SIMULATION-BASED SCHEDULING MODEL FOR MULTIPLE DESIGN PROJECTS

Jang-Jeng Liu[1] and Wei-Chih Wang[2]

ABSTRACT

A design firm often needs to allocate various types of design resources or participants to the multi-disciplinary activities of various design projects. Each of these design projects is undertaken either in a proposal phase, basic design phase, detailed design phase, or construction phase of a building project. Effective allocation of the design participants to activities depends on how the design activities of these design projects are scheduled. But the effect which is caused by design iterations in schedule and resource isn't considered before. This study finds design iterations by DSM and other methods and develops a simulation-based scheduling model to effective allocate design participants to multiple design projects under the effect of design iteration. This model is helpful to find how to lean the design schedule and design resources. Particularly, simulation algorithms are proposed to model the uncertainties of design iterations, draw amounts of iterations, design participants' man hour, and activity durations. The operation of the model is demonstrated by applying it to a Taiwanese design firm who deals with multiple design projects.

KEY WORDS

Multi-project, design iteration; design schedule; design process; simulation

INTRODUCTION

A design firm often needs to allocate various types of design resources or participants (including architects, designers or crafts) to the multi-disciplinary activities of multiple design projects. Each of these design project is undertaken either in a proposal phase (i.e., the firm is preparing a bidding proposal to compete for the project), basic design phase, detailed design phase, or construction phase (i.e., the firm needs to review the compatibility between the design deliverables and the constructed facility) of a building project. Effective allocation of the design participants to activities depends on how the design activities of these design projects are scheduled. But the effect which is caused by design iterations in schedule and resource isn't considered before.

Scheduling of design projects is complicated because design activities frequently depend differently on information about each other. Namely, the design process involves various iterations across activities (Austin et al 1994, Austin et al 1999,

[1] Graduate student, Department of Civil Engineering, National Chiao Tung University, Hsin-Chu 300, Taiwan. E-mail: sandroliu@nsrrc.org.tw.

[2] Professor, Department of Civil Engineering, National Chiao Tung University, Hsin-Chu 300, Taiwan. E-mail: weichih@mail.nctu.edu.tw.

Austin et al 2000, Baldwin et al 1998, Baldwin et al 1999, Luh et al 1999, Chua et al 2003, Chen et al 2003, Choo et al 2004, Wang et al 2005, Wang et al. 2006). Additionally, the fact that the numbers of iterations and the durations of design activities are uncertain makes difficult to define the precedence relationships among activities and to evaluate the durations of the design projects. Past researches may be helpful to find the design iteration. But how to calculate the effect caused by design iteration is ignored especially for multiple projects.

During the conceptual and schematic design phases of a building project, a chief designer (architect/engineer or A/E) aims to capture information from a wide range of disciplines, such as structural design, heating-ventilating-air-conditioning (HVAC) design and electrical design; candidate solutions are proposed, and new states are generated from the current ones based on the information available to meet the owner's requirements, including, for example, the budget and general spatial arrangements (Baldwin et al 1999, Rivard and Fenves 2000). These two early phases ensure that the design deliverables fulfill the owner's demands. A simple bar chart that expresses the due dates of design deliverables may suffice. In practice, the bar chart method is commonly used to represent the schedule for those design activities. Each bar represents a design activity and may identify several points of expected percentage completion (such as 25%, 50%, 75% and 100%) as milestones associated with the activity. Unfortunately, the bar chart is not sufficiently detailed to detect schedule slippage in a design activity a timely manner. Additionally, using the critical path method (CPM) that is commonly employed to schedule construction activities whose logical relationships are one direction, for design projects is difficult because of the existence of the above-mentioned iterative dependencies among design activities.

Recently, design scheduling has been receiving increasing attention because the total duration of a building project is commonly delayed by the lateness of design deliverables (including design drawings, calculations and reports) (Wang et al 2006).But Wang only considers the design schedule of one project This study finds design iterations by DSM and other methods and develops a simulation-based scheduling model to effective allocate design participants to multiple design projects. Particularly, simulation algorithms are proposed to model the uncertainties of design iterations and activity durations. Next section, the current practice of design firms in allocating design people is presented, followed by the illustration of uncertainties of design iterations and activity durations. Then, the simulation-based model is proposed and the operation of the model is demonstrated by applying it to a firm who faces multiple design projects. Finally, future research directions are indicated.

