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IMPROVING PRODUCTIVITY, WORKFLOW MANAGEMENT, AND RESOURCE UTILIZATION IN PRECAST CONSTRUCTION

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Construction industry has long dealt with problems such as low productivity, unstable workflow in projects and low utilization rate of resources. Off-site construction, which is a hybrid of mass manufacturing and construction, has significant potential to address aforementioned problems. In order to realize this potential, off-site construction needs to avoid replicating the traditional subcontracting approach and therefore fragmented practice in the construction industry. The current research focuses on restructuring the interaction of resources by using cross-training. Findings show that cross-training resources results in transferring excess capacity from underutilized to over utilized resources in direct or indirect pathways. Such initiatives can significantly improve productivity, workflow management and resource utilization in precast construction that highly specialized resources are not required. The study contributes to the construction management literature by providing insight into dynamics of using multi-skilled resources in off-site construction.

Keywords: Agile workforce, Bottleneck optimization, Cross-training, Fuzzy-TOPSIS theory, Lean production, Off-site manufacturing, Planning and control, Prefabrication, Process optimization, Project management, Resource leveling.

1 INTRODUCTION

Off-site production has significant potential to improve productivity and performance of the construction industry. Off-site construction is a unique hybrid of manufacturing and construction in which structural and nonstructural elements are manufactured in controlled factory environments (Xiang *et al*. 2016). However, at present, off-site construction is being criticized for replicating the traditional subcontracting approach and therefore the fragmented practice in the construction industry (Construction 2011). Operations in this environment are often undertaken without the necessary coordination to prevent work blockages in the production network (Arashpour *et al*. 2016c). Therefore, there is currently not much difference between on-site and off-site construction processes where defragmentation initiatives such as process integration are yet to be adopted (Arashpour *et al*. 2012).

Flexibility in prefabrication networks is increased by the means of process integration and cross-training multi-skilled resources as production networks will be able to dynamically address variability in demand and resource availability (Alvanchi *et al*. 2012). Multi-skilled resources undertake their own operations first to maintain the network logic but are capable of handling other operations in their idle time. The focus of previous research has been on designing various integration architectures (Arashpour *et al*. 2016b) but to the authors' best knowledge, none of the aforementioned studies investigated the performance of such architectures in order to develop robust decision tools to identify the optimal process integration architecture in different off-site construction scenarios. This is due to the fact that evaluating process integration architectures is notoriously difficult because of various decision criteria and parameters involved.

To bridge this gap, the current study takes a multi-criteria decision making (MCDM) approach where the priority of alternative process integration architectures is determined by using a hybrid of the fuzzy theory and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Towards this aim, production data of three off-site manufacturers in Sydney, Brisbane, and Melbourne, Australia were collected and analyzed. Performances of five process integration architectures (full integration, skill chain, upstream, downstream and direct integration) were compared and contrasted against five main decision criteria (time and cost required for integration, skill transferability, network logic, and safety considerations).

2 IMPROVING PRODUCTIVITY, WORKFLOW AND RESOURCE UTILIZATION

Process integration and cross-training can facilitate the flow of work within prefabrication networks because multi-skilled resources are not limited to perform single tasks and can operate over a production zone or potentially the whole network (Arashpour *et al*. 2015c). A number of process integration architectures have been proposed by researchers for use in off-site construction networks:

- Direct integration, in which all resources are capable of covering processes undertaken by over-utilized (bottleneck) resources (see Figure 1(a)). This architecture transfers excess capacity from under-utilized resources in a direct path to bottlenecks and alleviates the problem of capacity imbalance in off-site construction networks (Hopp and Van Oyen 2004).

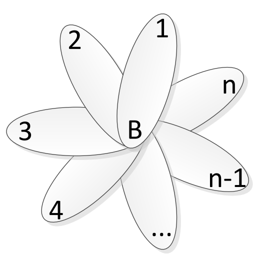

Figure 1(a). Direct integration.

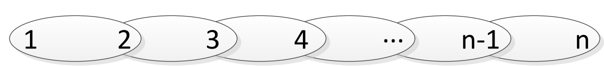

Figure 1(b). Skill Chain integration.

Figure 1. Process integration architectures in off-site construction networks.

