Optimization of Precast Production Planning using concepts of Prefabrication Configuration and Component Group

A.Khalili [1], Chua D.K.H[2]

Abstract

Construction projects adopting prefabrication method are feasible to reduce project uncertainties by producing components in factories and transported to construction site to satisfy installation demand. In order to create project plans, designers and planners should manage available resources and select appropriate ways to produce, store, transport, and install components. This study adopts two new ideas which are prefabrication configuration and component groups to optimize precast project resource cost. Based on these concepts, an MIP optimization model is proposed. Appropriate moulds and project plan can be created through the optimized project cost. An example experiment is demonstrated to explain the feasibility of the proposed model and the concepts.

Keywords: Prefabrication Configuration, Component group, Project Planning, Optimization, Mixed Integer Programming

Introduction

Construction projects are sensitive while underway. Uncertainties such as weather-related factors have influence on both project schedule and quality. In order to overcome these uncertainties, the prefabrication method was adopted to the construction industry. Prefabrication has taken advantages of manufacturing industry to increase productivity and efficiency. Nowadays, the precast method has been successfully applied in projects of constructing bridges, factories, tunnels, and various buildings.

Generally, prefabrication is one form of industrialization in construction industry that was made feasible with the advancement of production techniques and equipment for transportation and erection (Warszawski 1999; Zlatanova et al. 2004).

[1] PhD scholar, Department of Civil and Environmental Engineering, National University of Singapore, 1 Engineering Drive 2, Singapore 117576, E-mail: alireza@nus.edu.sg.
[2] Associate Professor, Department of Civil and Environmental Engineering, National University of Singapore, 10, Kent Ridge Crescent, 119260, Singapore, E-mail: ceedavid@nus.edu.sg.

Another form of industrialization is standardization. Standardization provides faster production, lower cost, and more efficient assembly of elements due to uniform dimensions that eliminate costly and time-consuming custom-made applications while still allowing multiple configurations. This study is an effort to combine two forms of industrialization for optimization of resources in prefabricated construction.

Optimization on prefabrication is one of the sparkling areas in this industry that has been studied from various perspectives since 1976. Several planning and scheduling models have been developed and optimized specifically for precast concrete production (Chan and Zeng 2003; Chan and Zeng 2005; Dawood 1995; Dawood and Neale 1993; Huang et al. 2005). Research on the resource and planning optimization of precast elements reveals that the main equipment in a prefabrication plants are casting moulds (Chan and Hu 2001; Chan and Hu 2002; Hao 2007; Huang et al. 2005; Zhai et al. 2008). Hao (2007) believed that previous studies on precast production scheduling seldom consider resource planning issues, especially moulds which are the main resources in a prefabrication plant. Studies show that in all the developed models, building elements are assumed to be produced individually. However, there may be several types of precast elements that can be produced on the same mould group with slight variations (grouping concept) (Huang et al. 2005). Further to this, there is, no approach or model that has yet been reported in which higher level of prefabrication (component or modular level) has been considered in precast planning and resource optimization (configuration concept). However, Tatum (1987) proposed four basic levels where prefabrication can occur: total building prefabrication, system prefabrication, components prefabrication and elements prefabrication as depicted in Figure 1.

