

Planning and Scheduling Prefabrication Construction Projects Using Dependency Structure Matrix (DSM)

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ABSTRACT

Fast project delivery is a common goal for all participants (owners, constructors, vendors, etc.) within the construction industry. Prefabrication is attractive because it offers an approach to complete construction projects within a much shorter duration than traditional construction methods (Retik 1994). However, the successful completion of prefabrication projects requires careful planning prior to implementation. The complex nature of prefabrication project scheduling makes traditional scheduling tools (CPM, PERT, Gantt charts, etc.) ineffective due to a common phenomenon termed iteration. Iteration is a cyclic process and results from activity interdependency. Dependency Structure Matrix (DSM) is an alternative approach that has had much success in manufacturing but has seen limited application in construction. It offsets the shortcomings of the traditional scheduling tools in dealing with the phenomenon of iteration. This paper first discusses the applicability of DSM to prefabrication projects. An example model that demonstrates the application of DSM is then developed and used to demonstrate determining an optimal schedule in terms of total feedback distance. To improve the accuracy of project duration estimations, the Reward Markov Chain method is employed to estimate durations of sequential iterations. In addition, an example of using the Reward Markov Chain method is demonstrated. The paper concludes with a discussion of the advantages and disadvantages of the approach.

INTRODUCTION

It is in the best interest of all participants within the construction industry to complete projects with shorter duration. As a matter of fact, the duration of construction projects using traditional construction methods is seriously constrained by numerous factors at the jobsites. Prefabrication offers an alternative approach to significantly reduce the duration of construction projects through prefabricating components within specialized factories, and then assembling the components at the construction site. Manufacturing components offsite can save an enormous amount of time because it slips the leash that most construction activities are limited by the

jobsite conditions, like inclement weather and limited working space (Chen et al. 2010). Nevertheless, the speedy and successful completion of prefabrication construction projects requires careful planning and scheduling at earlier stages due to their complex nature. The traditionally used scheduling tools, such as CPM, Gantt chart, PERT cannot fulfill the job satisfactorily due to their limitation in dealing with iterative processes (Austin et al. 2000; Baldwin et al. 1999; Fayez et al. 2003; Maheswari and Varghese 2005; Yassine 2004). DSM has been widely applied in the manufacturing industry to schedule iterative processes. But, it has seen limited application within the construction industry.

RESEARCH BACKGROUND

Prefabrication in Construction. Despite the fact that the construction industry has the longest history among all industries, it is far behind its counterparts in terms of productivity, level of industrialization and automation, since the uniqueness of each project severely hinders the possibility of using mass production. In fact, other industries, particularly manufacturing, have minimized the need for labor for most manual work via automation. Prefabrication is very attractive to the stakeholders in the construction industry; it overcomes all these hindrances by manufacturing components or sections of the buildings in specialized facilities and then shipping them to site for assembly (Everett and Slocum 1994). Consequently, onsite construction time is radically lessened. In practice, construction time is considered to be one of the five most important factors for choosing prefabrication (Chen et al. 2010).

In the 1960s, the first building using prefabricated panels was constructed (Molnár 2002). This project showed that mass production of panels offsite significantly reduced the unit cost (Molnár 2002). As time passed, researchers have found that prefabrication has many other advantages, including radical productivity improvement, an improved working environment, better quality control, reduction of material waste, more effective use of human resources and sophisticated equipment, reduction in the use of forms and scaffolding onsite, overall cost reductions, prevention of onsite environmental damage, immunity to inclement weather, greater safety (Azhar et al. 2012; Chen et al. 2010; Retik and Warszawski 1994). Nevertheless, this research only focuses on the advantage in productivity improvement, as this advantage possessed by prefabrication has the greatest potential to align the construction industry with its counterparts.

Based on the percentage of the building being prefabricated off the construction site, prefabrication is divided into three subcategories: manufactured housing, modular prefabrication, and prefabricated components. Manufactured housing is where the entire house is fabricated offsite and then delivered to site. Prefabricated components include pre-assembled doors, windows, plumbing pipes, etc. Modular prefabrication is prefabricating segments of housing and then putting them together on the jobsite (Zhao and Riffat 2007). The latter two forms of prefabrication are more widely used because they are more applicable to industrialized production (McGraw Hill Construction 2011).

Overview of Dependency Structure Matrix.The DSM method was proposed by Steward (1981) to resolve the difficulty in scheduling iterative processes, which characterizes design processes (Austin et al. 2000; Baldwin et al. 1999; Smith and Eppinger 1997). Design iteration leads to rework of design tasks, which is often caused by new information discovered after the tasks have started (Smith and Eppinger 1997). This has been a widely recognized driver of schedule risk.

