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Modeling of design iterations through simulation

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Abstract

Enhancing the scheduling of a design project can markedly reduce its total duration. However, accurately representing the schedule of a design project is complex, largely owing to that design activities generally depend on information about each other. That is, the design process involves many iterations across activities. Iterative dependency makes difficult defining the logical relationships among activities in the network and evaluating the duration of the project. This work applies a dependency structure matrix to identify design dependencies. Causes and various types of design iterations for a building project are presented. Additionally, an innovative simulation-based model is developed to incorporate the design iterations, deliverables and participants for generating a schedule of a design project. The proposed model can not only assess how design iterations affect the duration, but also evaluate the idle durations of the design participants to support the assignment of design tasks. Effectiveness of the model is demonstrated through its application to an example project.

Keywords: Design iteration; Design schedule; Design process; Dependency structure matrix; Simulation

1. Introduction

Constructing a building involves design tasks and construction tasks. Both practitioners and researchers have paid increasing attention to the control of the schedule of design work, because construction is commonly delayed by the lateness of design deliverables (including drawings, calculations and reports). Research has indicated that about one third of public and private architect/engineer projects exceed their budgets and fail to keep to their target schedules because of some design-related problems [1]. A survey has also shown that a successful design process is a key to the success of projects in the UK [2]. Difficulties in scheduling remain the major problem in managing design [3,4].

Current practice uses the bar chart method to represent the schedule for design work, which comprises multi-disciplinary design activities. Each bar covers several months and represents a design activity. Some responsible design managers may identify points of expected percentage completion (such as 25%, 50%, 75% and 100%) or control points (for example, drawing is begun; drawings are ready for review by engineers, and readiness for bid/construction) as milestones associated with each design activity. Unfortunately, the bar chart is not sufficiently detailed to detect schedule slippage in a design activity a timely manner.

The critical path method (CPM) of network analysis is also a technique for scheduling design activities [5]. However, performing CPM analysis in design projects is difficult because design activities often have information dependencies between each other. Namely, the design process involves various iterations across activities [6–15]. Such iterative information dependency makes defining the logical relationships among activities in the CPM network and evaluating the duration of design project difficult.

Design work involves the generation of a variety of deliverables and the allocation of interested parties (such as the architect, the structural designer, and the electrical designer). However, current models often do not explicitly incorporate design deliverables and participants in their scheduling process. This investigation proposes a simulation-based model to incorporate the design iterations, deliverables, and participants for generating the schedule of a design project. The methodology employed in this study consists of the following stages. First of all, previous studies are reviewed. Next, the characteristics of design iterations are elucidated, and the proposed model is developed. The operation of the model is

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then demonstrated by applying it to an example project. Finally, several lessons learned from this work are summarized and future research directions are indicated.

2. Review of research

During the conceptual and schematic design phases of a building project, a chief designer (architect/engineer or A/E) captures 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 [10,16]. The two early phases attempt to 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 controlling the duration of these two early phases.

In the detailed design phase, the required design work is explicitly stated; the design deliverables must be delivered to prevent future construction work from being delayed. Much research has been done to improve the control of the detailed design process, increasing the effectiveness of the control of the design duration. For instance, Sanvido and Norton [17] proposed a building design process model that specified the keys that are required in a successful design. Their model also identified the flow of information and knowledge that supports the development of a design. Some researchers have addressed design process problems in a collaborative environment, including, for example, miscommunication among designers and incompatibility among design deliverables caused by changes in the design [18–21].

Chang [22] presented performance indices of whether a design project is ahead of or behind schedule, by comparing planned and actual design man-hours. Such schedule indices are most useful at the level of the overall project, but they do not provide detailed information about the scheduling of design activities. With reference to the uncertainty in the number of iterations associated with design activities, Luh et al. [11] developed an optimization-based method to schedule the design of a manufacturing project.

