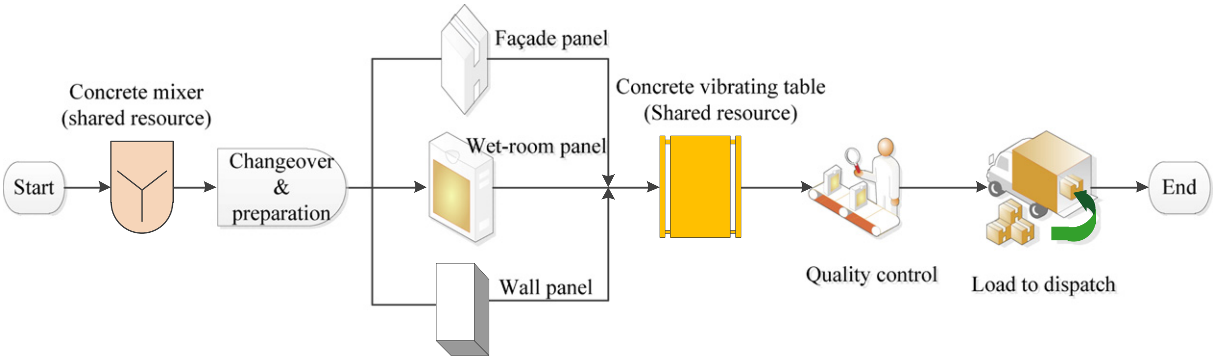


Fig. 1. Production process of concrete panels (use of shared resources).

exogenous variable of periodic demand. Accordingly the first proposition of the paper is advanced as,

Proposition 1. Optimal sequencing for multiple classes of products in off-site construction can be formulated as a function of endogenous production variables (processing and changeover times), and exogenous production variables (periodic demands).

4. Empirical analysis and validation of analytical models

Production data of two off-site manufacturers in Melbourne and Brisbane, Australia were used to evaluate the functionality of developed models. In both plants, concrete panels of different type are produced to be used in the process of construction. Fig. 1 illustrates a simplified network of production in the two off-site construction plants.

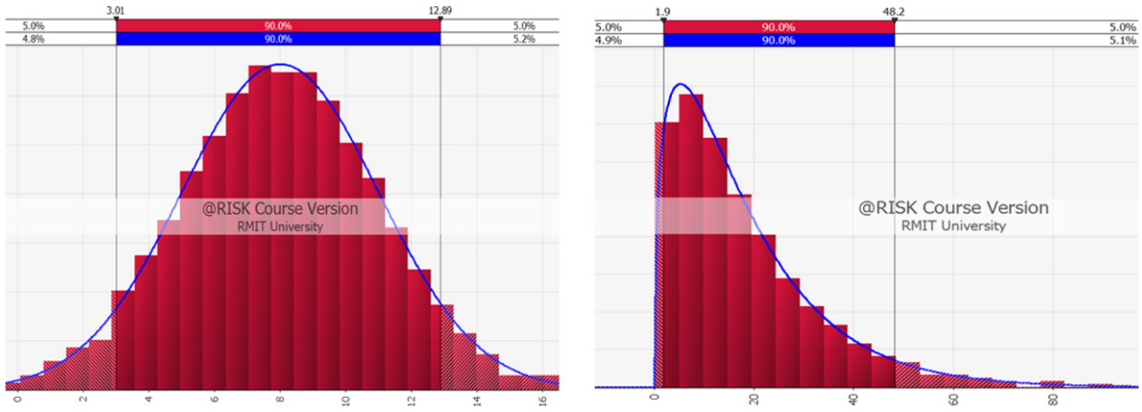
As Fig. 1 illustrates, concrete mixer and vibrating table are two shared resources in the production network. Process integration and use of shared resources have shown to be effective means of improving productivity in off-site construction because of their variability reduction effects [52]. However, the real challenge for off-site construction plants with multiple classes of products is to find an optimal production sequence that synchronizes production and demand. Scheduling in these plants is particularly difficult as process times are sequence dependent and changeover time is required to switch from one class of product to another. For example, in the two investigated plants a lighter concrete mix is used in façade panels. Furthermore, wet-room panels have an additional isolation layer acting as the moisture barrier. Therefore, changeover time is spent on mixing a new concrete batch or preparation of formwork, when switching from one panel class to another. In addition, cleaning of equipment is often required in between processes.