UNCERTAINTIES OF DESIGN ITERATIONS AND ACTIVITY DURATIONS

Design is iterative. Design iterations influence the capacity to evaluate exactly the duration of a design project (Austin et al 1994, Austin et al 1999, 2000). In the detailed design phase, a certain amount of design information must flow among activities several times until design deliverables are compatible or regulatory requirements are met. For example, a downstream design review may require particular upstream activities to rework some developed deliverables to respond to comments made in a review (such as those concerning errors and omissions). In an unexpected situation, iterations become necessary because of "external forces". A typical example is a design change in a downstream activity, such that the deliverables of some upstream activities must react to such a change (Wang et al 2005).

The occurrence of design iterations may be due to the following causes:

- Cyclic decision making process. — During designing, decisions often are made iteratively until the design deliverables meet the needs.
- Exchange of design information. — Design information often requires to be exchanged among intra-disciplines, inter-disciplines and multi-disciplines.
- Design review. — Design review always creates design iterations and certain activities may require to be revised to reflect the reviewing comments.
- Design rework. — Design rework produces design iterations because certain activities have to be performed again.
- Design change. — A design change may require extra design deliverables of an activity.
- Non-conformance of clients' requirements — Nonconformance of design deliverables will also produce design iterations. This usually happen in schematic design phase that the project owner selects rejects the proposed alternative. An experienced designer will carefully produce the minimal design deliverables for ensuring that the proposed alternative meets the needs.

The uncertainties of design iterations comprises the uncertainties of iteration occurs and the uncertainties of a certain amount of design information for rework. However, various projects and various companies situation is dissimilar, the occurrence probability of iteration is very difficult with certain formula to calculate by a formula. Therefore in this pattern, the user can input the probability of the design iteration occurrence and rework, based on a three-point estimate of duration using the Program Evaluation Review Technique..

PROPOSED MODEL

The proposed model extends a previous study of Wang et al. (2006) to deal with multiple design projects simultaneously (from the perspective of a design firm), to incorporate the uncertainties of design iterations and the uncertainties of task durations, and to offer a cost analysis. The proposed model is executed via the following three five phases, - representing the design process of multiple projects (Phase I); establishing a simulation-based network (Phase II); identifying deterministic input parameters (Phase III), incorporating the uncertainties (Phase IV), and defining output variables and computer coding (Phase V). The following sections illustrate the details of each phase.

- Phase I: representing the design process of multiple projects

Three steps are implemented in this phase - setting the general priority of multiple projects, identifying design activities and their dependencies, and applying DSM to facilitate the identification of design iterations.

- Phase II: establishing a simulation-based network

Phase II establishes a simulation-based network, and assigns design participants (such as architects, designers and assistant designers) to each activity.

A simulation language, Stroboscope (Martinez, 1996) (refer to http://strobos.cee.vt.edu/), is adopted to implement the simulation-related algorithms in the proposed model. Stroboscope can dynamically access the state of the simulation and the properties of the resources (including design participants and deliverables).

In this model, assuming the architect, designer (structural, HVAC, electrical consultant), and assistant designer (structural, HVAC, electrical engineer) of design participants work in sequence (Figure1). In the fact, the work order isn't only regular but also may change sequence. But the work order of design participants for each activity isn't the main issue in this research. Moreover, the real work order would make the working time of design participants for each activity divide several part that is difficult to be get.

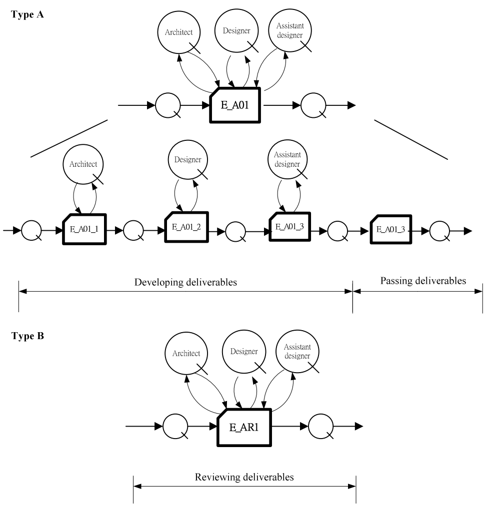

Figure 1: Two Types of Detail Simulation Model

- Phase III: identifying input parameters

This phase identifies input parameters for evaluating the duration and cost of each activity. These inputs include the type and number of participants involved in each activity, the time of participants for completing each activity, the time of each activity for review meeting, the probability and effect of iterations, and the quantity and wage rate of each design participant.

