Multiskilled Human Resource Problem in Off-Site Construction

A. Nasirian[a], M. Arashpour [b] and B. Abbasi [c]

[a] School of Business, IT and Logistics, RMIT University, Melbourne, Australia
[b]School of Property, Construction and Project Management, RMIT University, Melbourne, Australia
[c]School of Business, IT and Logistics, RMIT University, Melbourne, Australia
E-mail: araz.nasirian@rmit.edu.au, mehrdad.arashpour@rmit.edu.au, babak.abbasi@rmit.edu.au

Abstract –

Using multiskilled manpower refers to the ability of dynamically reallocate labour from one stage of production process to another one in response to bottlenecks configuration. This paper investigates improvements in tangible performance measures which can be achieved by incorporating multiskilled workforce in off-site construction. To this end, scheduling in off-site construction analysed in flowshop environment with multiskilled human resource in which operations processing time depends on the amount of human resource allocated to it. The objective of this optimisation problem is to minimise production makespan taking into account labour costs associated with different flexibility strategies. To this end, a mathematical framework incorporating flowshop principles developed, formulations coded in an open source programming interface and solved with a commercial solver providing free license to academic usage. Production data from a prefabrication factory based in Melbourne, Australia fed to the model providing a basis for comparison based on different indicators of productivity. The findings of this study are insightful for human resource development in off-site construction by providing cost and productivity corresponding to different multiskilling strategies.

Keywords –

Multiskilling; Prefabrication; Optimisation; Labour; Flowshop; Skill

1 Introduction

Several factors including increasing workforce wages [1], shortage of skilled workforce [2] and a general boost in construction completion time [3] contribute to decrease productivity in the construction industry. Using prefabricated construction is one of managerial and technological innovations to compensate aforementioned pitfalls [1]. Precast construction enhance productivity in different manners including but not limited to reducing costs of site supervision [4], reduction in delay [5] and better construction quality [6]. However, disintegrated processes is a fundamental consequence of prefabricated construction [7]. Crosstraining of workforce is an appropriate way of dealing with task heterogeneity [8].

Crosstraining of workforce simply means learning multiple skills to workers so they can be assigned when and where they are needed [9]. Crosstraining of workforce is beneficial for the employer by enhancing productivity and quality [10] and advantageous for employees by increasing employability, safety and job satisfaction [11,12]. The drawback of incorporating crosstraining is outlined as decreasing efficiency with increasing the number of skills [13] learning and forgetting effects [14], switching costs [15], training cost [16], and extra salary [17].

Despite, body of literature investigating crosstraining in on-site construction is considerable [3,10,13,18,19], off-site construction literature mainly focused on single skilled crew [20]. Considering high potential of enhancing productivity with incorporating multiskilling in manufacturing [9] and semi-manufacturing environment like prefabricated construction [7] enhancing productivity by using crosstrained workers in off-site construction is a significant area of research.

The novelty of this research originates from employing and modifying operational research techniques to evaluate the effect of construction related human resource strategies on performance measures of prefabricated construction with a reasonable solution time. Presented method has the capacity to incorporate a wide range of human resource policies and can be calibrated to deliver different objective functions.

To this end, this study identifies principles of flowshop applicable to off-site construction [21] and presents a mathematical modelling approach to optimise makespan of production as the most famous productivity measure in shop environment [22], incorporating multiskilled workforce taking into account crosstrained manpower cost.

2 Literature Review

Crosstrained labour allocation problem is a subset of human resource allocation problem in which all or some of workers should be multiskilled. Human resource allocation problem is to optimise the use and allocation of human resource with an aim to maximise or minimise certain functions [23].

Despite, there are several techniques in operations research and management science literature for resource allocation problems [24] no one is directly applicable to the construction industry and modifications should be applied on them [19]. Therefore in the following section, selection process of an appropriate framework to solve multiskilled human resource problem in off-site construction argued.

Since, the critical path method does not properly works in precast production [20] considering general production layout, repetitive routines, precedence and dependency of different products, it is suggested to implement principles of flowshop scheduling in precast production [5]. Additionally, optimisation of production performance such as makespan and flow time in prefabricated construction shifts the problem formulation toward shop scheduling in general and flowshop scheduling specifically [20].

