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Optimization of process integration and multi-skilled resource utilization in off-site construction

Abstract:

Traditional approaches in construction project management assign each process to a trade contractor with an individual specialisation, and trades with the greatest work content (bottlenecks) have a significant influence on the progress rate of projects. A system with integrated processes, however, is able to function dynamically in response to variability in product demand and labour resources. This investigation aims to compare and contrast cross-training strategies that are applicable to off-site construction in order to create multi-skilled resources. To this end, the optimal number of additional skills was formulated as a constrained optimization problem. Then, production data from two prefabricated production facilities in Melbourne and Brisbane, Australia were used to construct a total of 1080 simulation experiments. Tangible performance metrics of systems were used to compare process integration strategies and use of multi-skilled resources. Findings show choosing optimal process integration architecture depends on the level of capacity imbalance and processing time variability. This investigation optimizes the decision making on process integration in off-site construction networks.

Keywords: Building operations; Flexible cross-training; Multi-skilled resources; Off-site production; Prefabricated construction; Productivity and performance measures; Project management; Process integration

1. Introduction

Construction sites are variable environments experiencing inclement weather conditions [1], quality problems resulting in rework [2], and shortage of specialised subcontractors [3]. The variability results in time and budget overruns, which are endemic problems in construction projects. Prefabricated construction or off-site manufacture can reduce variability in construction and improve performance metrics [4, 5].

Prefabricated construction can improve performance measures because less time is spent on onsite operations and commissioning [6]. It also improves quality through the trial and testing of products under factory conditions using consistent standards [7]. Furthermore, system performance is improved by lowering costs, and increasing added value and certainty, all of which facilitate more accurate measurement of productivity [8]. Finally, prefabricated construction can benefit logistics and site operations by reducing site disruptions, excessive subcontracting and spatial requirements.

Despite these benefits, prefabricated construction has been criticised as a replication of the traditional subcontracting approach and therefore the fragmented practice in the construction industry [9]. Off-site operations are undertaken by trades with individual specialisations often without the necessary coordination to prevent work starvations in the production system. In other words, there is currently not much difference between onsite and off-site construction processes and initiatives used in other production settings such as integrating processes and cross-training have not yet been implemented in the prefabricated construction sector [10].

There is little research into optimal use of multi-skilled resources in off-site construction and its resulting benefits [11]. In this paper, finding the optimal number of additional skills is formulated as a constrained optimization problem. Then, different process integration strategies and their effects on tangible performance measures are compared by means of simulation modelling. Production data from two prefabricated house factories in Melbourne and Brisbane, Australia were collected. In both cases, different components of a house such as roof trusses, frames, and wall panels are built in a production network. In this research, tangible performance metrics are computed in the base case that is a production line with no flexibility (NF), entirely operated by individually specialised resources. Results of the base case are then compared to other production scenarios that use five different cross-training strategies. Investigated strategies are: Direct Capacity Balancing (DCB), Partial Skill Chaining (PSC), Closed Skill Chains (CSC), Hybrid Cross-Training (HCT), and Full Cross-Training (FCT).

The structure of this investigation is as follows. First, the prefabricated house construction process and applicable cross-training strategies are explained. Then, the optimal model for the use of multi-skilled resources is formulated as a constrained optimization problem, leading to statement of the first proposition. Finally, real-world off-site production data are used to construct 1080 simulation experiments from which further propositions about optimal process integration strategies are derived.

2. Research Background

Traditional ways of managing construction projects are inflexible and fragmented as each process is assigned to a trade contractor with an individual specialisation, and trades with the greatest work content (bottlenecks) limit the progress rate of projects. In addition to improving this situation, off-site construction offers a great opportunity for alternative workforce training and process integration approaches in the industry. For example, in Australia, construction workforce undergoes long periods of apprenticeship in order to gain individual specialisations required for undertaking single construction processes. There are strong barriers of entry to other areas as it takes years to become fully licenced in a specialty.

As a result, the construction industry is in continuous need of specialised trades who become scarce resources particularly during boom periods [12].