In this work, the calculation of design duration is divided to the common design activity and the stage finish activity. Wang et al. (2006) divide the common design activity into the time of actual design and delivers. In other word, the time required to complete a design activity i ($D_{i(0)}$) without iterations, is the sum of two parts - the time (d_i) required to complete the amount of deliverables, the time (dd_i) required to process the received and the to-be-delivered deliverables That is,

$$D_{i(0)} = d_i + dd_i \tag{1}$$

The time required to develop deliverables for activity i without considering iterations, di is,

$$d_i = Q_i \times P_{i1} + Q_i \times P_{i2} + ... + Q_i \times P_{iJ} \tag{2a}$$

$$= Q_i \times \sum_{j=1}^{J} P_{ij} \tag{2b}$$

where the unit of measure of Q_i can be “suits” (for drawings) and “each” (for reports, proposals, a set of calculations, etc.).P_{ij} is the time of participant j completes unit work of activity i.

Time taken to process the received and to-be-delivered deliverables (dd_i) — In completing the deliverables associated with an activity i, participants must take time to digest and clarify the deliverables received from the activities that preceded activity i. After the deliverables for activity i have been completed, a certain period is also required to synthesize the deliverables and then deliver them with official documents to those involved in subsequent activities. In the same time, designer may need to communicate that the deliverables can’t explain clearly by telephone or e-mail. The time also The time also include in the time taken to process the received and to-be-delivered deliverables. For simplicity, the time required to process the received deliverables and the to-be-delivered deliverables for activity i, dd_i, is assumed to be a constant. Such a period of processing is longer when the deliverables are passed among many design firms than when they are shared within a single design firm. In this research, dd_i doesn’t use the manpower.

The stage finish activity need all participants to discuss, check and revise. Also users can input by most optimistic, most possible, the most pessimistic three ways. That is,

$$d_i = T_i \tag{3}$$

where T_i is the review time of activity i.

While the stage finish activity is completed, the design discipline doesn’t wait for the feedback of the owner or the government organization to work for other project. Because the feedback will be get before the stage of other project be completed. So in this work, the stage finish activity doesn’t consider the effect of the time taken to process the received and to-be-delivered deliverables (dd_i).

That is,

$$D_{i(0)} = d_i = T_i \tag{4}$$

The time required to complete a design activity i ($D_{i(0)}$) with iterations is also divided to the common design activity and the stage finish activity.

In the common design activity, the time required to complete a design activity i ($D_{i(n)}$) with n iterations, is the sum of three parts - the time (d_i) required to complete the amount of deliverables, the time (dd_i) required to process the received and the to-be-delivered deliverables, and the time ($\sum_{n=1}^{N} IterD_{i(n)}$) required to rework drawings due to iterations. That is,

$$D_{i(n)} = d_i + dd_i + \sum_{n=1}^{N} IterD_{i(n)} \tag{5}$$

Time taken to rework drawings due to iteration ($IterD_{i(n)}$) — When an activity is iterated, some of the developed deliverables associated with the activity must be reworked or modified (Chen et al 2003). Also, additional time is needed for communication within a discipline or across various disciplines to allow participants to clarify errors, omissions or incompatibilities before the deliverables can be reworked. Therefore, the period required to rework deliverables because of the nth iteration (n = 1 to N) for activity i, $IterD_{i(n)}$, is

$$IterD_{i(n)} = d_{i(n)} + dd_{i(n)} \tag{6}$$

$$d_{i(n)} = IterDR_i^n \times d_i \tag{7}$$

$$dd_{i(n)} = (l_{i(n)} \times \frac{IntraD_i}{2^{n-1}}) + (m_{i(n)} \times \frac{InterD_i}{2^{n-1}}) + (r_{i(n)} \times \frac{MultiD_i}{2^{n-1}}) \tag{8}$$

where $IterDR_i$ is the fraction of the developed drawings associated with activity *i* that must be reworked at each iteration. d_i is the time taken to complete an activity *i* without iteration. $l_{i(n)}$=1 if an intra-iteration arises for activity i; otherwise, $l_{i(n)}$=0. Similarly, $m_{i(n)}$ (1 or 0) and $r_{i(n)}$ (1 or 0) are employed to identify the occurrence of an inter-iteration and a multi-iteration of activity i, respectively. $IntraD_i/2^{n-1}$, $InterD_i/2^{n-1}$ or $MultiD_i/2^{n-1}$ represent the additional time required for communication concerning activity i, for an intra-iteration, an inter-iteration or a multi-iteration, respectively. The communication time increases with the number of disciplines involved. Thus, $IntraD_i < InterD_i < MultiD_i$ is expected.