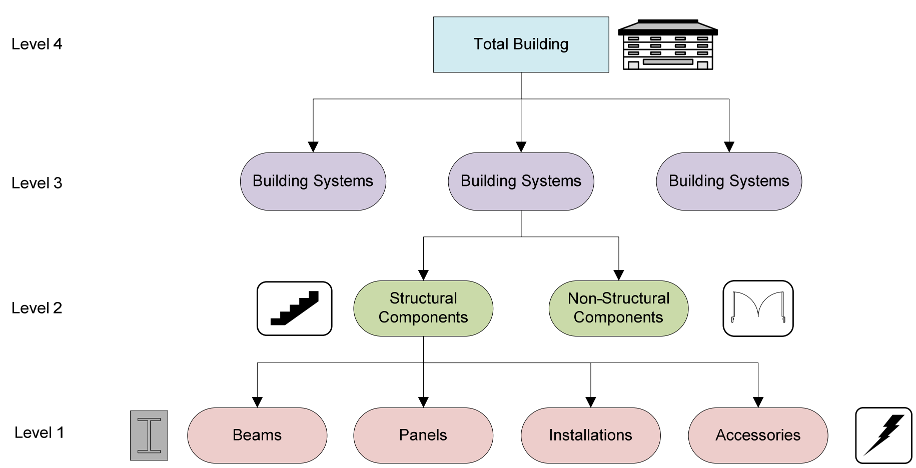

Figure 1: Possible levels of prefabrication

Figure 1 shows that the scope of prefabrication ranges from the production of individual elements of a building to the prefabrication of a complete building. If elemental prefabrication can be combined into bigger components, complicated mould can be used for production of smaller units. Moreover, as the number of component is reduced, there would be less handling and erection cost so that the total cost of production to installation could possibly be reduced.

The objective of this paper is defined to develop an optimization model for production of precast components using both ideas of prefabrication configuration and component grouping which are seldom considered in previous studies.

Framework Explanation

The quantity of components for a construction precast project can be hundreds or even thousands. Grouping components is necessary in precast projects. In practice, components are standardized into groups for at least three advantages: (1) components can be unified, and work can be simplified; (2) high production efficiency can be achieved, and resources can be utilized repeatedly; (3) components can be reciprocal substitutes. Before planning a project from the perspective of the precast factory, component information and installation information are required as stipulations in a contract. First, to achieve higher degree of prefabrication, feasible configurations of components are automatically obtained through the 3D CAD model. Second, for each configuration, the components of the project are grouped into component types according to standardized shapes, strengths, and materials based on the architect's design. Numbers of component types and ways to produce components are recognized. Third, component requirements are scheduled as installation information. The installation information indicates when and how many components of each component type are required. Based on the known component information and installation information, the precast factory arranges resources to produce and transport components under the contract. The overall process of precast projects is represented as Figure 2.

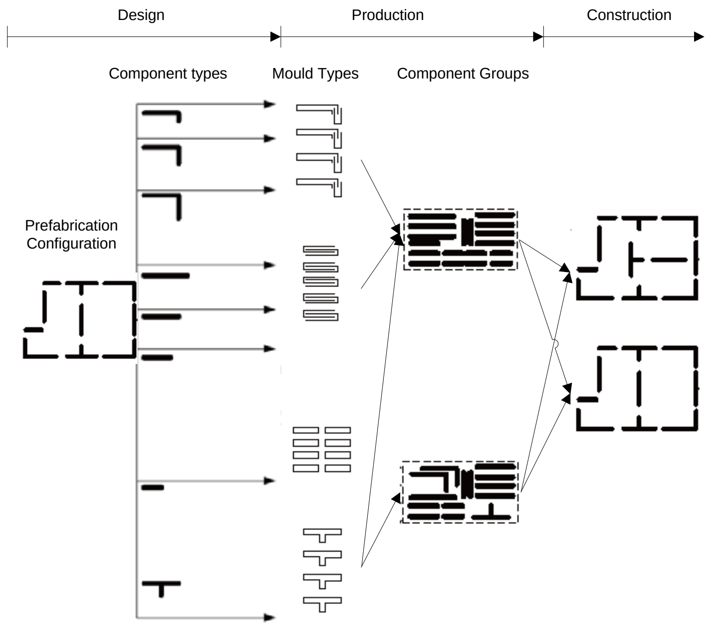

Figure 2: Application of prefabrication configuration and component groups in precast projects

Prefabrication Configuration and Component Grouping concepts

To understand the mechanism of implementing the ideas of prefabrication and component grouping concepts following explanation is required:

Prefabrication Configuration: The framework for implementation of prefabrication configuration is described in Khalili (2010). Essentially, the framework is designed to extract topological relationships and geometrical properties of building elements from IFC file and map this data to a topological graph model. Using graph algorithms such as Depth First search (DFS) and graph isomorphism, all possible configurations are generated and compared against production and construction rules. Each feasible configuration comprises of several types of components and hundreds or thousands of identical components. An optimization model is needed to find out which configuration has less production cost.