In order to analyze optimum product sequencing problem, the production networks of the two off-site manufacturers were modeled. Endogenous production data such as process and changeover times along with exogenously generated variables such as periodic demands were collected during several site observations. In a similar approach to that used by Akhavian and Behzadan [53], best-fitting probability distributions to collected data were evaluated by common goodness-of-fit tests. Fig. 2 illustrates the distribution of processing and changeover times for wet-room panels.

A total of 3645 discrete event simulation experiments were constructed by varying different production parameters. Interested readers can refer to Arashpour, et al. [54] and Arashpour, et al. [55] for further details about simulating similar construction networks. Simulation runs were followed by a sensitivity analysis to evaluate and compare the effects of input variables on production performance. The tornado diagram in Fig. 3 illustrates the results of sensitivity analysis.

As can be seen in Fig. 3, among all important input variables in off-site construction of multiple products, variations in periodic demand have the most significant effect on total production time. In other words, for finding the optimum production sequence in off-site construction, the most important variable is the distribution of customer demand for each product class. This is consistent with findings of analytical modeling in the previous section and highlights the importance of exogenously generated variables such as customer demand on the internal production decision of finding the optimal production sequence. This result leads to the second proposition of this paper,

Proposition 2. Optimal sequence of multiple classes of products in off-site construction is most sensitive to the external periodic demand amongst other production variables.



(a). Processing times (wet-room panels) **(b). Changeover times (wet-room panels)**

Fig. 2. Probability distributions fitted to the processing and changeover times in experiments.

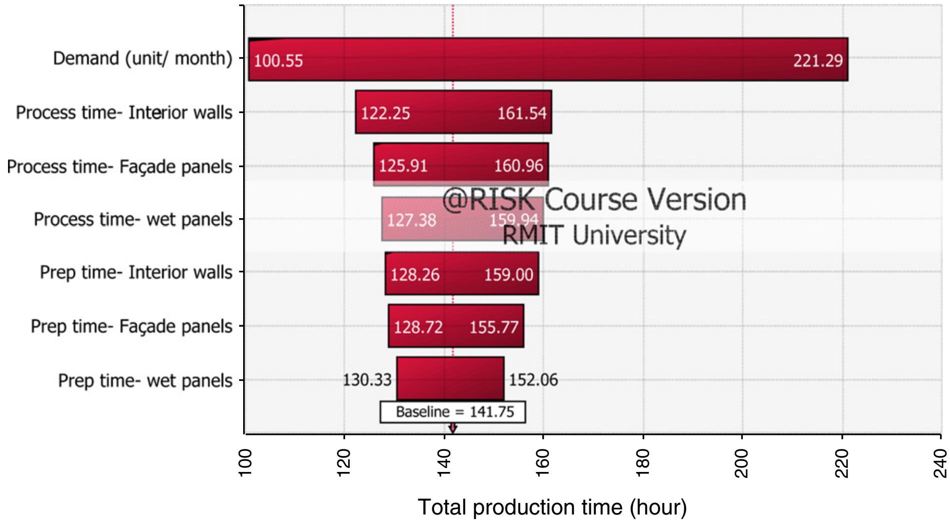


Fig. 3. Sensitivity analysis in production of multiple classes of products - Effects of top-seven input variables on production time.