The house building sector can benefit greatly from off-site production. House building processes are very repetitive in nature and can be undertaken in the controlled environment of a factory instead of highly variable construction sites. Furthermore, off-site production of house components can offer mass customisation, modularisation and delayed product differentiation [13]. In both factories, different elements of houses are manufactured in a climate-controlled environment by a network of specialty trades. Production cycle time have been reduced by elimination of some building processes such as bricklaying, external wall painting and substantial rendering. Both factories have a gross production capacity of around 500 houses per annum. Fig. 1 illustrates the off-site production environments in the two case studies.

Fig. 1. Off-site construction plants in the two cases

The delivery of construction projects is similar to processes in a typical assembly operation [14]. In prefabricated house construction, different subcomponents such as wall frames, panels and roof trusses are made in a network of subassembly lines. The complete house package (final product) is made by merging subassembly lines. Fig. 2 shows the processes in the investigated case studies where light concrete boards and steel frames are the main subcomponents of a house.

Fig. 2. Simplified network of prefabricated construction operations

The in-tree network in Fig. 2 can be serialised using the technique used by Bartholdi III, et al. [15], in which processes are ordered based on the continuity of workflow. That is, building a subcomponent of the house will progress as much as possible before making a new subcomponent. On this basis, it is preferable to undertake operations on the right branch of the Y-shaped line and complete the panel before moving to the left branch to make the roof trusses. Fig. 3 illustrates the serialised line for the building processes in the two case studies.

Fig. 3. Serialised prefabricated house construction line

The fact that off-site construction operations are semi-automated and fairly simple makes process integration and using multi-skilled resources feasible. An agile or flexible cross-trained workforce is able to function dynamically in response to variability in product demand and labour resources.

3. Integrating construction processes

Process integration and cross-training can make production systems flexible. In such environments, resources are not restricted to performing a single task but are able to operate over a production zone if partially cross-trained (applicable to onsite construction), or over the whole production line if fully cross-trained (applicable to off-site construction). Previous research has shown that multi-skilled resources enable production systems to share work dynamically and increase the production throughput rate [16]. It can also be motivating for workers as it reduces repetitive stress, fatigue and boredom [17, 18]. Builders can also enjoy more flexibility in reallocating a process to secondary cross-trained operators when the primary trade is unavailable [19].

However, process integration and creating multi-skilled resources incur cost. Full cross-training is not feasible in many production settings but are not in many environments. In such cases, the best approach is to specify a throughput rate (TH) target and find the optimal cross-training strategy that enables the system to achieve that TH with minimal investment in additional skills (S^+). The current research will model and solve this problem. Process integration strategies are briefly described in the following sections.

3.1. Direct Capacity Balancing (DCB)

The most intuitive strategy for process integration and cross-training is to compensate for work overload in bottleneck stations by borrowing the excess capacity of non-bottleneck operators [20]. In this setting, every resource is trained to cover processes in their primary station and a secondary station, which is always a bottleneck. Fig. 4 shows that seven additional skills (S^+) will be required in the previously illustrated production line when the fourth station has the greatest work content (bottleneck).

Fig. 4. Direct capacity balancing: borrowing capacity from non-bottleneck operators

3.2. Partial Skill Chaining (PSC)

Multi-skilled crews can be cross-trained in order to operate over a limited zone of the production line. If there are overlapping work zones, processes will be chained by means of flexible cross-trained crews [21-23]. This strategy helps accelerating production processes in the bottleneck stations indirectly. Fig. 5 illustrates a production line where resources are partially cross-trained to cover two consecutive stations, with the exception of the operator of station eight, which is the bottleneck in this case. As can be seen, S^+ is equal to seven in this scenario.

Fig. 5. Partial skill chaining: bottleneck operator (number 8) is not a multi-skilled resource

3.3. Closed Skill Chains (CSC)

In this approach every resource is multi-skilled, even bottleneck trades. CSC can prevent occasional work starvations of the bottleneck operators and improve production performance [24]. This is applicable in production cells or U-shaped lines where workers do not have to spend unproductive time in order to walk between stations [25]. Fig. 6 shows an off-site construction network equipped with a closed skill chain. Eight additional skills (S^+) are required in this setting.