The proposed model offers a cost analysis by assigning wage rate data (dollar per hour) to participants. The cost per participant equals the period of his or her participation (working and idle hours) multiplied by his wage rate. The total design costs are the sum of the participant costs. A design manager can thus make an improved decision in allocating design participants to activities, to ensure satisfactory project duration and cost.

- Phase IV: incorporating the uncertainties

The uncertainties incorporated into the proposed model include uncertainties of activity durations, uncertainties of iterations

By eq(1), activity durations is the productivity of the development of the deliverables multiplied by the amount of deliverables. In this research, the amount of deliverables is assumed a constant. So the uncertainty of activity durations is affected by the productivity of the development of the deliverables. The productivity of the development of the deliverables is measured in terms of unit rate (hour/unit). In this research, unit rate is also input by PERT. Moreover, various participants with different degrees of productivity are involved in completing the drawings of an activity.

In the detailed design phase, a certain amount of design information must flow among activities several times until design deliverables are compatible or regulatory requirements are met. In this model, user can input the occur probability $IterHpro_j$ of iteration by PERT, where j means iteration j. The rework percentage of iteration j $IterDR_i$ also can be input by PERT.

- Phase V: selecting output variables and computer coding

All the abovementioned input parameters and derived equations must be suitably coded using Stroboscope statements. Stroboscope automatically generates most of the output variables (called system-maintained variables) (Martinez 1996). Typical system-maintained output variables include the start time, the finish time and the duration of each activity and of the whole project, as well as the idle time for each participant. In this investigation, Stroboscope was run in the Windows XP environment, with a P3 850 CPU and 256 Mbytes of RAM. One thousand iterations took under one minute for the example project.

EXAMPLE

The operation of the model is demonstrated by applying it to a Taiwanese design firm who deals with multiple design projects in two months. In two months, the design firm must finish change order of two building project (Project A and B), a detail design project (Project C), a basic design phase project (Project D), a just beginning project (Project E), and a bidding propose of project F. Figure 2 is the bar-chart which is the initial assignment of architectural firm.

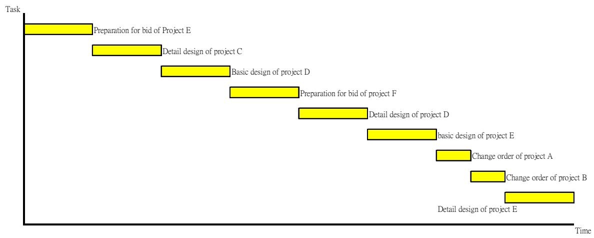

Figure 2: Bar-Chart of Architectural Firm's Initial Assignment

Table 1 lists the 3 participants involved in the architectural disciplines. An architect, a designer and an assistant designer are responsible for performing the architectural work. Other input data is shown on PhD dissertation of Jang-Jeng Liu.

Table 1: Input Data of each Activity for Architect in the Example Project

Architect Task No.	Architect			Designer			Assistant designer		
	Opt.	Pro.	Pes.	Opt.	Pro.	Pes.	Opt.	Pro.	Pes.
A_ACH2	1	1	1.5	7	8.5	10	5	6.5	8
B_ACH1	0.5	1	1	7	8.5	10	7	8.5	10.5
C_A09	-	-	-	10	12.5	15	-	-	-
C_A10	1	1	1.5	4.5	6	7	-	-	-
D_A03	1	1.5	2	4.5	6	7	2.5	3	3.5
D_A04	-	-	-	9.5	12	14.5	-	-	-
D_A05	-	-	-	-	-	-	12.5	15.5	19
D_A06	-	-	-	-	-	-	14.5	18	22
D_A07	-	-	-	5.5	6.5	8	3.5	4.5	5
D_A08	-	-	-	2.5	3	4	9	11	13.5
D_A09	-	-	-	8	10	12	-	-	-
D_A10	0.5	1	1	4	5	6	-	-	-
E_A01	9	10	11	-	-	-	-	-	-
E_A02	3	3.5	4	5	6.5	7.5	-	-	-
E_A03	1.5	1.5	2	4.5	6	7	2.5	3	3.5
E_A04	-	-	-	9.5	12	14.5	-	-	-
E_A05	-	-	-	-	-	-	15	19	22.5
E_A06	-	-	-	-	-	-	12	15	18
E_A07	-	-	-	5.5	7	8.5	3.6	4.5	5.5
E_A08	-	-	-	2	2.5	3	7.5	9.5	11
E_A09	-	-	-	9.5	12	14.5	-	-	-
E_A10	1	1	1.5	3.5	4.5	5.5	-	-	-
F_A01	8.5	9.5	11	-	-	-	-	-	-
F_A02	1.5	2	2.5	3	4	5	-	-	-