- Skill chain integration, in which there are overlapping work zones and multi-skilled resources are capable of handling operations of their immediate successors (see Figure 1(b)). Under this process integration architecture, process variability is minimized by indirect acceleration of bottleneck processes (Arashpour *et al*. 2016a).
- Upstream/downstream integration, in which processes are integrated over a limited manufacturing zone at early stages of production (upstream) or at end stages

(downstream). These architectures provide a production cell at which multi-skilled resources can swiftly shift between work stations with minimized wasted time.

- Full integration, in which multi-skilled resources are able to operate over the whole production network. Although this architecture simultaneously addresses both problems of capacity imbalance and process variability, it requires substantial cross-training of resources within production networks (Tekin *et al*. 2009).

Despite the fact that numerous process integration architectures have been designed for off-site production, there is still much room for investigating their performance and potential application in different construction scenarios (Arashpour 2015).

3 RESEARCH METHOD

The methodology used for identifying the optimal process integration architecture in off-site construction should account for multi objectives such as, 1- minimizing the cost of process integration and cross-training; 2- minimizing the time required to create multi-skilled resources; 3- maximizing compatibility with the network logic and workflow among predecessors and successors; 4- maximizing skill transferability by grouping similar skills; and 5- maximizing safety of operation undertaken by multi-skilled resources. Arashpour *et al*. (2014b) suggest several requirements in order to achieve the aforementioned objectives. First, decision making on the optimal process integration architecture should be based on a hybrid of quantitative and qualitative criteria. Second, a range of off-site construction scenarios should be analyzed to avoid biased results. Third, the process of identifying the optimal process integration architecture should address uncertainty in decision making. Only hybrid decision making methods such as fuzzy-TOPSIS would be able to address this high level of complexity in problem solving (Chan *et al*. 2009). Furthermore, the method is a practical tool for identifying the optimal process integration architecture in a range of off-site production scenarios.

Development of the fuzzy-TOPSIS model was followed by empirical research. Production data of three off-site manufacturers in Sydney, Brisbane and Melbourne, Australia were collected and analyzed. Quantitative data regarding the time and cost required for cross-training multi-skilled resources was collected along with qualitative data on optimality of process integration architectures in terms of network logic, skill transferability, and safety considerations (see Figure 2 for reference).

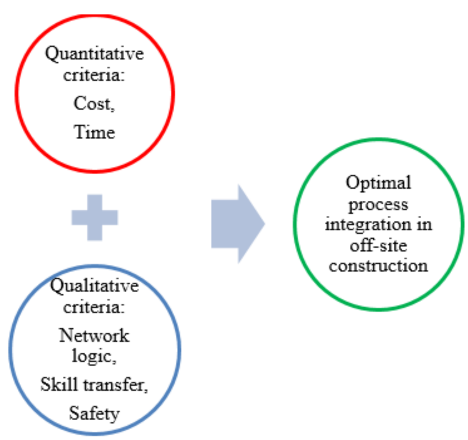

Figure 2. Combination of quantitative and qualitative criteria for identifying the optimal process integration architecture.

The developed fuzzy-TOPSIS model evaluates different alternatives under a systematic and objective regime. The relative importance of qualitative criteria for identifying the optimal process integration architecture in off-site construction is evaluated using a triangular fuzzy set (Eq.1). The set is defined by a membership function $\mu(k)$ that maps elements of k to a real number in the interval $[0,1]$.

$$\mu(k) = \begin{cases} \frac{k-\alpha}{\beta-\alpha} & if\ \alpha \leq k \leq \beta \\ \frac{\gamma-k}{\gamma-\beta} & if\ \beta \leq k \leq \gamma \\ 0 & Otherwise \end{cases} \quad (1)$$

In a similar approach to Arashpour *et al*. (2014a), variables related to qualitative criteria are translated to triangular fuzzy numbers. Instead of using a Boolean logic for true or false (1 or 0), fuzzy logic represents several degrees of truth on a $[0,1]$ interval.

4 TECHNIQUE FOR ORDER OF OREFERENCEBY SIMILARITY TO IDEAL SOLUTION (TOPSIS)

TOPSIS theory objectively compares performance of decision alternatives against multiple criteria (Arashpour *et al*. 2015a). Use of TOPSIS in the current research enables identifying the optimal process integration architecture that is nearest to the ideal solution (I_r^+) and farthest from the anti-ideal solution (I_r^-). An ideal solution is composed of the best performance values for each process integration alternative whereas the anti-ideal solution consists of the worst performance values. The ideal and anti-ideal solutions can be found using Eq. 2 and Eq. 3. Results of calculation for I_r^+ and I_r^- have been shown in Table 1.

$$I_r^+ = max\ (cw_r \times n_{sr}) \quad for\ criteria\ 1, \dots, r \quad (2)$$

$$I_r^- = min\ (cw_r \times n_{sr}) \quad for\ criteria\ 1, \dots, r \quad (3)$$

Table 1. Ideal and anti-ideal solutions in TOPSIS search for the optimal process integration architecture.