Fig. 6. Closed skill chain in a U-shaped production network

3.4. Hybrid Cross-training (HCT)

Skill chaining (SC) has the potential to buffer against the variability in production systems. Within the construction context, however, processing times are often highly imbalanced [26]. In cases where both process imbalance and variability are significant, SC can be implemented together with direct capacity balancing (DCB) to create an optimal cross-training strategy [27, 28]. That is, multi-skilled resources are capable of covering a zone in the production line as well as bottleneck stations. Fig. 7 illustrates the hybrid cross-training strategy in the off-site construction network where S^+ is equal to 15. Results of simulation experiments in the next section will show that the hybrid strategy can result in throughput rates that are almost equal to full cross-training (FCT), which needs 56 additional skills in the off-site construction network illustrated in Fig. 1.

Fig. 7. Hybrid cross-training in the off-site production

4. Optimal process integration strategy in off-site construction with an output target

Some operations in off-site construction take longer than others, causing the production line to become imbalanced. Different production rates mean that workstations and their relative resources are either over utilized (bottlenecks) or underutilized (non-bottlenecks). There are different approaches to buffer against variable processing times resulting in delay prevention. Work-in-process (WIP) buffers can be used in order to increase the utilization of resources and avoid work starvations [29] but oversized buffers are wasteful, hindering performance and impeding the workflow [30]. Another approach, which is the focus of this paper, is to integrate work processes and use multi-skilled resources, in which capacity is borrowed from underutilized resources to help the over utilized.

Since every resource has a unique productivity level, individual performance can be benchmarked against the exemplar performance of a standard resource [31]. In measuring Performance ability ratio (PAR), different factors such as work velocity and work quality are taken into consideration, as productivity is not all about speed of producing an output [32, 33]. For every worker PAR_w can be defined as,

$$PAR_w = \frac{P^o}{P^s} \quad (1)$$

In Eq. (1), P^o is the productivity of an observed resource and P^s is the standard (estimated) productivity. Construction labor productivity is determined by many factors such as level of experience and familiarity with construction operations [34, 35]. For instance, a standard crew with sufficient amount of training would be able to install 5-6 windows per hour without any rework required. Performance of other crews in the station can be benchmarked against this standard performance. On this basis, PAR for a standard resource, with a reasonable work velocity and quality, is equal to one. For a very productive resource, PAR will be greater than one and for the less productive, it will be close to zero.

For a standard resource, the mean processing time at station K is denoted by T_k. Understandably, for a given resource (W), the mean processing time at station K is ${T_k}/{PAR_{wk}}$. The estimated line throughput ($\widehat{TH}$) that is achieved by process integration can be computed using Eq. (2),

$$\widehat{TH} = \frac{\sum_1^k PAR_{wk}}{\sum_1^k T_k} \qquad (2)$$

Since learning of extra skills by flexible workers to cover other stations in addition to their primary tasks incurs cost, it would not be feasible to fully cross-train crews. In this research, the optimal level of process integration is sought that enables the system to achieving a specified throughput $(\widehat{TH})$. This problem can be modelled as a constrained optimization problem to find the minimal number of additional skills necessary in construction networks [36]. The main objective in this part of the study is to minimise the number of additional skills while achieving a targeted output rate.

Consider that the off-site construction line has k stations, each attended by one specialised resource. To achieve $\widehat{TH}$, every workstation requires enough capacity to process jobs at a balanced rate. Since resources have different performance ability ratios, there is a level of capacity imbalance (LCI) for a given resource (W) that covers station K. Level of capacity imbalance can be computed using Eq. (3),

$$LCI = \left| PAR_w\left(\frac{\widehat{TH} \times T_k}{PAR_w} - 1\right)\right| = \left|\widehat{TH} \times T_k - PAR_w\right| \quad (3)$$

For example, consider that the specified output rate of the line is equal to one completed house every seven days. If the required processing time in station K is eight days and resource W has a standard processing rate with performance ability ratio of $PAR = 1$, then $\widehat{TH} \times T_k - PAR_w$ will have a positive value. This indicates that station K is a bottleneck and has a capacity deficiency (D_k) and needs to borrow additional capacity from other underutilized resources. In this case, one or more resources have to have an additional skill in order to accelerate the process in station K. Under the same setting but when the processing time of K is reduced to six days, $\widehat{TH} \times T_k - PAR_w$ will be negative, indicating that resource W has excess capacity (E_w). Provided that resource W is multi-skilled, excess capacity can be used to accelerate bottleneck processes.