*Component Type***:** Component types are obtained from each feasible configuration. For instance, one feasible configuration of component for prefabrication of the given concrete building is shown in Figure 3. This configuration comprises of four component types (I-IV) as depicted in Figure 3.

Mould Type: Production work can be unified in most factories. Steel moulds with high initial cost are usual to produce components smoothly and to utilize moulds repeatedly. Furthermore, moulds are always used to produce component groups of given shapes. Thus, utilization of moulds becomes the key issue. Mould types are defined based on the component types achieved from configuration. The given configuration in Figure 3 depicts that four Mould types (I,II,III and IV) can be used to produce all component types.

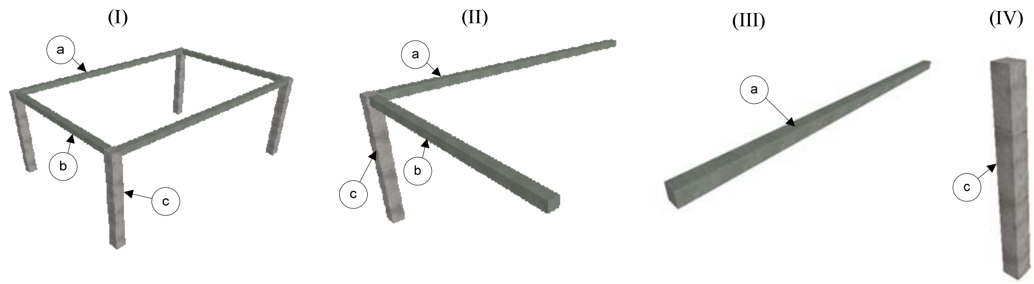

Figure 3: Sample concrete component types and mould types

Component Group: Based on the component types, ways to produce components are recognized. Components within a component group can be produced with one mould type in one casting cycle. Component groups are classified based on the mould types. For instance, mould I can produce either one component I which is named as Component Group 1 or two of component II which is named as Component Group 2. Component classification is the second key issue in terms of fully utilization of complicated moulds. Moulds are needed to be replaced with new one after certain number of casting. Therefore an effort needed to fully utilize moulds during their life cycle. Mould changeover occurs when moulds produce different component groups. A production plan can be represented as a schedule of mould utilization for all moulds. Planners organize moulds to produce required components. Resources in factories are in harmony with the moulds. However, several issues are concerned: (1) what type and how many moulds are required; (2) efficiency and economy of mould utilization; (3) how to identify and avoid mould changeovers; (4) other resource limitations of factories.

Mathematical Model and Optimization

An overview of precast project planning can be organized by combining proposed concepts of group and configuration.

Assumptions

To build a specific context of precast project planning, further assumptions and descriptions are made as follows:

Mould: each mould can daily produce only a component group. Mould changeover causes penalty cost for extra manpower and time. Production process takes on day and includes: cleaning, casting, curing and removing.

Production limitation: most resources are unlimited. However, limitation of daily use of concrete and limitation of production space in the factory are concerned because they are common factors to restrain productivity.

Construction Cycle: a construction cycle is defined as prefabrication of required components for a certain number of storey or part of a project.

A mathematical model integrating the mentioned issues is built as follows. Symbols refer to Table 1.