Steward [23] considered design iterations and defined possible relationships between a pair of design tasks—dependent (serial or sequential), independent (parallel or concurrent) and interdependent (coupled). Austin et al. [6–8] elucidated a planning methodology (Analytical Design Planning Technique; ADePT) for planning building design. The core of ADePT is the dependency (or design) structure matrix (DSM) analysis that helps to order the design tasks into the optimal sequence, to minimize the number of iterations in the multi-disciplinary design process. ADePT is now used commercially, with its own web-based software applications. Furthermore, an Internet-based framework, called the process-parameter-interface (PPI) model, was developed to address the design management issues associated with improving design process scheduling and increasing the efficiency of collaboration, with a view of design as a flow of information (that is, from the parameter perspective) [12].

Baldwin et al. [9,10] 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 (DFDs) and DSM. This model was concerned with the exchange of information required for members of design teams to complete their activities. DFDs were employed to identify interdependencies between different design activities and their information requirements. Simulation enabled the impact of design changes, such as a change in client requirements, a delay in design approval and a change in the availability of resources, to be evaluated.

Wang and Dzeng [24] 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 tasks. Eventually, a CPM-based schedule network was established for a design project. The model of Wang and Dzeng simplified the effect of the duration of design iterations by specifying a duration distribution for each design activity, based on a three-point estimate of duration using the Program Evaluation Review Technique. The pessimistic duration of each activity was increased to cover the possible consequences of the effects of the iterations.

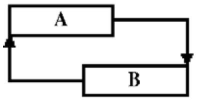
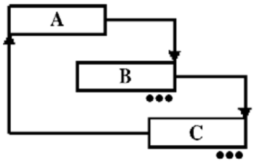
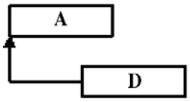
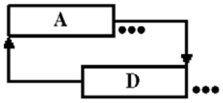
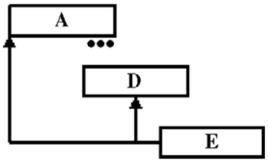
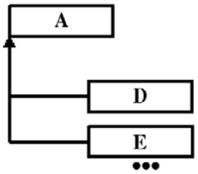
Many design process models were presented to handle each design characteristic (including dependency on information, design iterations and the collaborative environment) using various methods to improve design management [25]. However, available models do not explicitly and simultaneously consider design iterations, deliverables and participants in scheduling.

3. Design iterations

Design is iterative. Design iterations influence the capacity to evaluate exactly the duration of a design project [6,7,8]. 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.

Design iterations may be implemented by the staff of a single design firm or among various firms. An intra-iteration and inter-iteration occur among the activities conducted by each design firm and different design firms, respectively. A multi-iteration arises among the activities executed by several design firms. The existence of design iterations reveals that sequences of activities are not one-way progressions along

Table 1
Typical examples of design iteration

Type of iteration	Illustration of dependencies among activities	Description
Simple intra-iteration (Type 1)		● Iteration arises between two activities conducted by a single design firm. ● A complete loop.
Complex intra-iteration (Type 2)		● Iteration arises among at least three activities conducted by a single design firm. ● A complete loop.
Simple inter-iteration (Type 3)		● Iteration arises between two activities undertaken by various design firms. ● The iteration occurs when the downstream activity D causes the upstream activity A to be partially reworked. ● An incomplete loop.
Complex inter-iteration (Type 4)		● Iteration arises between two activities undertaken by different design firms. ● Activities A and D depend on each other; each may have its own successors. ● A complete loop.
Multi-iteration 1-to-N (Type 5)		● Iteration arises among numerous activities performed by different design firms. ● The iteration occurs when the downstream activity E causes the N upstream activities (A,D and others) to be partially reworked. ● An incomplete loop.
Multi-iteration N-to-1 (Type 6)		● Iteration arises among numerous activities performed by various design firms. ● The iteration occurs when the N downstream activities (D, E and others) causes the upstream activity A to be partially reworked. ● An incomplete loop.

paths. Table 1 displays six typical types of design iteration—simple intra-iteration (Type 1), complex intra-iteration (Type 2), simple inter-iteration (Type 3), complex inter-iteration (Type 4), multi-iteration 1-to-N (Type 5) and multi-iteration N-to-1 (Type 6).