A classical flowshop problem defined as a problem which consists of two main elements: a group of M machines and a set of N jobs which should be processed in these machines [22]. There are four basic assumptions for a classic flowshop problem: the jobs should be processed in all of the machines, job splitting is not allowed, operations are non-preemptive and set up times are included in the processing time [22]. There is a wide range of assumptions for different settings of a flow shop problem however, flowshop problem with and without permutation are the best fit to optimise off-site construction scheduling [21].

Considering applicability of flowshop principles to off-site construction with single skilled human resource policy few studies investigated performance of makespan pertaining to specialist manpower [1,20,25,26]. To the best of our knowledge so far there is no study which investigates enhancing productivity in precast construction implementing crosstraining techniques using flowshop fundamentals.

Referring to management science and operations research literature few studies investigated productivity enhancement within flowshop framework via full crosstraining of workforce [27,28] and partial crosstraining of crews [29]. Considering our research follows same objective in off-site construction context, on one hand, and taking into account similarity of off-site construction and manufacturing [21], on the other hand, reviewing this literature exposed same principles with some modifications can be used in our study.

3 Problem Description

Notation (n, m) is an indication of processing product n in workstation m when $\mathbb{N} = \{1,2,\ldots,\mathrm{N}\}$ is set of products and $\mathbb{M} = \{1,2,\ldots,\mathrm{M}\}$ is set of workstations. $\mathbb{W} = \{1,2,\ldots,\mathrm{w}\}$ is set of workers and $\mathbb{K} = \{1,2,..,\mathrm{K}\}$ is set of status meaning the number of workers which can be allocated to a specific operation. $\mathbb{T} = \{1,2,\ldots,\mathrm{T}\}$ is set of time periods where T is upper bound on makespan. Equation (1) requires each procedure to have a unique status and corresponding specific completion time.

$$\sum_{k=1}^{K}\sum_{t=1}^{T}\theta_{nmkt} = 1\,, \qquad n \in \mathbb{N}, m \in \mathbb{M} \tag{1}$$

Equation (2) presents behaviour of binary variable θ_{nmkt}.

$$\theta_{nmkt} = \begin{cases} 1 \; if\ operation\ (n,m)\ with\ k\ labour\ finished\ at\ t \\ 0 \; otherwise \end{cases} \tag{2}$$

Given d_{nmk} is duration of procedure (n,m) when k workers are assigned to it, actual duration of procedure (n,m) indicated by D_{nm} is computable according to the equation (3).

$$D_{nm} = \sum_{k=1}^{K}\sum_{t=1}^{T} d_{nmk}\,\theta_{nmkt}\,, \qquad n \in \mathbb{N}, m \in \mathbb{M} \tag{3}$$

Completion time of procedure (n,m) indicated by C_{nm} can be calculated as formula (4).

$$C_{nm} = t\sum_{k=1}^{K}\sum_{t=1}^{T}\theta_{nmkt}\,, \qquad n \in \mathbb{N}, m \in \mathbb{M} \tag{4}$$

Constraints (5) and (6) satisfy the requirement for flowshop problem with permutation.

$$C_{nm} \geq C_{n(m-1)} + D_{nm}, \qquad n \in \mathbb{N}, m \in \mathbb{M} \tag{5}$$
$$C_{nm} \geq C_{(n-1)m} + D_{nm}, \qquad n \in \mathbb{N}, m \in \mathbb{M} \tag{6}$$

Let a_{wmt} and s_{wm} be binary variable and binary parameter behaving as equations (7) and (8), respectively.

$$a_{wmt} = \begin{cases} 1 \; if\ worker\ w\ is\ allocated\ to\ station\ m\ during\ [t-1,t) \\ 0 \; otherwise \end{cases} \tag{7}$$

$$s_{wm} = \begin{cases} 1 \; if\ worker\ w\ is\ trained\ to\ be\ staffed\ in\ station\ m \\ 0 \; otherwise \end{cases} \tag{8}$$

Inequality (9) denotes that workers can just be allocated to workstations for which they are crosstrained.