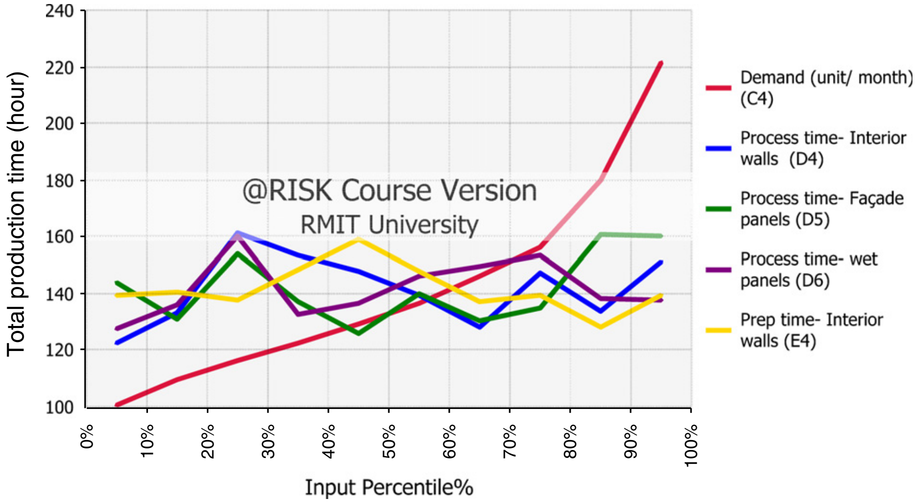


Fig. 4. Change in dependent variable (production time) across a range of input values.

The above proposition suggests that the optimum allocation of a shared resource to each product class is mainly influenced by periodic demand as the most significant production variable. This is also revealed in Fig. 4 where changes in the production time has been plotted against a range of production input values. As can be seen, the impact of periodic customer demand for different product classes is evident by the steep slope of its trend.

In order to suggest a solution approach to the problem of finding the optimal sequence of jobs, production processes for a set of 20 jobs in the two off-site construction plants were analyzed. As can be seen in Table 1, there are three product classes and an average changeover time of eight hours is required whenever switching from one product class to any other. In the job sequencing practice, the off-site manufacturer intuitively arranges jobs in the earliest due date order to minimize the maximum delay (minimax optimization).

As can be seen in Table 1, minimax is not an effective decision rule for job sequencing as it results in nine changeovers and an average delay of 32.2 h per job. A comparison of due dates and completion times in Fig. 5 illustrates the poor production performance as a direct result of suboptimal sequencing. Using the minimax decision rule, completion times for all jobs are longer than due dates, and except for the first five jobs, the trend of the completion time deviates farther from

Table 1
Sequence of 20 jobs in the earliest due date order (minimax decision rule).

Job ID	Product class	Due time (hour)	Completion time	Delay (hours)
1	Wall panel	1	13	12
2	Wall panel	8	18	10
3	Wall panel	15	23	8
4	Wall panel	22	28	6
5	Wall panel	29	33	4
6	Wet-room panel	36	46	10
7	Wall panel	43	59	16
8	Wet-room panel	50	72	22
9	Wall panel	57	85	28
10	Wet-room panel	64	98	34
11	Wall panel	71	111	40
12	Façade panel	78	124	46
13	Wet-room panel	85	137	52
14	Wet-room panel	92	142	50
15	Façade panel	99	155	56
16	Façade panel	106	160	54
17	Façade panel	113	165	52
18	Façade panel	120	170	50
19	Façade panel	127	175	48
20	Façade panel	134	180	46
			Average	32.2

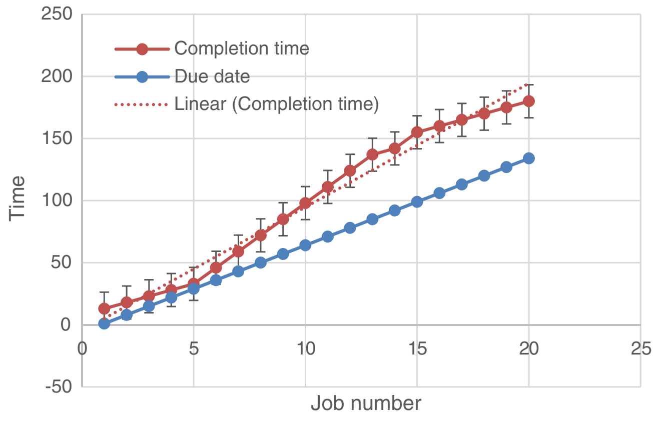


Fig. 5. Production performance (sequencing jobs to minimize maximum delays = minimax).

the due dates. Thus the minimax solution fails to find the optimal job sequence in the off-site production setting.