Figure 3 presents the partitioned matrix for the example project E case obtained by applying the DSM algorithms. Each "X" in the matrix indicates that the activity on the left-hand side depends on the activity at the top of the matrix. This partitioned matrix demonstrates that one completed case 34 activities contribute to three kinds of iterative loops (iterations A, D, and G with complete loops). In the same way, Case D has iteration C and H, Case F has iteration B. Furthermore, two incomplete iterative loops (E and F) are identified. Figure 4 depicts the established simulation-based network for this example project. The network incorporates the 79 activities (represented by Combi nodes), 9 participants (represented by Queue nodes) and the dependencies among activities (represented by links). Additionally, Dynafork nodes (each represented by a cycle enclosing five rays) that have routing capabilities for activating downstream activities are used to control the simulation of Eight iterations. Moreover, all small Queues shown in the network are used only to control the resource flows.

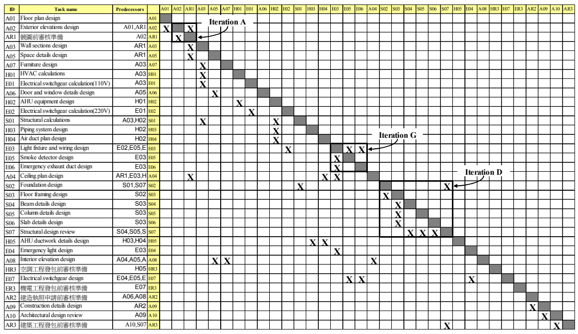

Figure 3: Three Iterations Identified by DSM in the Example Project Case E

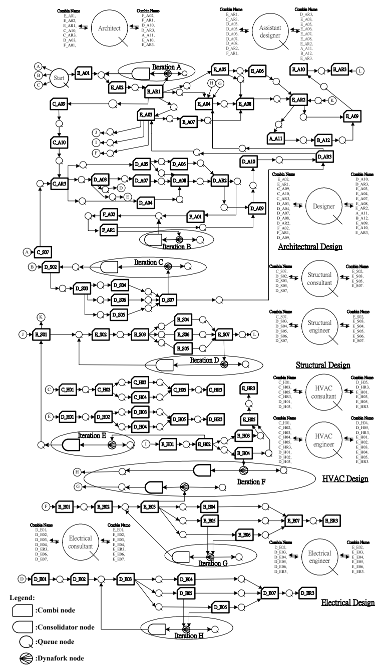

Figure 4: Simulation-Based Network of the Example Project

A base case is analyzed by assuming that each iteration (iterations A ~ H) arises for probability users set. Also, this base case includes 9 persons, one of each type of participant. In this base case, the duration of the complete design project is 468.43 hours (approximately 58.55 working days, eight hours per day). The average times spent on architectural, structural, HVAC and electrical tasks are 466.56, 297.09, 383.47 and 435.90 hours, respectively.

Table 2 provides the total cost, idle cost working and idle times of each participant involved in the example project. For instance, the idle times of the architect, the designer and the assistant designer in performing the architectural activities are 256.98, 76.69 and 165.32 hours, respectively. Thus, a design manager can assign additional design tasks (of the same project or other projects) to the architect who is very idle.

Table 2: Simulated Working Time, Idle Time, Total Cost and Idle Cost

	Working time (Hours)	Idle time (Hours)	Total cost (Dollars)	Idle cost (Dollars)
Architectural discipline			48248.29	
Architect	211.45	256.98	23421.50	12848.82
Designer	391.74	76.69	14052.90	2300.77
Assistant designer	303.11	165.32	10773.89	3802.40
Structural discipline			30916.38	
Structural consultant	221.81	246.62	18737.20	9864.99
Structural engineer	291.01	177.42	12179.18	4612.92
HVAC discipline			29511.09	
HVAC consultant	154.55	313.88	17800.34	11927.44
HVAC engineer	252.80	215.63	11710.75	5390.75
Electrical discipline			29979.52	
Electrical consultant	218.39	250.04	16863.48	9001.27
Electrical engineer	212.20	256.23	13116.04	7174.49