An iteration can be a complete loop (such as Type 1, Type 2 and Type 4) or an incomplete loop (such as Type 3, Type 5 and Type 6). A complete design loop exists when the involved activities are interdependent. An incomplete design loop applies when downstream activities (such as activity D in Type 3; E in Type 5; D and E in Type 6) necessitate the reworking of upstream activities. Notably, an iteration can combine the various typical iterations presented in Table 1.

4. Proposed model

The proposed simulation-based model for establishing a schedule of a design project comprises four modeling phases (Fig. 1)—representing the design process (Phase I), establishing a simulation-based network (Phase II), identifying input parameters (Phase III), and selecting output variables and running the simulation (Phase IV). The following sections illustrate the details of each phase.

4.1. Phase I: representing the design process

Two steps are implemented in this phase- identifying design activities and their dependencies, and applying DSM to facilitate the identification of design iterations.

4.1.1. Identifying design activities and their dependencies

A design activity herein must have a deliverable. An activity is a functional primitive task that produces specific information requirements of design [9]. For instance, the design activities considered herein include floor plan design and exterior elevation design activities, with the deliverables “plans” and “elevations”, respectively. The high-level activities, such as developing and coordinating design concepts, do not involve definite outputs and therefore are not considered in this investigation. 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.

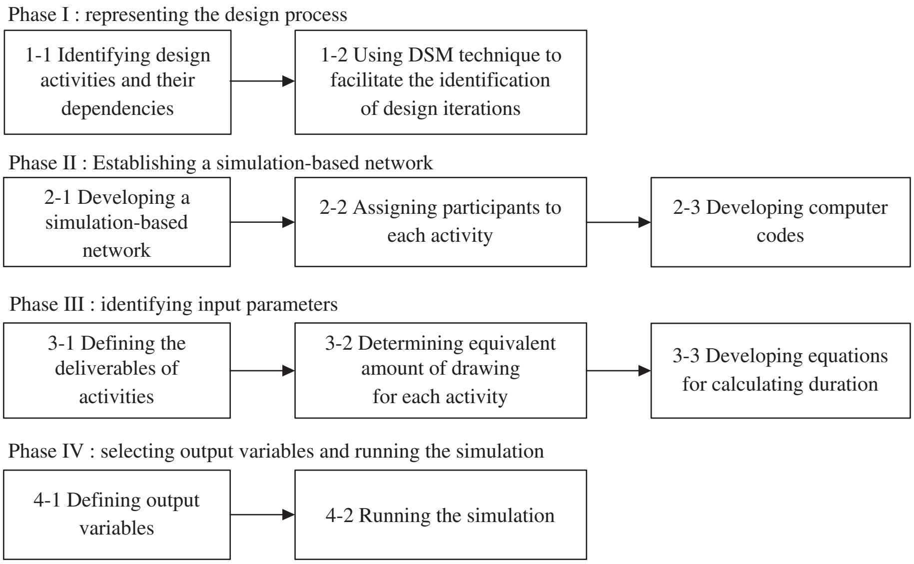


Fig. 1. Modeling steps for developing design schedule.

4.1.2. Applying DSM to facilitate the identification of design iterations

Based on the identified activities and their dependencies, DSM is applied to help identify design iterations with complete loops. DSM has its own web-based software applications (refer to http://www.dsmweb.org/). Steward [23] 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 (such as Type 3, Type 5, and Type 6) are present, based on past experience. (See Section 5 for examples.)

4.2. Phase II: establishing a simulation-based network

Phase I identifies dependencies and iterations. Phase II establishes a simulation-based network, assigns design participants (such as architects, designers and assistant designers) to each activity, and develops computer codes. A simulation language, Stroboscope [26] (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 applying the Stroboscope to the model, "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. Martinez detailed the Stroboscope method [26]. This phase generates a simulation-based network that consists of numerous nodes and links in a design project.