	Cost	Time	Network logic	Skill transferability	Safety
Ideal solution ($\boldsymbol{I_r^+}$)	0.308718	0.66087	0.39	0.642963	0.73
Anti-ideal solution ($\boldsymbol{I_r^-}$)	0	0	0.274444	0.252593	0.33

In the following step, the Euclidian distance method is used to evaluate the proximity of decision alternatives to the ideal and anti-ideal solutions. Proximity values can be computed using Eq. 4 and Eq. 5, where δ_s^+ represents the distance between the ideal solution and process integration alternatives, and δ_s^- represents the distance between the anti-ideal solution and integration alternatives. Results of calculations for δ_s^+ and δ_s^- have been presented in Table 2.

$$\delta_s^+ = \sqrt{(I^+ - cw_r \times n_{sr})^2} \ \ for\ integration\ architectures\ 1, \dots, s \quad (4)$$

$$\delta_s^- = \sqrt{(I^- - cw_r \times n_{sr})^2} \ \ for\ integration\ architectures\ 1, \dots, s \quad (5)$$

Table 2. Distance from I_r^+ and I_r^+ for off-site integration alternatives.

	Full integration	Skill chain integration	Downstream integration	Upstream integration	Direct integration
Distance from ideal solution ($\boldsymbol{\delta_s^+}$)	0.91894	0.03852	0.55621	0.31711	0.11879
Distance from anti-ideal solution ($\boldsymbol{\delta_s^-}$)	0.11556	0.92216	0.4258	0.66985	0.8701

Process integration architectures have non-similar performance against different decision criteria. For example, full process integration performs well in terms of compliance with network logic because of its maximum flexibility in the use of multi-skilled reources everywhere in the production network. However, this process integration architecture performs poorly against quantitative criteria such as cost and time requirements for cross-training multi-skilled resources that are able to cover processes over the entire production network.

In the final step of the proposed fuzzy-TOPSIS methodology to identify the optimim process integration architecture in off-site construction, the priority of each decision alternative is computed. Degree of superioririty (DS_s) simulteneously represents the distance to ideal and anti-ideal solutions for each alternative. The ideal value of DS_s is one and less prefered alternatives secure scores close to zero. To compute DS_s, Eq. 6 can be used and results are presented in Table 3. Understandably, the best integration alternative has the largest δ_s^- and smallest δ_s^+.

$$DS_s = \frac{\delta_s^-}{\delta_s^+ + \delta_s^-} \quad for\ integration\ architectures\ 1, \ldots, s \tag{6}$$

Table 3. Degree of superiority for process integration architecures in off-site construction.

	Full integration	Skill chain integration	Downstream integration	Upstream integration	Direct integration
$\boldsymbol{DS_s}$	0.1117	0.9599	0.4336	0.6787	0.8799
Preference ranking	5	1	4	3	2

Process integration alternatives in Table 3 have been ranked based on their degree of superiority. Results show that in the production environments of the three investigated off-site manufacturers, skill chaining is the optimal process integration architecture under which excess capacity of multi-skilled resources are shifted to bottleneck (overutilized) resources in an indirect pathway ($DS_s = 0.9599$). The second preferable alternative is direct integration architecture in which the problem of capacity imbalance is directly addressed by borrowing excess capacity from under-utilized cross-trained resources.

5 CONCLUSIONS

Previous research has documented the effectiveness of process integration in creating the much needed network coordination and addressing resourcing problems (Arashpour *et al.* 2015b). However, these studies have only focused on introducing new architectures for process integration and have not analytically evaluated the performance of such architectures. To bridge this gap, the current investigation adopted the hybrid use of fuzzy and TOPSIS theories to find the optimal process integration architecture considering both quantitative and qualitative decision criteria.

Results of the current analysis clearly show the effectiveness of process integration and cross-training resources over production zones in off-site construction. Transfering excess capacity from underutilized to overutilized resources in a direct pathway can address the issue of capacity imbalance within the network. An indirect capacity shifting to bottlenecks (skill chaining) will be optimal when networks are exposed to high levels of process variability.

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