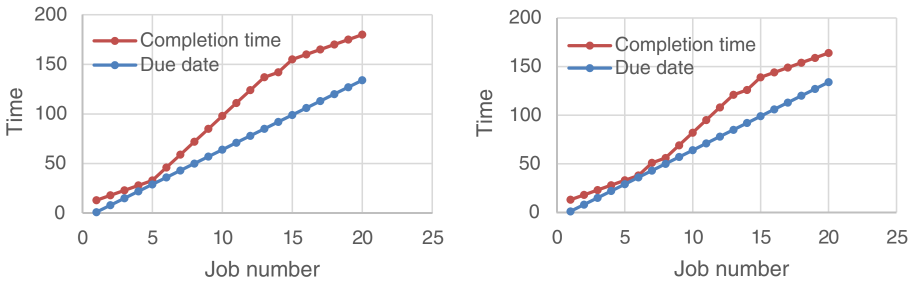
In the process of finding an optimal sequence of jobs to be processed by a shared resource, some different scheduling approaches can be used. The first approach is simulation-based scheduling that develops often deterministic but detailed what-if scenarios instead of undertaking optimization [56]. A disadvantage of the simulation approach is that it needs enormous amount of production data [57]. Furthermore, since simulation models use a trial-and-error process to find an effective schedule, solving big and complex problems can be very time consuming [58]. The second solution approach is optimization-based scheduling that actively searches for a good schedule using an algorithm [59]. A standard optimization technique for scheduling is branch and bound in which a partial schedule is defined as a branch and then an active search starts to determine bounds or possible lowest limits on job completion times [60]. This is a method of implicit enumeration that only focuses on small fractions of possible schedules at each run but is still tediously slow for solving complex problems [61].

The third approach to find the optimal sequence of jobs in production settings is to use optimization-based metahuristics. This approach is adopted in this research as analyzing all possible job sequences $(20\,! = 2.4\ e^{+18})$ by other methods will not be feasible. In complex scheduling problems, a practical metaheuristics approach can facilitate finding optimal/near optimal solutions [62].

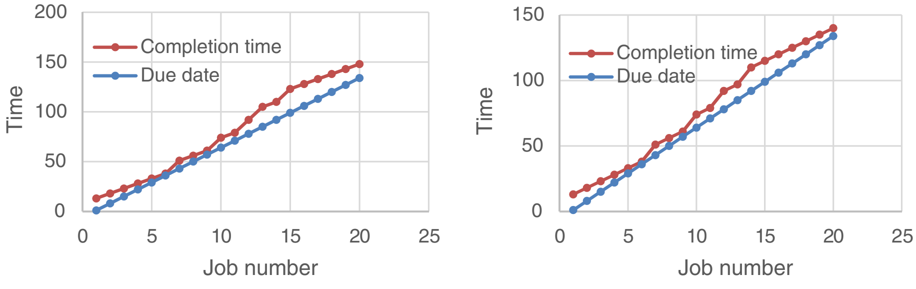
To show the effectiveness of a metaheuristic method such as tabu search, its performance is compared with the local search optimization technique. This technique iteratively seeks for local optima with the hope of finding a global optimum [63–65]. Pairwise interchanges of jobs are analyzed in order to improve the production performance. The aim in this sequencing problem is to reduce changeovers (non-value-added or wasted times) and the local search only considers moves that eliminate switches from one product class to another to shorten completion times. The first move is to swap jobs 6 and 7, resulting in two changeover eliminations and reduction of the average delay to 21 h per job. In the second search step, job 9 is moved after job 10 and as a result one changeover is eliminated and the average delay is reduced to 12.2 h per job. In the third search for a better sequence, job 12 is moved after job 14, resulting in one changeover elimination and reduction of the average delay to 9.4 h per job. At this stage, no further single job move can improve the production performance. Fig. 6 illustrates the consecutive reductions in completion times as a result of using better job sequences in the off-site construction plant.

Although local search optimization results in significant improvements in the sequencing practice, it quickly converges to a local optimum without considering nonadjacent solutions [66–68]. A metaheuristic method such as tabu search [69–71] can be used to overcome this problem. To improve the performance of local search optimization, worsening moves are temporarily accepted by tabu method if the search is stuck in suboptimal regions. Furthermore, coming back to a previously-visited solution is discouraged by making a tabu (forbidden) list. Optimization of job sequencing in the off-site production of panels using tabu search results in the sequence illustrated in Table 2.

As can be seen in Table 2, there are only three changeovers and a comparison of due dates and completion times in Fig. 7 reveals the significant improvement in the production performance.



