Multiskilled Human Resource Problem in Off-Site Construction

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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

Crosstraining 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 work 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 prefabrication 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 \(N = \{1,2,\ldots,N\}\) is set of products and \(M = \{1,2,\ldots,M\}\) is set of workstations. \(W = \{1,2,\ldots,w\}\) is set of workers and \(\Psi = \{1,2,\ldots,\Psi\}\) is set of status meaning the number of workers which can be allocated to a specific operation. \(T = \{1,2,\ldots,T\}\) 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.

\[
\sum_{k=1}^{K} \sum_{t=1}^{T} \theta_{nmkt} = 1, \quad n \in N, m \in M
\]  

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

\[
\theta_{nmkt} = \begin{cases} 
1 & \text{if operation} \ (n,m) \ \text{with} \ k \ \text{labour} \ \text{finished} \ \text{at} \ t \\
0 & \text{otherwise}
\end{cases}
\]

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).

\[
D_{nm} = \sum_{k=1}^{K} \sum_{t=1}^{T} d_{nmk} \theta_{nmkt}, \quad n \in N, m \in M
\]

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

\[
C_{nm} = t \sum_{k=1}^{K} \sum_{t=1}^{T} \theta_{nmkt}, \quad n \in N, m \in M
\]

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

\[
C_{nm} \geq C_{n(m-1)} + D_{nm}, \quad n \in N, m \in M
\]

\[
C_{nm} \geq C_{(n-1)m} + D_{nm}, \quad n \in N, m \in M
\]

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

\[
a_{wmt} = \begin{cases} 
1 & \text{if worker} \ w \ \text{is allocated to} \ \text{station} \ m \ \text{during} \ [t - 1, t) \\
0 & \text{otherwise}
\end{cases}
\]

\[
s_{wmt} = \begin{cases} 
1 & \text{if worker} \ w \ \text{is trained to be} \ \text{staffed in station} \ m \\
0 & \text{otherwise}
\end{cases}
\]
Inequality (9) denotes that workers can just be allocated to workstations for which they are crosstrained.
\[ s_{wm} \geq a_{wmt}, \quad w \in \mathcal{W}, t \in \mathcal{T} \]  
(9)

Total labour cost, denoted by Q, can be computed as equation (10) considering \( q_w \) be daily cost of labour \( a_{wmt} \).
\[ \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{w=1}^{W} q_w a_{wmt} = Q \]  
(10)

Constraint (11) insures that in each interval of time each worker can just be allocated to one workstation.
\[ \sum_{m=1}^{M} a_{wmt} = 1, \quad w \in \mathcal{W}, t \in \mathcal{T} \]  
(11)

Equation (12) match operations status with needed number of labour.
\[ \sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{w=1}^{W} \theta_{nmkt} a_{wmt} = \sum_{k=1}^{K} \sum_{t=1}^{T} k \theta_{nmkt}, \quad n \in \mathcal{N}, m \in \mathcal{M}, w \]  
(12)

Equation (13) force labour to remain in workstation for the whole duration of operation.
\[ \sum_{k=1}^{K} \sum_{t=1}^{T} \sum_{l=t-d_{nmk}+1}^{t-d_{nmk}} a_{wml} a_{nmk} \theta_{nmkt}, n \in \mathcal{N}, m \in \mathcal{M}, w \]  
(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 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].

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Operation</th>
<th>Workstation</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Labourer</td>
<td>S7</td>
<td>Carpenter</td>
</tr>
<tr>
<td>S2</td>
<td>Caulker</td>
<td>S8</td>
<td>Electrician</td>
</tr>
<tr>
<td>S3</td>
<td>Mechanical contractor</td>
<td>S9</td>
<td>Waterproofer</td>
</tr>
<tr>
<td>S4</td>
<td>Tiler</td>
<td>S10</td>
<td>Glazer</td>
</tr>
<tr>
<td>S5</td>
<td>Plumber</td>
<td>S11</td>
<td>Joiner</td>
</tr>
<tr>
<td>S6</td>
<td>Plasterer</td>
<td>S12</td>
<td>Painter</td>
</tr>
</tbody>
</table>

Figure 1. No flexibility

Figure 2. Hiring singleskilled crew

Figure 3. Direct capacity balancing


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.

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

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