$$s_{wm} \geq a_{wmt} \,, \qquad w \in \grave{W}, t \in Ţ \qquad (9)$$

Total labour cost, denoted by Q, can be computed as equation (10) considering q_w be daily cost of labour a_{wmt}.

$$\sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{w=1}^{W} q_w a_{wmt} = Q \qquad (10)$$

Constraint (11) insures that in each interval of time each worker can just be allocated to one workstation.

$$\sum_{m=1}^{M} a_{wmt} = 1, \qquad w \in \grave{W}, t \in Ţ \qquad (11)$$

Equation (12) match operations status with needed number of labour.

$$\sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{w=1}^{W} \theta_{nmkt}\, a_{wmt} = \sum_{k=1}^{K} \sum_{t=1}^{T} k\ \theta_{nmkt} \,, \quad n \in Ņ, m \in Ṃ, \qquad (12)$$

Equation (13) force labour to remain in workstation for the whole duration of operation.

$$\sum_{k=1}^{K} \sum_{t=d_{nmk}}^{T} \sum_{l=t-d_{nmk}+1}^{W} \theta_{nmkt}\, a_{wml} = \sum_{k=1}^{K} \sum_{t=1}^{T} a_{wml} d_{nmk} \theta_{nmkt} \,, n \in Ņ, m \in Ṃ, w \in \grave{W} \qquad (13)$$

4 Case Study

The case which is adopted in this study is a modular prefabrication factory that produces bathroom pods located in Melbourne, Australia. Figure 1 shows twelve processes in the production line corresponding to their order in the real fabrication layout. S and L are indications for workstations and labour, respectively. Table 1 shows workstations operation in sequence. At the moment, no crosstrained worker employed in this production line equivalent to no flexibility scenario in which traditionally one worker is allocated to each workstation. There are three bottlenecks in this production line in labour, carpenter and electrician

Table 1. Workstations' operation

Work station	Operation	Work station	Operation
S1	Labourer	S7	Carpenter
S2	Caulker	S8	Electrician
S3	Mechanical contractor	S9	Water-proofer
S4	Tiler	S10	Glazer
S5	Plumber	S11	Joiner
S6	Plasterer	S12	Painter

workstation. Site manager of case study factory believed single skilled workforce should be allocated to bottlenecks. Figure 2 is an illustration of this decision. Figure 3 and 4 illustrate direct capacity balancing and chaining multiskilling strategies which already investigated in off-site construction [7,8]. Red lines show secondary skills making single skilled labour multiskilled. Last strategy is hiring multiskilled workforce and allocate them to bottlenecks which is already investigated in linear construction projects [17].