(a). Initial job sequence (minimax rule) **(b). First search for the optimal sequence**



(c). Second search for the optimal sequence **(d). Third search for the optimal sequence**

Fig. 6. Optimization of production performance in off-site construction (local search for the optimal job sequence).

Table 2
Optimal sequence of 20 jobs in three classes.

Job ID	Products class	Due time (hour)	Completion time	Delay (hours)
1	Wall panel	1	13	12
2	Wall panel	8	18	10
3	Wall panel	15	23	8
4	Wall panel	22	28	6
5	Wall panel	29	33	4
7	Wall panel	36	38	2
6	Wet-room panel	43	51	8
8	Wet-room panel	50	56	6
10	Wet-room panel	57	61	4
13	Wet-room panel	64	66	2
14	Wet-room panel	71	71	0
9	Wall panel	78	84	6
11	Wall panel	85	89	4
12	Façade panel	92	102	10
15	Façade panel	99	107	8
16	Façade panel	106	112	6
17	Façade panel	113	117	4
18	Façade panel	120	122	2
19	Façade panel	127	127	0
20	Façade panel	134	132	-2
			Average	5

Using tabu search as a practical metaheuristic resulted in decreasing the average delay of 32.2 h/job (under minimax decision rule) by 644%. Tabu search for finding the optimal sequence in off-site production of building elements can be further refined by eliminating moves that cannot improve the off-site production performance. Iterative search with the tabu algorithm showed that moving to sequences other than earliest due dates within a product class increases completion times. Therefore, such sequences should be excluded from the search for the optimal job sequence. This is in line with findings of Brusco and Johns [72] and Arashpour, et al. [73], and leads to the next proposition in this research,

Proposition 3. Optimal sequencing for multiple classes of products in off-site construction can be achieved by prioritizing jobs based on earliest due dates within product classes.

The above proposition suggests that upon presence of significant changeover times in off-site construction, simple sequences based on the minimax decision rule are not sufficient. Using an optimal sequence of jobs in producing multiple classes of products will increase the chance of meeting due dates. The next section of this manuscript analyzes the problem of quoting responsive and feasible due dates in off-site construction.

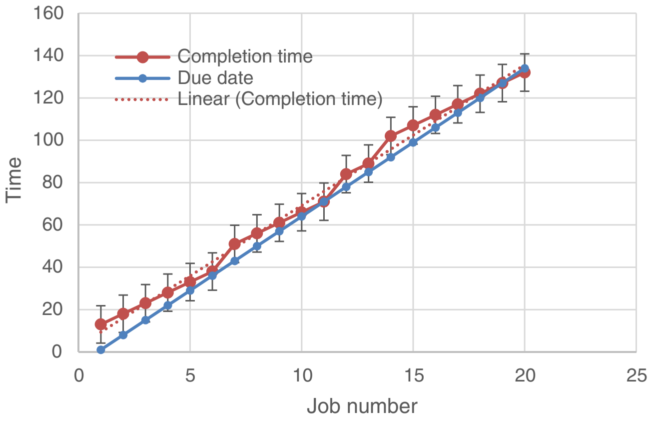


Fig. 7. Effect of optimal job sequencing on the production performance in off-site construction of multiple product classes.

5. Optimal production due date in off-site construction with time constraints

Production due date (t_{dd}) needs to be both responsive to on-site construction demand [74] and feasible in terms of off-site production capacity [75]. The performance of due date quoting can be measured by the service level (SL) that records the number of jobs whose production time is equal or less than due dates [54]. Missing a targeted service level means production output (O_t) is less than periodic demand (d) over the course of production $[0, t_{dd}]$, and the following must be true

$$P=\left\{\sum_{t=1}^{t_{dd}} O_t \le d\right\} = 1-SL. \qquad (7)$$

Production output (O_t) in off-site construction is also dependent to plant capacity that is reflected by mean (μ) and variance (σ) of production [76]. Assuming a normal distribution for the repetitive production of building elements, Eq. (7) can be rewritten as,

$$P\left\{Z \le \frac{d-\mu t_{dd}}{\sigma\sqrt{t_{dd}}}\right\} = 1-SL \qquad (8)$$

where Z is the standard normal deviation. Hence,

$$\frac{d-\mu t_{dd}}{\sigma\sqrt{t_{dd}}} = z_{1-SL}. \qquad (9)$$

By raising both sides of Eq. (9) to the power of two, it can be rewritten as,

$$\mu^2 t_{dd}^2 - t_{dd}\left(2d\mu + \sigma^2 z_{1-SL}^2\right) + d^2 = 0. \qquad (10)$$