The occurrence of design iteration has several reasons. For instance, discovery of some kind of error or incongruity in a downstream task, can lead to rework of an upstream activity. Likewise, repetition of a downstream activity may result from discovery of adjusted information in an upstream activity, possibly due to correction of an earlier error or change of project direction (Smith and Eppinger 1997).

There are three types of relationships between activities, which are illustrated by Figure 1: parallel (or concurrent), sequential (or dependent), coupled (or interdependent) (Yassine 2004). Parallel relationship indicates that tasks A and B are independent and can be executed concurrently. Sequential relationship indicates that task B is dependent on the information provided by task A. Coupled relationship indicates that tasks A and B are interdependent on each other.

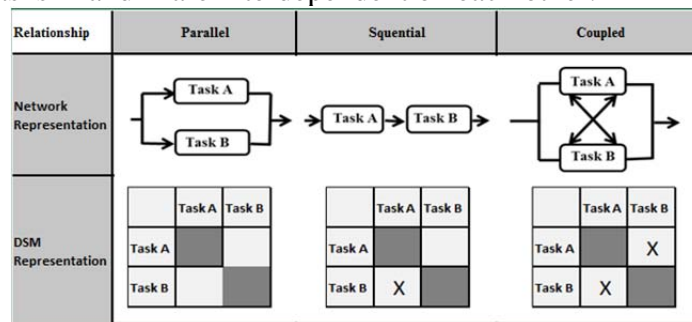


Figure 1. DSM Presentation of the Relationships between Activities.

Marks in each row (of the DSM) suggest the task corresponding to the row needs output from all activities corresponding to the columns. Likewise, marks in a specific column indicate which tasks in different rows receive information from the task of the column.

The tasks can be re-ordered so that iteration is reduced or eliminated. The techniques include partitioning and tearing. Partitioning is a way to rearrange the sequence of the rows and columns in the DSM so that all the marks only present in lower diagonal cells in the new DSM. Lower diagonal DSM means the information flows forward and no feedback from downstream tasks. Whereas a complex engineering system is highly unlikely to be manipulated to produce a lower triangular DSM. Tearing is a way to select the group of marks in the upper diagonal cells, and removal of the selected marks from the matrix (and then reorder the DSM rows and columns) will present a lower triangular matrix. The eliminated marks in upper diagonal cells are called “tears” (Yassine et al. 2001).

Steward (1981) utilized level numbers to replace a simple “X” or “.”. Level numbers in the matrix reveal the ranks where the feedback marks should be torn. So, the mark ranked the highest will be torn first and then the matrix will be re-sequenced (Yassine 2004).

Browning and Eppinger (2002) proposed a method to estimate the duration of product development projects by taking into account the rework probability and rework impact. Rework probability represents the probability that a task is affected by another task (Smith and Eppinger 1997). Rework amount is a product of rework impact factor and the original duration of the task (Cho and Eppinger 2005). The figures present in the DSMs in Figure 2 and Figure 3 indicating the rework probabilities and rework impacts for each activity, respectively.

	Task A	Task B	Task C
Task A		0.2	
Task B			0.4
Task C	0.1		

Figure 2. Rework Probabilities.

	Task A	Task B	Task C
Task A		0.8	
Task B			0.3
Task C	0.5		

Figure 3. Rework Impacts.

It is rather difficult to accurately estimate the duration of iterative processes. Smith and Eppinger (1997) introduced the Markov Chain method to estimate completion time of iterative processes by taking into account rework probability. Cho and Eppinger (2005) improved the method through considering iteration, rework amount, and learning curve stochastically. Zhang et al. (2007, 2008) further improved the Reward Markov Chain method and used different factor for the rework amount, rework probability, and learning curve in various iterations. This research adopts the method proposed by Zhang et al., as their model is closer to reality.

METHODOLOGY

DSM Model Construction and Optimization. Using the Work Breakdown Structure (WBS) approach, all the tasks required to complete a project are identified to establish a DSM model. The estimated duration of each task should neither be longer than 30 days nor be shorter than one day (Hinze 2012). Then, the relationships among these tasks are confirmed by experts and marked in the matrix using “0” and “1”. “0” represents no relationship or information exchange between the corresponding tasks. However, for the sake of clarity, “0”s are left blank.

The sequence of tasks is then rearranged to decrease feedback and rework using partitioning and tearing techniques. In the processes, the cell with “1” and the longest distance to the diagonal is rearranged first, as long feedback distance suggests more uncertainty. The tasks between the recipient and releaser could be affected. The same procedure is used for the rest of the tasks in order to form a lower triangle.