Table 1: Parameters and variable symbols

Parameter Symbols			
Symbol	Explanation	Symbol	Explanation
i	Index of mould type	j	Index of component type
l	Index of mould number	k	Index of workdays
t	Index of construction cycle	h	Index of component group
nm	Number of considered mould types	nc	Number of considered components
nl	Number of considered mould number	K	Number of workdays in a construction cycle
T	Number of construction cycles	LC_i	Mould operational life
$ma_{i,h}$	Ability of mould i to produce component group h	LC_h	Changeover cost of component group h
$bigM$	A big Number	w_h	Idle index for component group h
$D_{j,k,t}$	Required components of type j on day k of construction cycle t	sm_i	Required workspace of mould I (m^2)
$Mouldcost_i$	Fabrication cost of mould type i	vc_j	Required concrete volume for component type j (m^3)
$Wastecost_h$	Penalty cost for idle mould for component group h	psl	Production space limit (m^2)
$CPT_{h,j}$	Number of component type j in component group h	csl	Concrete supply limit (m^3)
Variable Symbols			
TPC	Total production cost	IMC	Total mould initial cost
$MchC$	Total mould changeover cost	MwC	Total mould waste penalty cost
MUC	Total mould utilization cost	$M_{i,l,h,k,t}$	Binary variable to decide Mould type i, number l, producing component group h, on day k of the t construction cycle

Z_{ili}	Binary variable for adoption of mould type i, number l	$Y_{i,l,h,h',k+1,t}$	Binary variable to show mould type i, number l, producing component group h, on day k of the t construction cycle precedes to produce component group h' on day k+1

The objective function includes members of project costs that are initial cost of moulds (*IMC*), cost of mould usage and replacement after their life cycle (*MUC*), mould changeover cost (*MchC*), and penalty cost for minimizing partially utilization of moulds (*MwC*). Equations (2)-(5) represent calculation of each cost respectively.

Objective function:

$$Minimize\ IMC + MUC + MchC + MwC \quad (1)$$

Where:

$$IMC = \sum_i \sum_l Z_{i,l} \times MouldCost_i \quad (2)$$

$$MUC = \sum_i \sum_l \left(\frac{\sum_h \sum_k \sum_t M_{i,l,h,k,t}}{LC_i}\right) \times MouldCost_i \quad (3)$$

$$MchC = \sum_i \sum_l \sum_h \sum_{h'} \sum_k \sum_t Y_{i,l,h,h',k,t} \times CH_h \quad (4)$$

$$MwC = \sum_h \left(\sum_i \sum_l \sum_k \sum_t M_{i,l,h,k,t}\right) \times w_h \times WasteCost_h \quad (5)$$

Subject to:

$$\forall i,l \quad Z_{i,l} \times bigM \geq \sum_h \sum_k \sum_t M_{i,l,h,k,t} \quad (6)$$

$$\forall i,l,h,k,t \quad M_{i,l,h,k,t} \leq ma_{i,h} \quad (7)$$

$$\forall i,l,k,t \quad \sum_h M_{i,l,h,k,t} \leq 1 \quad (8)$$

$$Y_{i,l,h,h',k,t} = \begin{cases} 1 \text{ if } M_{i,l,h,k,t} \text{ producing } h \text{ on day } k \text{ preceeds to } h' \text{ on day } k+1 \text{ when } h \neq h' \\ 0 \text{ otherwise} \end{cases} \quad (9)$$

$$\forall i,l,h,t,k = 1,...,K-1 \quad Y_{i,l,h,h',k,t} = M_{i,l,h,k,t} \times M_{i,l,h',k+1,t} \quad (10)$$

$$\forall i,l,h,t < T, k = K \quad Y_{i,l,h,h',k,t} = M_{i,l,h,k,t} \times M_{i,l,h',1,t+1} \quad (11)$$

$$\forall k,t \quad \sum_i \sum_l \sum_h M_{i,l,h,k,t} \times sm_i \leq psl \quad (12)$$

$$\forall k,t \quad \sum_{j}\sum_{i}\sum_{l}\sum_{h} M_{i,l,h,k,t} \times CPT_{h,j} \times vc_j \leq csl \tag{13}$$

$$\forall j,k,t \quad \sum_{i}\sum_{l}\sum_{\alpha=1}^{k}\sum CPT_{h,j} \times M_{i,l,h,\alpha,t} - \sum_{\alpha=1}^{k-1} D_{j,\alpha,t} \geq D_{j,k,t} \tag{14}$$

Equations (6)-(8) are related to moulds. First, moulds can not produce components unless they are adopted. Next, moulds can produce components only if they have the ability to produce the component groups. Finally, the daily productivity of each mould is one component group.

