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Simulation-based Scheduling Model for Multiple Design Projects Considering Uncertain Design Iterations

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Abstract
Although slightly improving the control of the design schedule may greatly reduce the total duration of the project, but little effort has been made to control the schedule of the design project. Current practice typically uses a bar chart method or a CPM network to represent the schedule of a design project. But using those methods to plan design activities is complicated chiefly because of the design activities often have different degrees of information dependencies between each other, such that the design process involves a number of iterations. This work develops a simulation-based model to incorporate the design iterations for generating the schedule of a design project. Finally, this model is implemented and demonstrated by a real case study using STROBOSCOPE, a state and resource based simulation software.

Keywords
Uncertain Design Iteration, Simulation, Design Schedule, Design Process

1. Introduction

A design firm often needs to allocate various types of design participants (such as architects, designers and draftsmen) to the multi-disciplinary activities of various design projects that are in various project stages (such as the proposal stage, conceptual/schematic design stage, detailed design stage, or construction stage). Effectively assigning the design participants depends on how the design activities are scheduled. Recently, design scheduling has been receiving much attention because the total duration of a building project is commonly delayed by the lateness of design deliverables (including design drawings, calculations and reports).

Scheduling of design activities for multiple projects is complex because design activities frequently depend differently on information about each other. Namely, the design process involves various iterations across activities (Austin et al, 1994; 1999; 2000). Moreover, the fact that the numbers of iterations and the durations of design activities are uncertain makes difficult to identify the precedence relationships among activities and to evaluate the durations of the design projects. This study develops a simulation-based scheduling model to effectively allocate design participants for multiple design projects. Particularly, simulation algorithms are proposed to model the uncertainties of design iterations and activity durations.

2. Past Research

During the conceptual and schematic design phases of a building project, a chief designer (architect/engineer or A/E) gathers 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). These two early phases ensure that the design deliverables fulfill the owner's demands. For example, Baldwin et al. (1998; 1999) developed a simulation of the information flows between the design activities involved in the conceptual and schematic phases of a building design, based on data flow diagrams and dependency structure matrix (DSM) analysis.

Wang and Dzeng (2005) applied a modified cluster identification algorithm to evaluate the dependencies of design activities on information, to enable activities to be regrouped to support the assignment of design activities. Wang et al (2006) presented causes and various types of design iterations for a building project. And an innovative simulation-based model is developed to incorporate the design iterations to generate a schedule for a design project. The model is used to assess the effect of design iterations on the duration; the idle durations of the design participants are evaluated to support the assignment of design activities.

Finally, Cho and Eppinger (2005) proposed a DSM-based process model using simulation for managing industrial design projects. The model accounts for information flows between activities, uncertain activity durations, resource conflicts, overlapping and sequential iterations, and activity concurrency. However, the allocation of different types of design participants is not explicitly incorporated in their model.

3. Proposed Model

The proposed model extends a previous study of Wang et al. (Wang et al 2006) to deal with multiple design projects, to incorporate the uncertainties of design iterations and the uncertainties of activity durations, and to offer a cost analysis. The model, developed from the perspective of a design firm, includes four major phases (Fig. 1).