The quadratic equation can be used to solve for t_{dd},

$$t_{dd} = \frac{\mu^{-2}\sigma^2 z_{1-SL}^2}{2}\left[1+\sqrt{\frac{4d\mu}{\sigma^2 z_{1-SL}^2}+1}\right] + \frac{d}{\mu}. \qquad (11)$$

As Eq. (11) shows, an optimal due date is dependent to three variables of production mean, variance, and demand. This is in line with findings of Sacks, et al. [77] and Arashpour and Arashpour [78], and leads to the next research proposition,

Proposition 4. Optimal production due date in off-site construction can be formulated as a function of endogenous production variables (capacity mean and variance), and exogenous variables (periodic demands).

The model for computing the optimal production due date (Eq. (11)) is also capable of accounting for production variability. The first part of the model acts as a safety time buffer that adjusts the mean time to fulfill a periodic demand ($^{d}/_{\mu}$).

6. Empirical analysis and validation of analytical models

Production data of the two off-site manufacturers in Melbourne and Brisbane, Australia were used to evaluate the functionality of developed models. Several site observations were conducted to collect data such as production mean and variance, targeted service levels, and periodic demands. A total of 4400 discrete event simulation experiments were designed and run to analyze different what-if scenarios in production. The experimentation was followed by a sensitivity analysis to evaluate the effect of input production variables on optimal due dates. The results are illustrated in Fig. 8.

Each bar in Fig. 8 indicates how much due dates change as input variables change over their range. As can be seen, production capacity mean has the greatest effect on due dates. This is consistent with findings of analytical modeling in the previous section and highlights the

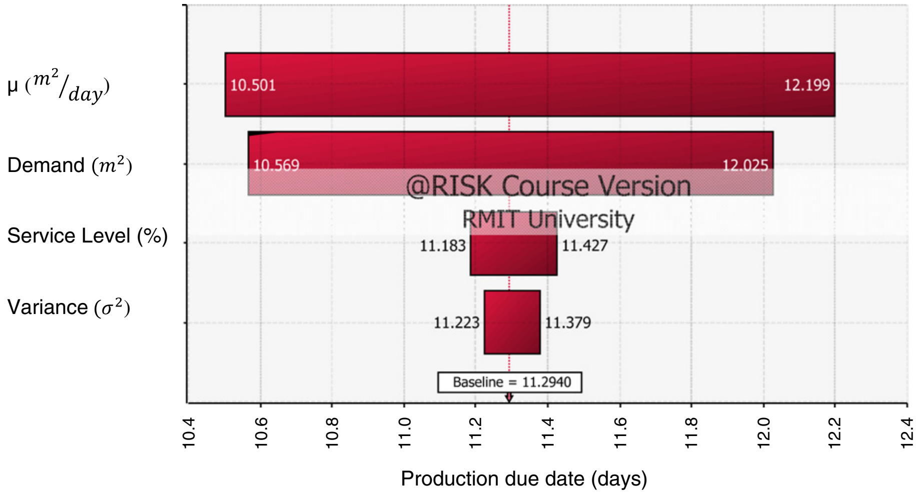


Fig. 8. Sensitivity analysis - Effects of input variables on production due dates.

importance of endogenously defined variable of production capacity in quoting due dates. Accordingly, the final proposition of this research is advanced as,

Proposition 5. Optimal production due dates in off-site construction should be endogenously quoted, rather than exogenously generated based on external demand, as due dates are most sensitive to the shop floor capacity.

The above proposition suggests that quoting responsive and feasible due dates is possible by focusing on the production side of off-site construction. Amongst other production variables, capacity mean is the most important of all because of its significant inverse relationship with t_{dd} – production due date (see Fig. 9). The second most influential variable is the periodic demand (d),which has a direct relationship with t_{dd} as demand growth creates long queues of jobs within the off-site production network.