To identify the mould changeover, a binary variable is adopted (Y) (Equ. 9). This variable depicts that the specific mould type and number (*i*,*l*) which produces certain component group (*h*) on day (*k*) precedes to component group (*h'*) on day (*k+1*) within construction cycle (*t*). Thus, if $h \neq h'$ then a changeover occurs. Equation (10) is used to control changeover within a construction cycle. However, equation (11) is used to monitor the same constraint between two different construction cycles. As can be seen equations (11) and (12) are not linear. McCormick method is applied to convert non-linear equations (11) and (12) to the following sets of linear equations respectively (Equs. (15) and (16)).

$$\begin{cases} Y_{i,l,h,h',k,t} \geq M_{i,l,h,k,t} + M_{i,l,h',k+1,t} - 1 \\ Y_{i,l,h,h',k,t} \leq M_{i,l,h,k,t} \\ Y_{i,l,h,h',k,t} \leq M_{i,l,h',k,t} \end{cases} \tag{15}$$

$$\begin{cases} Y_{i,l,h,h',K,t} \geq M_{i,l,h,K,t} + M_{i,l,h',0,t+1} - 1 \\ Y_{i,l,h,h',K,t} \leq M_{i,l,h,K,t} \\ Y_{i,l,h,h',K,t} \leq M_{i,l,h',0,t+1} \end{cases} \tag{16}$$

Two limitations of the factory restrain daily mould productivity: limitation of daily supplied concrete and limitation of factory production space, Eq. (12) and (13).

Finally, equation (14) forces the production process to meet the demand and schedule applied by constructor.

Optimization Tools and Methodology:

The proposed model presents a Mix Integer Programming (MIP) problem. It can be performed and solved with mathematical programming tool or software such as GAMS. However, such a model can contain large searching domain and need computational effort for a solution. The group concepts also lead an effective way on solution searching. Moulds types and number of each mould type which present ways to group components are key variables to determine the precast project plan. Component demands must be firstly satisfied by using moulds and scheduling what components and when they are produced. Therefore, determining variables $Z_{i,l}$ and $M_{i,l,h,k,t}$ can rapidly reduce infeasible variable domain. The searching strategy, branch-and-cut priority, is primarily advised for this model.

Case Experiment

An example of a precast project with component information and installation information is assumed. In order to represent and explicate project information and results transparently, the example project contains 4 component types, 4 mould types, and 13 component groups under a 10-day contract for each construction cycle. The total number of cycles is assumed to be 20. The detailed information is shown as Table 3.