4.3. Phase III: identifying input parameters

This phase identifies input parameters for evaluating the duration of each activity. These inputs are the type and number of deliverables required for each activity, and the type and number of participants involved in each activity.

4.3.1. Defining the deliverables of activities

The deliverables associated with a design activity can be sketches, 3D models, specifications, photographs, reports, calculations and proposals. Most of these deliverables are used to help various participants to communicate with each other. In this work, the design deliverables are classified according to AIA (American Institute of Architects) standard practice [27] and uniform drawing formats [28]. That is, the design deliverables addressed herein include the plans, details, elevations, sections, reports and calculations. The left of Table 2 presents the types of deliverable in the architectural, structural, HVAC and electrical disciplines.

4.3.2. Determining equivalent amount of drawing for each activity

The deliverables of activities may vary. The proposed model transfers the workload related to generating different deliverables into a single workload for producing the corresponding number of drawings. Thus, the simulation can be performed using uniform design drawings. Additionally, the number of uniform drawings transferred from each activity will be further modified to an equivalent number of drawings by considering the various degrees of work complexity in generating different kinds of deliverable.

4.3.2.1. Number of transferred drawings. A set of mini mock-up drawings is utilized to draft the required design deliverables and determine the number of drawings associated with each design activity [27,28]. A set of mini mock-up drawings is a deliverable of the schematic design phase; the outline, shape,

Table 2
Types of deliverables and conversion factors associated with various design disciplines

Discipline	Type of deliverable	Conversion factor
Architectural	Plan (PLA)	1.2
	Details (DET-A)	1
	Elevation (ELE)	0.85
	Section (SEC)	0.97
	Report (REP)	0.6
Structural	Calculation (CAL-S)	1.25
	Framing plan (FRA)	0.85
	Beam details (BEA)	0.8
	Column details (COL)	1
	Slab details (SLA)	0.8
HVAC	Calculation (CAL-H)	1.15
	Air duct plan (AIR)	0.80
	Water piping plan (WAT)	0.85
	Details (DET-H)	0.8
Electrical	Calculation (CAL-E)	1.15
	Lighting fixture plan (LIG)	0.60
	Emergency lighting plan (EME)	0.8
	Exhaust duct plan (EXH)	0.7
	Details (DET-E)	0.7

plan, number of floors, and several sections (viewed from east, west, south, north and other directions) of a building are sketched. Such sketches are not of detailed design elements, such as the locations and numbers of windows and doors.

Fig. 2 shows an example of a mini mock-up drawing [27]. Parts 1, 2, 3 and 4 in Fig. 2 display the outline, a bird's eye view, the sections (viewed from four directions) and the number of floors of a building, respectively. Part 5 of the figure depicts the parts of the vertical-section and horizontal-section drawings that have to be developed. For example, the area in Part 2 (the bird's eye plan) can be considered to estimate the number of sheets of paper of a specific size (given a particular drawing scale) required to present the details of the plan of the building.

Then, the estimated number of drawings associated with an activity is transferred to a standard number, which is determined by the size of the paper required for a reference activity (such as drawing an architectural floor plan). (The number of drawings associated with the reference activity is one.) Accordingly, the number of transferred drawings associated with activity i, TQ_i, is given by,

$$\mathrm{TQ}_i = \sum_{j=1}^{J}\left(B_{i(j)} \times \frac{\mathrm{Size}_{i(j)}}{\mathrm{Size}_\mathrm{s}} \times \left(\frac{\mathrm{Scale}_{i(j)}}{\mathrm{Scale}_\mathrm{s}}\right)^2\right) \tag{1}$$

where j is the size of the paper. $B_{i(j)}$ represents the number of sheets of type j required for activity i. $\mathrm{Size}_{i(j)}$ and $\mathrm{Scale}_{i(j)}$ are the size and scale of the paper of type j for activity i, respectively. Size_s and $\mathrm{Scale}_\mathrm{s}$ are the standard paper size (effective drawing size) and the standard scale for the reference activity, respectively. Notably, this study assumes that an experienced A/E can directly estimate a value of TQ_i that represents a deliverable that is either a calculation (CAL) or a report (REP).