Consider a line with y processes from which B of them have longer than average processing times (bottlenecks). The number of man-hours that multi-skilled resource W with extra capacity allocates to station K with capacity deficiency is x_{wk}. Consider the production network in Fig. 4 with eight stations and the mean processing times of 1, 1, 1, 2, 1, 1, 1, 1. Cross-training will enable each of the seven non-bottleneck resources to allocate $1/_y = 1/_8 = 12.5\%$ of their time to the bottleneck (station 4) and for an eight-hour working period, $x_{wk} = 1$ (man-hour). Fig. 8 illustrates the allocation of the resource excess capacity to bottleneck processes.

Fig. 8. Skill sharing in the off-site construction network with y stations

The objective is to minimise the amount of cross-training or in other words the number of additional skills (S^{+}),

$$Min\ S^{+} = \sum_{w=1}^{y-B} \sum_{k=1}^{B} x_{wk} \tag{4a}$$

The first constraint in this optimization problem limits the number of man-hours that resources can attend secondary (bottleneck) processes to the available excess capacity,

$$\sum_{y=1}^{B} x_{wk} \leq E_{w} \tag{4b}$$

Another constraint results because the number of allocated man-hours from underutilized resources to bottlenecks must always be less than the capacity deficiency,

$$\sum_{W=1}^{y-B} x_{wk} \leq D_{k} \tag{4c}$$

Finally, the last constraint enforces a balanced line. That is, sum of resource excess capacity is equal to the sum of bottlenecks' capacity deficiency,

$$\sum_{W=1}^{y-B} E_{w} = \sum_{y=1}^{B} D_{k} \tag{4d}$$

Eqs. (4a), (4b), (4c) and (4d) formulate the process integration problem as a transportation optimization problem. Accordingly, the first proposition in this research is advanced as:

Proposition 1 Finding the optimal number of additional skills in an off-site construction environment with multi-skilled resources can be formulated as a transportation problem with fixed edge costs.

In order to measure impacts of process integration, the developed model was used in order to compute tangible performance measures such as average utilization levels for crews in the base case (NF) and five proposed strategies (see Fig. 9). The strategies under investigation are: direct capacity balancing (DCB), partial skill chaining (PSC), closed skill chains (CSC), hybrid cross-training (HCT), and full cross-training (FCT).

Fig. 9. Resource utilizations in different off-site construction scenarios

As can be seen in Fig. 9, when there is no process integration and the system is not flexible (NF), resource utilization levels are very imbalanced. Implementation of more comprehensive cross-training strategies results in higher levels of resource utilization and consequently reduces the completion times. In order to further investigate the benefits of using multi-skilled resources, completion times were computed in different process integration scenarios (see Fig.10). Here the results of the simulation study for different number of houses under construction (work-in-process = WIP) were superimposed on completion times in the base case (NF).

Fig. 10. Reduction in completion times (CT) as a result of using multi-skilled resources

As expected, investment in a larger number of additional skills (S^{+}) and adopting the hybrid cross-training strategy results in shorter house completion times. Surprisingly, direct capacity balancing (DCB) outperforms partial cross-training (PCT) by resulting in shorter house completion times. It is worth mentioning that this only happens when the work-in-process level is more than 24 jobs. That is, flooding the production network with WIP has the same variability buffering effects as skill chaining strategies but excessive WIP hinders performance and impedes the workflow.

In prefabricated construction, swift delivery of the final product is the major concern for both house builders and buyers. As can be seen in Fig. 10, successive upgrades from a system with specialised resources to flexible systems with multi-skilled resources reduce cycle times significantly. This saving in time is also achievable in onsite construction production, in which integrating processes by cross-training is possible over limited production zones where processes are more technically similar.