Table 3: Information of case experiment

<table>
<tr><th colspan="6">Parameter Symbols</th></tr>
<tr><td>Symbol</td><td>Value</td><td>Symbol</td><td>Value</td><td>vc_j</td><td>[7.2, 3.8,1 ,0.8] (m^3)</td></tr>
<tr><td>nm</td><td>4</td><td>nc</td><td>4</td><td>psl</td><td>150 (m^2)</td></tr>
<tr><td>nl</td><td>10</td><td>K</td><td>10</td><td>csl</td><td>50 (m^3)</td></tr>
<tr><td>T</td><td>20</td><td>LC_i</td><td>[100,100,100,100]</td><td>sm_i</td><td>[18, 9, 2, 1.5] (m^2)</td></tr>
<tr><td>$ma_{i,h}$</td><td colspan="3">
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<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td>I</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>II</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>1</td><td>1</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>III</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>IV</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td></tr>
</table>
</td><td>LC_h</td><td>$200</td></tr>
<tr><td>w_h</td><td colspan="3">[0, 0, 1.6, .8, 4, 3.6, 1.2, 0, .8, 1.4, 1.8, 0, 0]</td><td>CH_i</td><td>[200,150,100,100]</td></tr>
<tr><td>$D_{j,k,t}$</td><td colspan="3">
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</td><td>$Wastecost$</td><td>$200</td></tr>
<tr><td>$Mouldcost_i$</td><td colspan="3">[25000,21000,12000,9000]</td><td></td><td></td></tr>
<tr><td>$CPT_{h,j}$</td><td colspan="3">
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At the beginning of solving the example model, a big number (for example ten in this case) of moulds are temporarily appointed for each of all four mould types. The final optimal solution of the example project is shown as Figure 4. The average solving time of the example project for all steps of the recursive procedure is about 2 minutes. The Cplex 12.2.0.2 in GAMS 23.6.5 is used by Dell Precision T5500 with Intel(R) Xeon (R) CPU X5650 @ 2.67 GHz Processor with 48 GB of RAM.

The optimal solution is achieved with total project cost *TPC*= \$168,000 where *IMC* is \$99,000; *MchC* is \$5,200; *MwC* is \$1,800; *MUC* is \$62,000. The optimal solution shows that only mould types 1and 3 are able to produce all different component types ($Z_{i,l}$). This variable also depicts that required number each mould type is 3 and 2 respectively. Number of changeovers is minimized as depicted in production plan for all adopted mould types. To understand the effect of changeover the model is solved with zero changeover cost. Result shows that the cost increases up to 4%. The model successfully forces moulds to produce configuration in which moulds are fully utilized. Resources are sufficient, so that daily supplied concrete and production space do not restrain production plan. The production plan is shown in Figure 4.

$Z_{i,l}$	*1*	*2*	*3*
1	1	1	1
2	0	0	0
3	1	1	0
4	0	0	0

Figure 4: Adopted mould to produce all component types

			Production Plan (days)									
			1	2	3	4	5	6	7	8	9	10
Mould Type	I	Comp 1	1	1	1	1	1	1	1	1	1	
		Comp 2										2
		Comp 3										
		Comp 4										
	I	Comp 1	1									
		Comp 2		2	2	2	2	2	2	2	2	2
		Comp 3										
		Comp 4		2	2	2	2	2	2	2	2	2
	I	Comp 1										
		Comp 2							2			
		Comp 3	2	2	2	2	2	2				
		Comp 4	4	4	4	4	4	4	2			
	III	Comp 1										
		Comp 2										
		Comp 3	1	1	1	1	1	1	1	1	1	1
		Comp 4										
	III	Comp 1										
		Comp 2										
		Comp 3	1	1	1	1	1	1	1	1	1	1
		Comp 4										

Figure 5: Optimized production plan for case experiment

The proposed model is only represented by an example experiment to conduct a guide of precast project planning. Although configuration and group concepts can structure a framework, grouping details can be case by case for different precast factories and different projects. Setting moulds is fundamental to present real situations. Planners are encouraged to survey on setting moulds based on their own circumstance. For example, setting moulds relate to techniques adopted in factory. Nevertheless, the proposed model is applicable and flexible for precast projects based configuration and component group ideas.

Conclusion

To propose a solution for precast project planning from the design and production perspectives, this study integrates two forms of industrialization which are prefabrication and standardization. A mathematical model is developed to adopt concepts of prefabrication configuration and component groups. To simplify the overall precast project process, components are standardized (or grouped) into component groups; moulds can produce components within grouped components. To determine required moulds to avoid immense models, moulds are also grouped into mould types. Finally, an example project demonstrates the feasibility of the proposed model. The example is successfully solved to offer a solution under overall consideration of precast projects. The proposed model can be modified to cater to any individual project environment.

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