Duration Estimation. The durations of iterative processes are estimated using the Reward Markov Chain method. The Markov Chain is broken down into stages. Each stage can also be considered as a state. The boundary of each stage is defined by the location in the chain when each task is executed for the first time. The reward of each stage in the chain is the length of time that the corresponding task consumed. The

completion time of the iterative process equals to execution time of the entire process. The total reward is computed through adding the time that the initial tasks consumed in each stage. The remaining time of the initial task in each stage consists of all the execution times in the stage (Zhang et al. 2007). This calculation process can be expressed as:

$$\begin{cases} R_1^{(i)} = P_{21}w_{21}R_2^{(i)} + p_{31}w_{31}R_3^{(i)} + \dots + p_{i1}w_{i1}R_i^{(i)} + l_1t_1 \\ R_2^{(i)} = p_{12}w_{12}R_1^{(i)} + p_{32}w_{32}R_3^{(i)} + \dots + p_{i2}w_{i2}R_i^{(i)} + l_2t_2 \\ \vdots \\ R_i^{(i)} = p_{1i}w_{1i}R_1^{(i)} + p_{2i}w_{2i}R_2^{(i)} + \dots + p_{i-1i}w_{i-1i}R_{i-1}^{(i)} + l_it_i \end{cases} \quad (1)$$

In matrix form this appears as:

$$(P \cdot * W) R^{(i)} = L \cdot * T \quad (2)$$

$$T = \sum_{i=1}^n [R_i^{(i)} + (1 - l_i)t_i] \quad (3)$$

In Equation 1, p_{ij} represents the probability of rework of task i resulting from task j ($i < j$). w_{ij} represents rework impact factor of task i caused by task j ($i < j$). l_i represents the learning curve effect for task i . It is assumed that the learning curve is constant and is equal to 1 after the first iteration. In Equation 2, “*” represents the dot multiplication operation. Equation 3 represents the sum of the completion time in each stage, which is equal to the total expected completion time of the iterative processes (Zhang et al. 2008).

In this research, the triangular probability distribution is proposed to represent task durations since this distribution is quite simple and familiar to field personnel. Three values (e.g., optimistic, most likely, and pessimistic) are assigned for each task by experts.

APPLICATION EXAMPLE

An example case is presented here to better show readers how to apply the proposed methods. All the numerical values in this example were randomly chosen for the purpose of demonstration. First of all, an initial DSM model was created and shown as Figure 4. This DSM model was then optimized in order to minimize feedbacks and reworks. As a result, a new sequence of tasks was produced as Figure 5 accordingly.

Element Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Task A	1																				
Task B	2	1																			
Task C	3		2																		
Task D	4	1		3																	
Task E	5		1		4																
Task F	6			1		5															
Task G	7	1					6														
Task H	8			1	1			7													
Task I	9					1			8												
Task J	10						1			9											
Task K	11			1				1			10										
Task L	12								1			11									
Task M	13				1	1							12								
Task N	14								1	1	1			13							
Task O	15											1			14						
Task P	16															15					
Task Q	17																16				
Task R	18																	17			
Task S	19																		18		
Task T	20																			19	

Figure 4. The Original DSM.

PARTITIONED DSM (Needs Updating!)	Task A	Task B	Task C	Task I	Task F	Task E	Task O	Task P	Task Q	Task G	Task H	Task M	Task L	Task T	Task S	Task D	Task J	Task K	Task N	Task R	
Task A	1																				
Task B	2	1																			
Task C	3		2																		
Task I	9			3																	
Task F	6				4																
Task E	5					5															
Task O	15						6														
Task P	16							7													
Task Q	17								8												
Task G	7	1								9											
Task H	8										10										
Task M	13											11									
Task L	12												12								
Task T	20													13							
Task S	19														14						
Task D	4															15					
Task J	10																16				
Task K	11																	17			
Task N	14																		18		
Task R	18																			19	

Figure 5. Partitioned DSM.

After that, an iterative block was selected and the duration of the iterative block was estimated. Durations (optimistic, most likely, and pessimistic) of the tasks are listed in Table 1. A total of 500 possible durations were generated for each task to reduce variability.

Table 1. Expected Durations of Each Task

Task Name	Exp. Duration		
	O	M	P
Task G	12	15	17
Task H	16	19	25
Task M	20	25	28
Task L	12	16	19
Task T	10	13	16

The corresponding rework probabilities matrix and rework impact matrix are presented as Figure 6 and 7. For instance, Task H and M could lead to rework of Task G according to the matrix. The rework probabilities are 0.4 and 0.5, and rework impacts are 0.1 and 0.6, respectively.

	Task G	Task H	Task M	Task L	Task T
	7	8	13	12	20
Task G	7	0.4	0.5		0.2
Task H	8	8	0.7		
Task M	13		13	0.4	
Task L	12			12	0.9
Task T	20				20

Figure 6. The Rework Probabilities Matrix.

	Task G	Task H	Task M	Task L	Task T
	7	8	13	12	20
Task G	7	0.1	0.6		0.8
Task H	8	8	0.7		
Task M	13		13	0.5	
Task L	12			12	0.3
Task T	20				20

Figure 7. The Rework Impact Matrix.