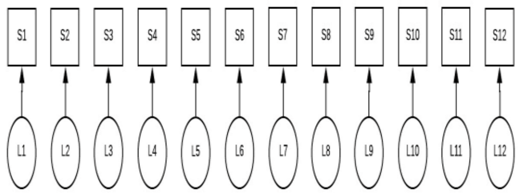

Figure 1. No flexibility

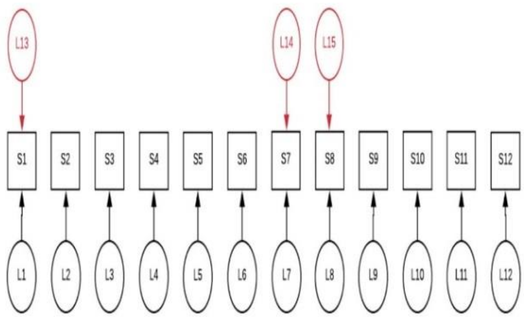

Figure 2. Hiring singleskilled crew

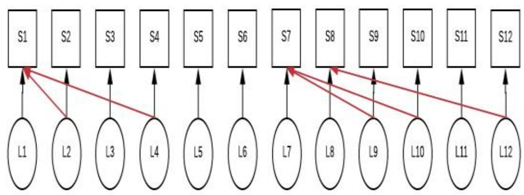

Figure 3. Direct capacity balancing

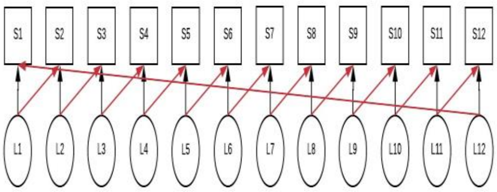

Figure 4. Chaining

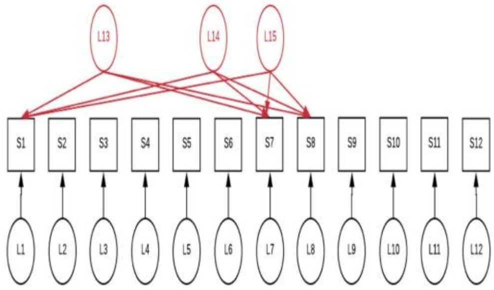

Figure 5. Hiring crosstrained crew

5 Results

Table 2 reflects outputs of computation pertaining to different human resource strategies' in terms of makespan and cost for production of 10 bathroom pods. No flexibility, hiring singleskilled crew, direct capacity balancing, chaining and hiring crosstrained crew abbreviated as NF, HSC, DCB, Ch and HMC, respectively. Also, makespan, makespan variation, cost and cost fluctuations abbreviated as M, MV, C and CF. Considering no flexibility strategy, makespan is 44 days with labour cost of 73776 AUD. To deal with bottlenecks site manager suggested to hire three single skilled workforce and allocate them to bottlenecks. Despite, by applying this strategy there is 27% improvement in makespan however significant amount of 78% enhancement in labour cost suggest this is not a good strategy. Direct capacity balancing led to 32% improvement in makespan and 25% decrease in labour cost which makes this strategy attractive. Implementing chaining leads to 27% decreasing in makespan and 26% enhancement in labour costs. The result of hiring crosstrained workforce is significant by bringing the most improvement in makespan equivalent to 41% and enhancement in labour cost equivalent to 17% which makes this strategy appropriate to deal with tight deadlines.

Table 2. Performance measure corresponding to different human resource strategies

	Human resource strategies				
	NF	HSC	DCB	Ch	HMC
M	44	32	30	32	26
MV	0	27%	32%	27%	41%
C	73886	131789	54850	93249	91062
CF	0	78%	-25%	26%	17%

6 Conclusion

Review of literature exposed optimisation of multi-skilled human resource problem in off-site construction is a promising area of research. Flowshop environment is recognised appropriate to incorporate prefabricated construction principles. A mathematical programming approach adopted to model scheduling processes in prefabrication context to allocate crosstrained crew to appropriate operations to optimise production makespan. An open source programming interface and a commercial solver employed in coding process. The findings of this study facilitate decision making with regard to appropriate crosstraining configuration considering makespan and labour cost. Also, this study presents a new understanding with regard to interaction of crosstraining configurations, labour costs and production makespan as a measure of productivity. Formulations which are presented in this study have the potential to incorporate other performance measures such as idleness and tardiness which can be used in future studies. Other industries in which productivity directly interacts with the number of human resource can use principles of this study.

7 References

[1] Leu S.S. and Hwang S.T., GA-based resource-constrained flow-shop scheduling model for mixed precast production, *Automation in Construction*, 11(4): 439–452, 2002.

[2] Ho P.H.K., Labour and skill shortages in Hong Kong's construction industry, *Engineering , Construction and Architectural Management*, 23(4): 533–550, 2016.

[3] Sacks R. and Goldin M., Lean management model for construction of high-rise apartment buildings, *Journal of Construction Engineering and Management*, 133(5): 374–384, 2007.

[4] Frondistou-Yannas S.A., Pugh A.L.I. and

Moavenzadeh F., Precast concrete industry: managerial dynamics, *Journal of the Construction Division,* 103(2): 259–271, 1977.

[5] Chan W.T. and Hu H., Production scheduling for precast plants using a flow shop sequencing model, *Journal of Computing in Civil Engineering*, 16(3): 165–174, 2002.

[6] Ko C.H. and Wang S.F., GA-based decision support systems for precast production planning, *Automation in Construction*, 19(7): 907–916, 2010.

[7] Arashpour M., Wakefield R., Blismas N. and Minas J., Optimization of process integration and multi-skilled resource utilization in off-site construction, *Automation in Construction,* 50: 72–80, 2015.