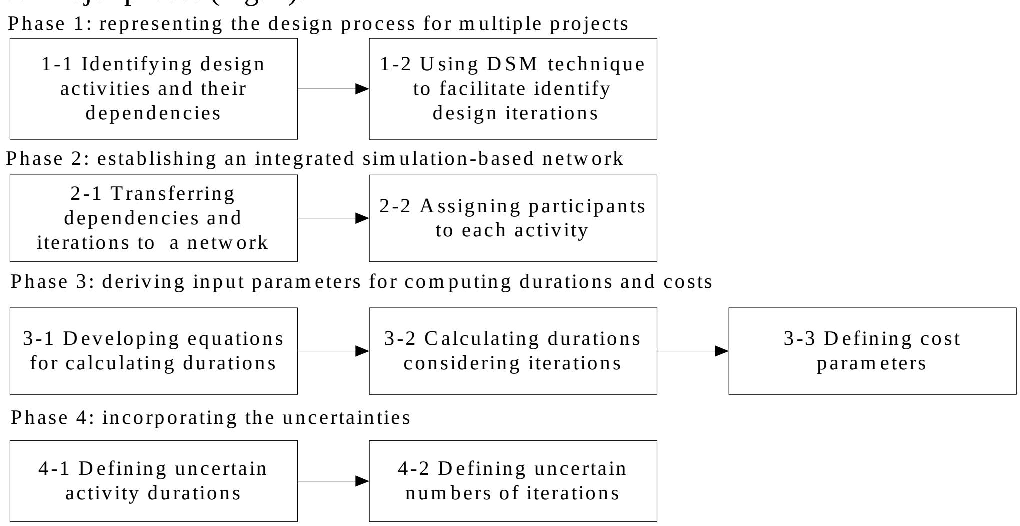

Figure 1: Proposed model

3.1 Phase I: Representing the Design Process for Multiple Projects

A common design activity usually has deliverables such as drawings, reports, and calculations. For instance, the design activities considered herein include floor plan design and exterior elevation design activities, with the deliverables "plans" and "elevations", respectively. Another type of design activity, called review/approval activity herein, does not have definite outputs and it involves in certain amount of discussions, clarifications and even revisions. A design dependency is the logical relationship between activities. The dependency between activities, A→B, demonstrates that the information flow delivers the design deliverables from A to B.

Based on the identified activities and their dependencies, DSM is applied to help identify design iterations with complete loops. Steward (1981) and many other publications provide details on the DSM methods. After iterations with complete loops have been found, the model user must explore whether incomplete design loops are present, based on past experience. (See Section 5 for examples.)

3.2 Phase II: Establishing an Integrated Simulation-Based Network

Phase I identifies dependencies and iterations. Phase II establishes a simulation-based network, and assigns design participants (such as architects, designers and assistant designers) to each activity. The proposed model uses the symbols of Stroboscope (Martinez, 1996) to represent the simulation-based network of schedule. In Stroboscope, "Combi" nodes refer to design activities that start when specific conditions are met. Each Combi node is shown with a cut at the top left-hand corner of a square box. Queue nodes hold idle design resources. Each queue (indicated by a "Q" in the network) is related to a particular class of resource. A link (→) connects two network nodes and presents the direction and type of design resources that flow through them. The node at the tail of the link is the predecessor, and that at the head (indicated by the arrow) is the successor.

This step, *assigning participants to each activity*, is to allocate the type and the number of participants (such as architect, design engineer, structural consultant, structural engineer, etc) to each activity.

3.3 Phase III: Deriving Input Parameters for Computing Durations and Costs

The first step of phase 3 is *developing equations for calculating durations*. Regarding the computations of the durations of design activities, two methods are proposed. The first method is developed to handle the common design activities that produce design deliverables, and the second method is to deal with the review/ approval activities that have no explicit design deliverables.

The second step of phase 3 is *calculating durations considering iterations*. 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.

The third step of phase 3 is *defining cost parameters*. The proposed model offers a cost analysis by assigning wage rates (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.

3.4 Phase IV: Incorporating the Uncertainties

The first step of phase is *defining uncertain activity durations*. In computing the duration of activity i (i.e., ($D_{i(0)}$)), the quantity of required deliverables (Q_i) is assumed to be certain. However, the value of design productivity (P_{ij}, hour per unit) is assumed to be probabilistic. The proposed model uses three-point estimates (optimistic, most likely, and pessimistic unit rates) to obtain a Beta distribution for the productivity for each participant j in each activity i. Notably, various participants with different degrees of productivity are involved in completing the drawings of an activity.

The second step of phase 4 is *defining uncertain numbers of iterations*. In the design process, a certain amount of design information may flow among activities several times until design deliverables are compatible or regulatory requirements are met. Whether an iteration with a complete or incomplete loop will arise is assumed to be probabilistic. The model also applies three-point estimates (lowest, most likely, and highest probabilities; between 0 and 1) to obtain a Beta distribution for the occurrence of an iteration loop x. A random variable ($Occur_x$) for each iteration loop is devised. For example, the model user may specify that the lowest, most likely, and highest probabilities for the occurrence of an iteration loop x are 0.2, 0.4, and 0.6, respectively. Then, in each simulation run, a value will be drawn from the distribution (0.2, 0.4, 0.6) to represent the probability that iteration loop x will occur.

Additionally, the value of $IterDR_i$ (the fraction of the developed drawings associated with activity i that must be reworked at an iteration) is also treated as an uncertain variable. Again, the model utilizes three-point estimates (lowest, most likely, and highest fractions; between 0 and 100%) to obtain a Beta distribution for indicating the fraction (or percentage) of $IterDR_i$.

4. Implementation

A simulation language, Stroboscope (Martinez, 1996), is adopted to implement the simulation-related algorithms in the proposed model. Stroboscope automatically generates most of the output variables (called system-maintained variables). 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. Five thousand simulations runs took under one minute for the example project.