The duration of each task the iterative block in state 5 was calculated and the average iterative durations are shown as following:

$$\left(\overline{R}^{(5)}\right)^T = \left[\overline{R}_1^{(5)} \quad \overline{R}_2^{(5)} \quad \overline{R}_3^{(5)} \quad \overline{R}_4^{(5)} \quad \overline{R}_5^{(5)}\right]^T = [5.60 \quad 9.02 \quad 22.16 \quad 12.14 \quad 12.96]^T$$

The total expected duration of this iterative block in this state is 61.88 and the standard deviation is 7.83. By following this method, the durations of all iterative processes can be calculated and then added to the total project duration.

CONCLUDING REMARKS

The DSM method provides a concise way to represent information-based relationships between activities. More importantly, this method offsets the shortcoming that the traditionally used scheduling tools are ineffective in dealing with iterative processes. Furthermore, many optimization techniques have been developed to reduce feedback and rework. The Reward Markov Chain method can greatly improve the accuracy of duration estimation for projects that contain iterative processes. However, this paper did not take into consideration overlapped iteration, which is left as a topic for future study. In addition, further work is required to

validate the approach against a comprehensive set of case studies drawn from industry.

REFERENCES

- Austin, S., Baldwin, A., Li, B., Waskett, P. (2000). "Analytical Design Planning Technique (ADePT): A Dependency Structure Matrix Tool to Schedule the Building Design Process." *Constr. Manage. Econ.*, 18(2), 173-182.
- Azhar, S., Lukkad, M., Ahmad, I. (2012). "Modular v. Stick-Built Construction: Identification of Critical Decision-Making Factors." *Proc., the 48th Annual Conference of Associated Schools of Construction, Birmingham, UK*.
- Baldwin, A. N., Austin, S. A., Hassan, T. M., Thorpe, A. (1999). "Modelling Information Flow during the Conceptual and Schematic Stages of Building Design." *Constr. Manage. Econ.*, 17(2), 155-167.
- Browning, T. R., and Eppinger, S. D. (2002). "Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development." *IEEE Transactions on Engineering Management*, 49(4), 428-442.
- Chen, Y., Okudan, G. E., Riley, D. R. (2010). "Sustainable Performance Criteria for Construction Method Selection in Concrete Buildings." *Autom. Constr.*, 19(2), 235-244.
- Cho, S., and Eppinger, S. D. (2005). "A Simulation-Based Process Model for Managing Complex Design Projects." *IEEE Transactions on Engineering Management*, 52(3), 316-328.
- Everett, J., and Slocum, A. (1994). "Automation and Robotics Opportunities: Construction Versus Manufacturing." *J. Constr. Eng. Manage.*, 120(2), 443-452.
- Hinze, J. (2012). *Construction Planning and Scheduling*, 4th ed., Pearson Prentice Hall, Upper Saddle River, N.J.
- McGraw Hill Construction. (2011). *Prefabrication and Modularization: Increasing Productivity in the Construction Industry*. McGraw Hill Construction, Bedford, MA.
- Molnár, V. (2002). "Tulips and Prefabrication: Hungarian Architects in the Bind of State Socialist Modernization in the 1970s." *Proc., the OACES Postgraduate Conference*, St. Antony's College, Oxford.
- Retik, A., and Warszawski, A. (1994). "Automated Design of Prefabricated Building." *Build. Environ.*, 29(4), 421-436.
- Smith, R. P., and Eppinger, S. D. (1997). "A Predictive Model of Sequential Iteration in Engineering Design." *Management Science*, 43(8), 1104-1120.
- Steward, D. V. (1981). "The Design Structure System: A Method for Managing the Design of Complex Systems." *IEEE Transactions on Engineering Management*, 28(3), 71-74.
- Yassine, A. (2004). "An Introduction to Modeling and Analyzing Complex Product Development Processes using the Design Structure Matrix (DSM) Method." *Quaderni Di Management (Italian Management Review)*, 51(9), 1-17.
- Yassine, A., Whitney, D. E., Zambito, T. (2001). "Assessment of Rework Probabilities for Simulating Product Development Processes Using the Design

- Structure Matrix (DSM)." *Proc., DETC '01: ASME 2001 International Design Engineering Technical Conferences*, Pittsburgh, Pennsylvania.
- Zhang, W., Zhou, B., Luo, W. (2007). "Model-Based Time Estimate of Software Test Processes." *Proc., Wireless Communications, Networking and Mobile Computing*. 4946-4949.
- Zhang, W., Zhou, B., Luo, W. (2008). "Modeling and Simulating of Sequential Iterative Development Processes." *Computer Integrated Manufacturing Systems*, 14(9), 1696-1703.
- Zhao, X., and Riffat, S. (2007). "Prefabrication in House Constructions." *International Journal of Low-Carbon Technologies*, 2(1), 44-51.