For instance, suppose that the standard scale of a drawing is 1/100 ($\mathrm{Scale}_\mathrm{s}$), and the standard paper size (Size_s) is 720 cm^2 (36 cm × 20 cm). Assume that the estimated number of sheets required for an activity (say, designing the wall sections) are $B_{i(j1)}=1$, $\mathrm{Size}_{i(j1)}=36\times 7\ \mathrm{cm}^2$, $\mathrm{Scale}_{i(j1)}=1/100$; $B_{i(j2)}=3$, $\mathrm{Size}_{i(j2)}=10\times 7\ \mathrm{cm}^2$, $\mathrm{Scale}_{i(j2)}=1/100$, and $B_{i(j3)}=3$, $\mathrm{Size}_{i(j3)}=1.2\times 7\ \mathrm{cm}^2$, $\mathrm{Scale}_{i(j3)}=5/100$. Hence, the number of transferred drawings for the wall section design activity is

$$\begin{aligned}\mathrm{TQ}_i = {} & \left[1 \times \frac{36\times 7}{720} \times \left(\frac{1/100}{1/100}\right)^2\right] \\ & + \left[3 \times \frac{10\times 7}{720} \times \left(\frac{1/100}{1/100}\right)^2\right] \\ & + \left[3 \times \frac{1.2\times 7}{720} \times \left(\frac{5/100}{1/100}\right)^2\right] = 1.52.\end{aligned} \tag{2}$$

4.3.2.2. Conversion factor. A conversion factor (CF) specifies how much more or less difficult a drawing is to draw than

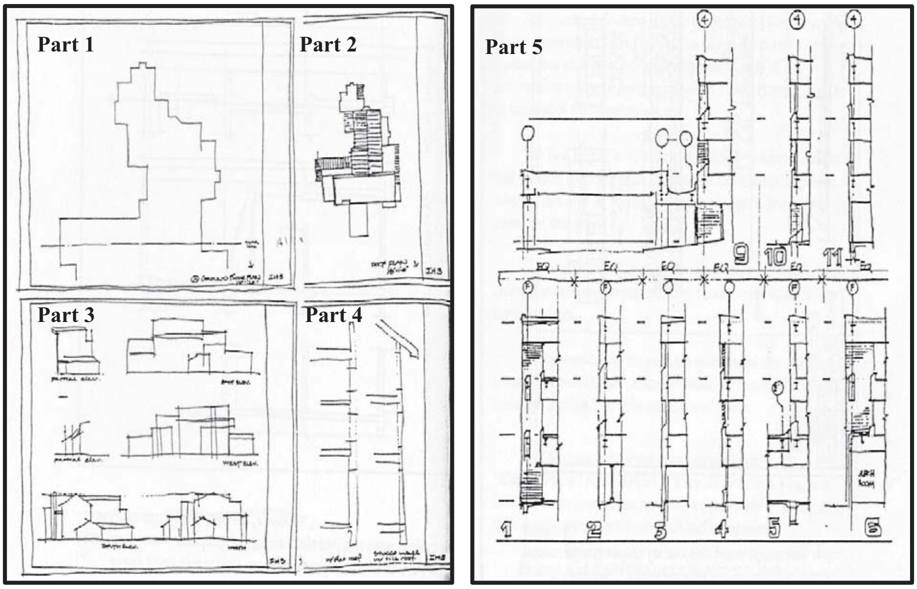


Fig. 2. Example of a set of mini mock-up drawings [27].

is the standard drawing. The most accurate estimate of the conversion factors of each type of deliverable for each discipline is determined by the measured data; however, very many data are required. In this work, the architectural details (DEL) design drawing is taken as the standard drawing (for which CF = 1.0). Then, the conversion factors associated with other types of drawing are estimated from the design productivity data provided by Thomas et al. [29] and modified by interviewing two architects who are familiar with building design. Table 2 provides current CF data.