5. Examples

5.1 Project description

A medium-size architectural design firm that is located in northern Taiwan is used for demonstrating the proposed model. This firm must handle six design projects in two months (i.e., about 60 days or 480 working hours). These design projects are related to 10~12-floor office buildings. Projects A, B and F are in construction phase and require certain design work caused by owner-directed change orders. Project C, D and E are in the construction tendering phase (i.e., design drawings have been finished and a tendering package must be prepared for selecting a contractor), conceptual design phase, and detailed design phase, respectively. Notably, the design work of these six projects involves four design disciplines - architectural, structural, HVAC and electrical. The design firm (A/E) designs the architectural part and subcontracts out the rest of the work to three outside specialty design firms.

5.2 Inputs

First, the design activities and their dependencies must be identified (Step 1-2). 79 activities are indicated in six projects. There are 1, 1, 10 (8 common activities and 2 review/approval activities), 30 (26 common activities and 4 review/approval activities), 34 (29 common activities and 5 review/approval activities), and 3 activities (2 common activities and 1 review/approval activity) are identified for projects A, B, C, D, E, and F, respectively. Four different disciplines perform these 79 activities.

The input data for structural, HVAC, and electrical design can also be provided in a similar manner. (These data are not displayed here due to the limitation of paper length.) Additionally, nine design participants are assumed to work on these projects. Table 1 displays the number and wage rate (US dollars per person per hour) for each participant. (Step 3-3)

5.3 Evaluations

Based on the identified precedence relationships between activities, the DSM is applied to search for iterations with a complete loop (Step 1-3). For example, Figure 2 presents the partitioned matrix for project E. 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 34 activities of project E contribute to three iterative loops (iterations R, Y, and U with complete loops).

There are eight iterations (iterations R, S, T, U, V, W, Y, and Z) in the six projects. Six iterations (R, S, T, U, Y, and Z) with complete loops are identified by DSM, while two iterations (V and W) with incomplete loops are indicated by the model user.

Table 1: Number of persons and wage rate of each design participant

Participants	Number of persons	Wage rate (US dollar / hour - person)
Architectural discipline		
Architect	1	50
Designer	1	30
Draftsman	1	23
Structural discipline		
Structural consultant	1	40
Structural engineer	1	26
HVAC discipline		
HVAC consultant	1	38
HVAC engineer	1	25
Electrical discipline		
Electrical consultant	1	36
Electrical engineer	1	28

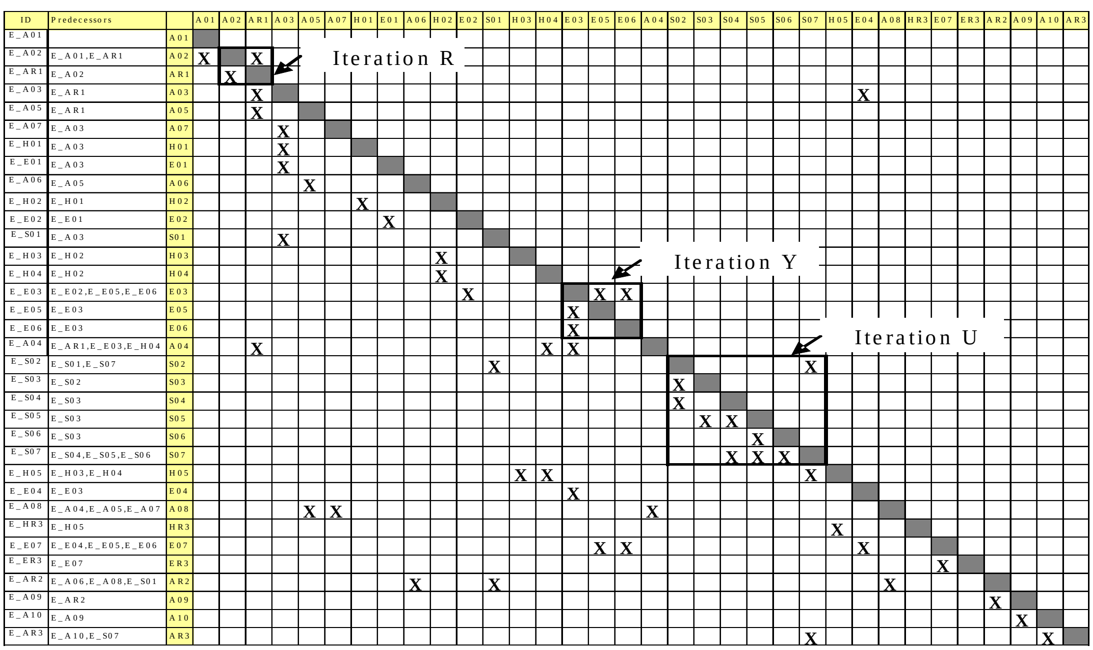

Figure 2: Three iterations identified by DSM in project E

Figure 3 depicts the established simulation-based network for the six design project (Step 2-1). 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, eight Dynafork nodes (each represented by a cycle enclosing five rays) that have routing capabilities for activating downstream activities control the occurrence of the eight iterations. All small Queues shown in the network are used only to control the resource flows.

