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

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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 that choosing optimal process integration architecture depends on the level of capacity imbalance and processing time variability. This investigation optimises the decision making on process integration in off-site construction networks.

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

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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 has 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.

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.

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.

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).

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

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