Simulation experiments were designed and run in the next part of this research in order to compare performances of different process integration strategies in a moderately sized off-site construction network.

5. Comparison of process integration strategies

In this section, performance of different cross-training strategies is compared in the two off-site construction networks that were explained earlier (see Fig. 1). The base case is a line with no flexibility (NF) where all resources are specialists. Five cross-training strategies are investigated; namely, Direct Capacity Balancing (DCB), Partial Skill Chaining (PSC), Closed Skill Chains (CSC), Hybrid Cross-Training (HCT), and Full Cross-Training (FCT).

5.1. Simulation modelling

In order to compare the performance of process integration strategies, discrete event simulation (DES) was used. DES is the most frequently used technique in classical analysis of construction operations [37]. Simulation models are powerful tools to assist managerial decision-making and when constructed precisely can yield valid results [38].

Prefabricated house construction processes were simulated using a computer code written in SIMAN which is a time tested discrete event simulation (DES) platform. The operations of the off-site construction were modeled as a discrete sequence of events, where the simulation time hops as there is no change of state in the system between consecutive events. Care was taken to make precise models that reflect the reality in the off-site construction environment. The biggest challenge in structuring the DES model was to simulate the use of multi-skilled resources and different cross-training strategies. To address this, resources were not directly assigned to processes but different sets of skills were defined based on the cross-training model. For example in the partial skill chaining (PSC) model, each set has two skills in it, with exclusion of the bottleneck that has only one skill in its set. Fig. 11 shows a snapshot of the SIMAN coding window for this purpose. Interested readers can refer to [39] and [40] for further details about simulation in the SIMAN environment.

Fig. 11. SIMAN code defining the cross-training strategies in off-site construction

In order to impose different levels of capacity imbalance, different system designs with 1, 2 and 4 bottlenecks were investigated. In each design, the bottleneck processing times were set to be 25%, 50%, 75% and 100% greater than non-bottlenecks. The coefficient of variability (CV) was set to 0.2, 1 and 3 to represent low, significant and high variability in processing times and availability of resources.

A total of 1080 simulation experiments were designed, each run for 365 working days with a warm up period of 79 days. One hundred replications of each experiment resulted in the desired confidence level of 99% with all standard errors within 0.2%.

Six approaches of process integration were modelled: NF, DCB, PSC, CSC, HCT, and FCT. Work-in-process (WIP) inventories were set to 8, 16, 24, 40 and 80 jobs. Overall, 1080 experiments were constructed using different combinations of three bottleneck designs, four levels of capacity imbalance, three CV values, six cross-training strategies, and five WIP levels.

While the method of investigation is similar to [41], their study focused on using multi-skilled resources in serial production lines. However, this research investigates benefits of different process integration strategies in off-site construction networks. The biggest challenge was to introduce multi-skilled resources to the simulation models. The special-purpose simulation code in SIMAN (see Fig. 11) defines diverse skill sets in the experiments.

5.2. Verifying the simulation model and validating the results

To verify the simulation model, its behaviour was evaluated to be consistent with the way the real-world system behaves and also in accordance with modelling assumptions. To this end, the model was double checked to find possible errors in data entry and unit consistency. Counter constructs were used in order to collect statistics on inputs to the model. Then input was checked to be equal to the sum of the work-in-process inventory and the output of the simulation. Long periods of simulation runs proved that there are no deadlocks in the model architecture. Operation animations and a slow model run ensured that the entities were routed into intended subassembly lines and the model behaved logically. Upon the completion of these steps, computer implementation of the model was reasonably considered to be error free (debugged) and verified.

Simulation results were validated by using a systematic approach that has been illustrated in Fig. 12.

Fig. 12. Process of calibration and validation of models

In the first step, case study participants were briefed about the methodology used to develop the model and the way historical data were treated to determine probability distributions. Suggestions and final agreement of case study participants about the models resulted in development of a model with high face validity.