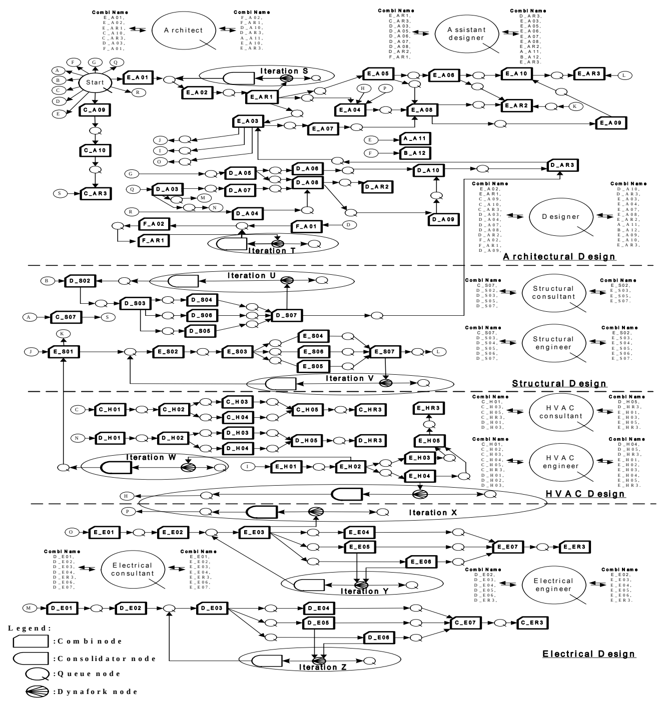

Figure 3: Simulation-based network of the six projects

5.4 Results

By assuming that one of each type of participant is present and simulation is run for 5,000 times, the duration of the design work of six projects is 466.6 hours (approximately 58.3 working days, eight hours per day). The simulation enables the model to evaluate the utilization rates of the participants (stored in Queues). Table 2 provides the working time, idle time, total cost and idle cost of each design participant involved in the six projects. For instance, the idle times of the architect, the designer and the draftsman in performing the architectural activities are 257.0, 76.7 and 165.3 hours, respectively. Thus, a design manager may assign additional design activities (of the same project or other projects) to the architect who is very idle.

Table 2: Working time, idle time, total cost and idle cost of each design participant

	Working time (Hours)	Idle time (Hours)	Total cost (Dollars)	Idle cost (Dollars)
Architectural discipline			48,248	
Architect	211.5	257.0	23,422	12,849
Designer	391.7	76.7	14,053	2,301
Draftsman	303.1	165.3	10,774	3,802
Structural discipline			30,916	
Structural consultant	221.8	246.6	18,737	9,865

Structural engineer	291.0	177.4	12,179	4,613
HVAC discipline			29,511	
HVAC consultant	154.6	313.9	17,800	11,927
HVAC engineer	252.8	215.6	11,711	5,391
Electrical discipline			29,980	
Electrical consultant	218.4	250.0	16,864	9,001
Electrical engineer	212.2	256.2	13,116	7,175

Also the consideration of iteration has increased the expected duration from 426.3 to 466.6 hours for the example project. The increase is about 40.3 hours (=466.6-426.3) or 9.5% (=40.3/426.3). Additionally, using the 2 months (480 hours) as the deadline, the probability of meeting that deadline is about 66.4% (considering iterations).

6. Conclusion

This work devises a new model to generate schedules for multiple design projects. The model incorporates the DSM technique to facilitate identify design iterations with complete loops. Then, the model user needs to indicate whether incomplete design loops are present. The interrelationships among activities and the competitions of design participants are captured using a simulation-based network. With the support of simulation technique, the model also considers the uncertainties on the durations of design activities and the occurrences of iterations for evaluating the risk of completion durations of design projects. Moreover, cost information with respect to different project durations can allow a trade-off analysis between the cost and time.

7. References

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