7. Conclusion

Previous research has shown the advantages of resource sharing in the off-site construction of building elements [13,16]. Few studies, however, have suggested a practical solution to the problem of finding an optimal sequence of jobs when shared resources undergo significant changeover times in switching from one product class to another. To bridge this gap, this paper modeled sequencing as an optimization problem. Then, real-world data were used in the subsequent empirical analysis resulting in five propositions of this research.

Managing the product mix and its scheduling were shown to be effective means of improving productivity in off-site construction because of their time saving effects. Off-site production schedules need to be both responsive to on-site construction demand and feasible in terms of off-site production capacity. Using the proposed product sequencing strategy, significant production performance improvements were recorded in terms of tangible performance measures such as service level that identifies the number of jobs whose production time is equal or less than due dates. Previous research has shown that off-site construction has consistently achieved higher productivity growth when compared to site-built construction. The results of the current research further increase off-site construction flexibility and its ability to produce high-volume and high-quality products.

The consistent results prove that upon presence of significant changeover times in the off-site construction of multiple product classes, simple sequences will result in missing due dates frequently. Practical metaheuristics, such as tabu search, can be used to prioritize jobs based on earliest due dates within product classes. Furthermore, the

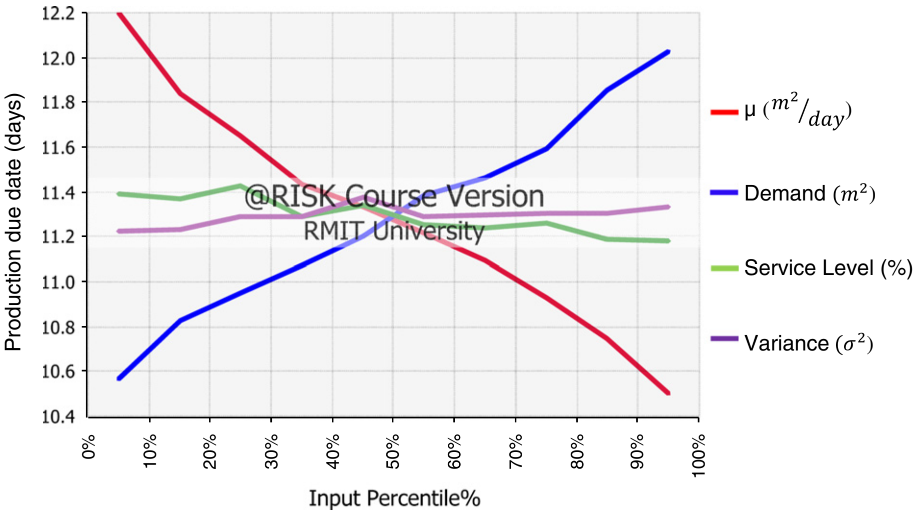


Fig. 9. Change in dependent variable (production due date) across a range of input values.

findings challenge the common practice of imposing due dates on the manufacturing floor based on periodic demands. The results of analysis suggest that optimal due dates should be endogenously quoted instead of exogenously generated.

8. Research limitations and opportunities for future research

A number of important limitations must be borne in mind when considering the implications of the results obtained. Firstly, in the panelized production scenario analyzed in this research, only three classes of products were considered. The size of the optimization problem grows exponentially by increasing the number of product classes and more sophisticated algorithms should be developed to solve the problem. Secondly, the operation cost of producing these three classes of products were assumed almost equal (as a fixed constraint) and therefore, the goal of optimization problem is to minimize the total production time (t_p).The authors are currently working on developing algorithms that can analyze production scenarios without the two aforementioned limitations and find the optimal production sequence for shared resources in complex off-site construction networks.

A number of extensions to the present work are recommended. Designing and applying heuristic algorithms in optimizing production performance in off-site construction is still in the embryonic stage and can be the focus of future research. Another potential research opportunity is to incorporate more variables into job sequencing models that affect work-sharing performance among multi-skilled resources in construction networks.

Appendix A. Notation and symbols

o_r	Output rate of production
u	Utilization level
t_p	Total production time
s_r	Start rate of new jobs
t_{ci}	Changeover time for the i_{th} product class
t_{pi}	Production time for the i_{th} product class
$\overline{t_{ci}}$	Mean changeover time on the shared resource
n_i^*	Optimum number of jobs in the i_{th} product class
μ	Production mean in standard units
σ	Standard deviation of production

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