To validate model assumptions, the first step is to identify the appropriate probability distribution. Histograms of the collected data points were plotted and best-matching probability distributions were fit to the data. In the second step, selected probability distributions were evaluated against three goodness-of-fit tests; Anderson–Darling test, Kolmogorov–Smirnov test, and Chi–Square test.

Furthermore, in order to validate the input-output transformation, the regular daily production processes of the two cases were modelled and run 100 times. Throughput rates and cycle times were checked against the actual data collected from March to November 2013. The simulation results and real-world production data were almost identical, with errors within the range of 0.2%. Table 1 shows the comparison between observed completion times and the results of simulation in the first case.

Table 1. Validation of simulation results against actual completion times *(CT)*

In the next step, well-founded analytical models such as Little's law [42] were used to compute the production parameters using the real data from the two off-site construction facilities. Results were found to be consistent with those of the simulation model. Table 2 shows the comparison between analytical computation of utilisation levels by Little's law and the results of simulation in the second case.

Table 2. Validation of simulation results against utilisations *(U)* computed by the analytical model

Finally a sensitivity analysis on results that was conducted by slight manipulation of the model input variables found no extreme variations in the results. With the completion of these steps, the modelling results were considered valid and reasonably robust.

5.3. Results and analysis of the simulation study

Production data from the two prefabricated house construction systems in Melbourne and Brisbane were fed to the simulation models. Tangible system performance metrics for different process integration scenarios were measured such as throughput rate (TH), cycle time (CT), average resource utilization level (U), number of house completions, and percentage of improvement in TH comparing with the base case (not flexible= NF). Results for a randomly selected line with $CV = 1$, capacity imbalance of 25% and $WIP = 16$ are presented in Table 3.

Table 3. Effect of different process integration strategies on performance in off-site construction

As can be seen in table 3, when workers are not flexible and are specialised to cover single work stations, there are 166 house completions over the production period. Throughput rate (TH) significantly increases by 9% when crews are trained to cover a bottleneck process in addition to their primary process (direct capacity balancing). This result is consistent with previous studies [43, 44], confirming that investment in training a multi-skilled resource will be offset by the increase in production output rates.

Another significant result is derived from comparison of partial skill chaining (PSC) and direct capacity balancing (DCB). A further improvement of 7% in TH was observed by switching from DCB to PSC and training crews to cover an adjacent work station so that a chain of skills is created. It is worth mentioning that no additional investment in training programs is required as the number of additional skills is equal to seven in both scenarios. Findings in this research for off-site construction networks are in line with those of Liu and Wang [19] for linear projects. The second proposition of this paper is derived from this result,

Proposition 2 In off-site construction networks with variable processing times and low levels of work-in-process (lean production), it is optimal to use multi-skilled resources in an indirect path to the bottlenecks (PSC) than directly train them to cover the bottlenecks (DCB).

Another significant result in Table 3 also shows that by adding only one more additional skill ($S^{+} = 8$) and upgrading the process integration strategy to a closed skill chain (CSC), throughput rate grows by 6% more than PSC. In fact, the small investment in training the bottleneck operator to cover the adjacent non-bottleneck process results in a substantial improvement in the system performance. Understandably, off-site network configurations such as those in Fig. 6 and Fig. 7 have ideal layouts for implementing CSC as resources do not have to spend a long period of unproductive time transferring between processes. This leads us to the development of the next proposition:

Proposition 3 Completing the skill chain by training the bottleneck operator to cover an adjacent work station is the optimal cross-training strategy to achieve a target output rate in off-site construction networks that are exposed to significant variability.

Trade-offs should be made in the selection of the process integration strategies in production environments. For example, using hybrid cross-training with 15 or full cross-training with 56 additional skills would not be justifiable, especially in onsite construction settings. This indicates that using comprehensive training programs such as HCT and FCT are only feasible in presence of both high capacity imbalance and variability.

It is the capacity balancing and variability buffering capabilities of process integration strategies that prevent multi-skilled resources from work starvations in the off-site construction network, resulting in high levels of resource utilization. Table 4 shows average utilization levels for labour resources in the base case (NF) and five proposed approaches for process integration.