The original design team has 9 participants (three for Architectural design and two for other disciplines). Three other scenarios are considered to improve resource allocation strategies. Scenario-1 involves 18 persons, two of each type of participant. Similarly, scenario-2 and scenario-3 involve 27 and 36 persons, respectively; in each case, the numbers of participants of the various types are equal. Figure 5 plots the simulated project durations in the base case and three other scenarios. As expected, using more designers reduces the duration of the project because they can perform more activities simultaneously. However, allocating four participants of each type (scenario-3) is not recommended because this strategy does not further reduce the duration of the project (adding hourly costs).

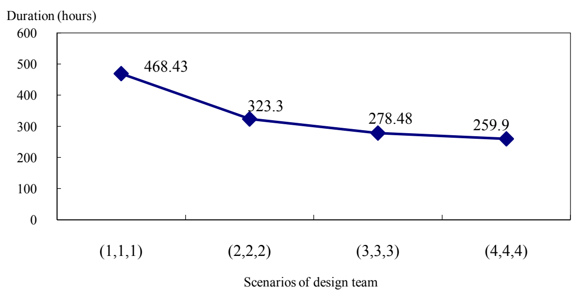

Figure 5: Project Durations under Different Design Teams

CONCLUSIONS

Design is iterative. The design schedule of one project can be difficult controlled because iterations occur and many type of design deliverables. In multiple projects, the order of projects and arrangement of manpower make the design schedule control more difficult. This studys proposes a simulation-based model to incorporate the design iterations, deliverables and participants for multi-project under uncertainty. The example project illustrates how to find how to lean the design schedule and design resources the model.

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Council of Taiwan for financially supporting this research under Contract No. NSC94-2211- E-009-038. Additionally, the authors are indebted to Mr. T.S. Liao (former graduate student of National Chiao Tung University) for providing valuable thoughts to this study.

REFERENCES

S. Austin, A. Baldwin, A. Newton, Manipulating the flow of design information to improve the programming of building design, Construction Management & Economics 12 (1994) 445-455.

S. Austin, A. Baldwin, B. Li, P. Waskett, Analytical design planning technique: a model of the detailed building design process, Design Studies 20 (1999) 279-296.

S. Austin, A. Baldwin, B. Li, P. Waskett, Analytical design planning technique (ADePT): a dependency structure matrix tool to schedule the building design process, Construction Management & Economics 18 (2000) 173-182.

Baldwin, S. Austin, T. Hassan, A. Thorpe, Planning building design by simulating information flow, Automation in Construction 8 (1998) 149-163.

Baldwin, S. Austin, T. Hassan, A. Thorpe, Modeling information flow during the conceptual and schematic stages of building design, Construction Management & Economics 17 (1999) 155-167.

P.B. Luh, F. Liu, B. Moser, Scheduling of design projects with uncertain number of iterations, European Journal of Operational Research 113 (1999) 575-592.

D.K.H. Chua, A. Tyagi, S. Ling, S.H. Bok, Process-parameter-interface model for design management, ASCE Journal of Construction Engineering and Management 129 (6) (2003) 653-663.

C.H. Chen, S.F. Ling W. Chen, Project scheduling for collaborative product development using DSM. Journal of Project Management 21 (2003) 291-299.

H.J. Choo, J. Hammond, I.D. Tommelein, S.A. Austin, G. Ballard, DePlan: a tool for integrated design management, Automation in Construction 13 (2004) 313-326.

Rivard, S.J. Fenves, A representation for conceptual design of building, Journal of Computing in Civil Engineering 14 (3) (2000) 151-159.

D.V. Steward, The design structure system: a method for managing the design of complex systems. IEEE Transactions on Engineering Management EM 78(3) (1981) 71-74.

W.C. Wang, R.J. Dzeng, Applying cluster identification algorithm and simulation to generate probabilistic network schedules for design projects, Construction Management & Economics, 23(2), (2005) 199-213.

J.C. Martinez, STROBOSCOPE: state and resource based simulation of construction Processes, PhD. Dissertation, University of Michigan, Ann Arbor, Michigan, 1996.

W.C. Wang, J.J. Liu, and T.S. Liao, Modeling of design iterations through simulation, Automation in Construction, 15(5), (2006)589-603.