[8] Arashpour M., Wakefield R., Abbasi B., Arashpour M. and Hosseini R., Optimal process integration architectures in off-site construction: theorizing the use of multi-skilled resources, *Architectural Engineering and Design Management,* 1–14, 2017.

[9] Hopp W.J. and Oyen M.P., Agile workforce evaluation : a framework for cross-training and coordination, *IIE Transactions*, 36(10): 919–940, 2004.

[10] Burleson R., Haas C., Tucker R. and Stanley A., Multiskilled labor utilization strategies in construction, *Journal of Construction Engineering and Management*, 124(6): 480-489, 1998.

[11] Srour I.M., Haas C.T. and Morton D.P., Linear programming approach to optimize strategic investment in the construction workforce, *Journal of Construction Engineering and Management*, 132(11): 1158–1166, 2006.

[12] Haas C.T., Rodriguez A.M., Glover R. and Goodrum P.M., Implementing a multiskilled workforce, *Construction Management and Economics*, 19(6): 633–641 2001.

[13] Hegazy T., Shabeeb A.K., Elbeltagi E. and Cheema T., Algorithm for scheduling with multiskilled constrained resources, *Journal of Construction Engineering and Management,* 126(6): 414–421, 2000.

[14] Ahmadian Fard Fini A., Rashidi T.H., Akbarnezhad A. and Waller S.T., Incorporating multiskilling and learning in the optimization of crew composition, *Journal of Construction Engineering and Management,* 142(5): 04015106, 2016.

[15] Lill I., Multiskilling in construction -a strategy for stable employment, *Ukio Technologinis Ir Ekonominis Vystymas*, 15(4): 540–560, 2009.

[16] Ahmadian Fard Fini A., Akbarnezhad A., Rashidi T.H. and Waller S.T., Job assignment based on brain demands and human resource strategies, *Journal of Construction Engineering and Management,* 143(5): 04016123, 2017.

[17] Liu S.S. and Wang C.J., Optimizing linear project scheduling with multi-skilled crews, *Automation in Construction*, 24: 16–23, 2012.

[18] Tam C.M., Tong T.K.L., Cheung S.O. and Chan A.P.C., Genetic algorithm model in optimizing the use of labour, *Construction Management and Economics,* 19(2): 207–215, 2001.

[19] Gomar J.E., Haas C.T. and Morton D.P., Assignment and allocation optimization of partially multiskilled workforce, *Journal of Construction Engineering and Management*, 128(2), 103–109, 2002.

[20] Benjaoran V., Dawood N. and Hobbs B., Flowshop scheduling model for bespoke precast concrete production planning, *Construction Management and Economics*, 23(1): 93–105, 2005.

[21] Yang Z., Ma Z. and Wu S., Optimized flowshop scheduling of multiple production lines for precast production, *Automation in Construction*, 72: 321–329, 2016.

[22] Hejazi S.R. and Saghafian S., Flowshop-scheduling problems with makespan criterion: A review, *International Journal of Production Research*, 43(14): 2895–2929, 2005.

[23] Bouajaja S. and Dridi N., A survey on human resource allocation problem and its applications, *Operational Research International Journal*, 17: 339–369, 2016.

[24] Iravani S.M., Oyen M.P. and Sims K.T., Structural flexibility: a new perspective on the design of manufacturing and service operations, *Management Science*, 51(2): 151–166, 2005.

[25] Leu S.S. and Hwang S.T., Optimal repetitive scheduling model with shareable resource constraint, *Journal of Construction Engineering and Management,* 127(4): 270–280, 2001.

[26] Anvari B., Angeloudis P. and Ochieng W.Y., A multi-objective GA-based optimisation for holistic manufacturing, transportation and assembly of precast construction, *Automation in Construction*, 71: 226–241, 2016.

[27] Daniels R.L. and Mazzola J.B., A tabu-search heuristic for the flexible-resource flow shop scheduling problem, *Annals of Operations Research*, 41(3): 207–230, 1993.

[28] Daniels R.L. and Mazzola J.B., Flow shop scheduling with resource flexibility, *Operations Research*, 42(3): 504–522, 1994.

[29] Daniels R.L., Mazzola J.B. and Shi D., Flow shop scheduling with partial resource flexibility, *Management Science*, 50(5): 658–669, 2004.