Table 4. Resource utilization levels in the off-site construction network

When trades are individually specialised and production is not flexible (NF), concrete board crews are fully utilized and have the longest processing time (bottleneck). Adopting the strategy of direct capacity balancing (DCB) seems to be excessive and make the concrete board worker the least utilized labour resource ($U = 60.32\%$). In partial skill chaining (PSC), however, the situation in DCB is improved but the adjacent labour resource to the bottleneck (steel frame crew) becomes the highest utilized resource as the task is only covered by a single resource ($U = 100\%$).

A closed skill chain strategy behaves more optimally than DCB and PSC. Implementing this strategy, the highest utilization level still belongs to the labour resource with the greatest work content (concrete board) and other resources are utilized almost fully, representing a balanced and efficient production network.

6. Value of hybrid cross-training in prefabricated construction networks

The capacity balancing potential of DCB and variability buffering capability of PSC were observed in previous sections. However, in highly variable and imbalanced production networks, the individual use of these strategies will not be sufficient. Based on results from the simulation study, a hybrid cross-training strategy can substantially improve performance measures. Results for a line with $CV = 3$, capacity imbalance of 75% and $WIP = 8$ are presented in Table 5.

Table 5. Effect of process integration strategies on tangible performance measures

As can be seen in table 5, a more comprehensive process integration strategy such as HCT increases the throughput rate by 43% comparing to the base case. In fact, a hybrid use of cross-training strategies can simultaneously solve two common problems of high capacity imbalance and variability in off-site construction. Since the number of additional skills in the production network is only 15, investments are likely to be offset by the growth in throughput rate. Findings in this research for off-site construction networks are consistent with those of Wongwai and Malaikrisanachalee [16] and leads to the fourth proposition,

Proposition 4 In the presence of high capacity imbalance and variability in off-site construction networks, using a hybrid strategy (direct capacity balancing + skill chaining) is the optimal (or near-optimal) process integration approach in order to yield a specified output rate.

It is worth mentioning that improvements made by using the propositions in this research have great potential to be used in onsite construction, in which integrating processes by using multi-skilled resources is possible over limited production zones where processes are more technically similar.

7. Conclusion

Despite previous research that shows the advantages of off-site construction [45, 46], few studies have tested the applicability of process integration strategies in this production environment in order to increase continuity and flexibility in the workflow. To bridge this gap, this paper models and analyses process integration strategies that result in four propositions on optimal utilization of multi-skilled resources.

Findings of this research show that when capacity imbalance is the only issue in the construction network, it can be addressed by borrowing capacity from underutilized resources (non-bottlenecks) and helping over-utilized resources (bottlenecks). On the other hand, when processing times are variable, indirect skill chaining is the optimal process integration policy. That is, processes are covered by more than one resource and capacity is shifted in an indirect path to the bottlenecks. Finally, when both capacity imbalance and variability are significant, the hybrid use of both strategies can best boost the production performance. Our findings on off-site construction networks extend those of Liu and Wang [19] who focused on linear projects and indicate that process integration can effectively be used in order to improve continuity and flexibility in construction workflow.

8. Research contributions and opportunities for future research

This research contributes to the body of knowledge by expanding the insight into impacts of different process integration strategies on performance in off-site construction networks. Furthermore, models and propositions can be used in order to make optimal decisions regarding the investment in cross-training and process integration.

A number of extensions to the present work are recommended. Cost of cross-training differs across various skills in construction networks. Authors are currently conducting a cost optimization study to include cross-training costs in off-site construction of structural elements of bridges. That study focuses on minimization of the expenses associated with process integration over different production zones. Preliminary findings show that extra costs of having additional skills in the production network can be offset by improvements in throughput and performance if appropriate categorization of similar skills is considered in the cross-training program.

There is a research gap for investigating the applicability of process integration in onsite construction. Furthermore, fundamental human behaviour issues such as motivation, learning curve and communication, significantly affect the success of any process integration program, and require further research in construction networks. Finally, operational-level models could be used to investigate the implementation of process integration architectures and their effect on work-sharing among multi-skilled resources in construction networks.

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