4.3.2.3. Equivalent amount of drawing. The equivalent amount of drawing for each activity is the number of transferred drawings multiplied by a conversion factor. The equivalent amount of drawing associated with activity i, EQ_i, is given as follows,

$$\mathrm{EQ}_i = \mathrm{TQ}_i \times \mathrm{CF}_i \tag{3}$$

where CF_i is the conversion factor that corresponds to the type of deliverable for activity i. For instance, the TQ_i of the aforementioned example activity is 1.52 sheets. $\mathrm{CF}_i = 0.97$, based on the assumption that the deliverable for the activity is SEC (section). (See Table 2.) Then, the EQ_i of the activity is $1.52 \times 0.97 = 1.47$ (sheets).

4.3.3. Developing equations for calculating duration

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 equivalent amount of drawing, the time (dd_i) required to process the received and the to-be-delivered deliverables, and the time ($\sum_{n=1}^{N} \mathrm{IterD}_{i(n)}$) required to rework drawings due to iterations. That is,

$$D_{i(n)} = d_i + \mathrm{dd}_i + \sum_{n=1}^{N} \mathrm{IterD}_{i(n)}. \tag{4}$$

4.3.3.1. Time taken to develop equivalent amount of drawing (d_i). The time required to develop drawings for an activity is the equivalent amount of drawing multiplied by the design productivity. The productivity of the development of the drawings is measured in terms of unit rate (h/sheet). Various participants with different degrees of productivity are involved in completing the drawings of an activity. Hence, the productivity associated with the activity is weighted according to the percentages of the work done by each participant. The weighted unit rate for activity i, $\mathrm{WeightUR}_i$, is

$$\mathrm{WeightUR}_i = \sum_{p=1}^{P} \left(\mathrm{UR}_{i(p)} \times \mathrm{Ratio}_{i(p)}\right) \tag{5}$$

where $\mathrm{UR}_{i(p)}$ and $\mathrm{Ratio}_{i(p)}$ are the unit rate and proportion of activity i completed by participant p, respectively. Consider for example, the abovementioned activity (wall section design). Suppose three participants are involved in designing the activity—an architect, a designer, and an assistant designer. The participation proportions and productivity of these participants are (10%, 60%, 30%) and (8 h/sheet, 10 h/sheet, 15 h/sheet), respectively. Then, $\mathrm{WeightUR}_i = (10\% \times 8) + (60\% \times 10) + (30\% \times 15) = 11.3$ h/sheet.

The time taken to complete the drawing for activity i, d_i, is defined as,

$$d_i = \mathrm{EQ}_i \times \mathrm{WeightUR}_i. \tag{6}$$

For example, the time required to complete the drawing for example activity (d_i) = 1.47 (sheet) × 11.3 h (h/sheet) = 16.66 h.

4.3.3.2. Time taken to process the received and to-be-delivered deliverables (dd_i). In completing the drawings associated with an activity i, participants must take time to digest and clarify the deliverables received from the activities that precede activity i. After the drawings for activity i have been completed, a certain period is required to synthesize the drawings and then deliver them with official documents to those involved in subsequent activities. 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. For instance, dd_i for the example activity (wall section design) might be 4 h because deliverables of this activity commonly are passed only within an architectural firm. The value dd_i for an electrical activity (such as making calculations that pertain to the electrical switchgear) may be large, say, 8 h, because this activity involves deliverables from other disciplines.

4.3.3.3. Time taken to rework drawings due to iteration ($IterD_{i(n)}$). When an activity is iterated, some of the developed drawings associated with the activity must be reworked or modified [13]. 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 drawings can be reworked. Therefore, the period required to rework drawings because of the nth iteration ($n = 1$ to N) for activity i, $\mathrm{IterD}_{i(n)}$, is

$$\mathrm{IterD}_{i(n)} = \mathrm{IterDR}_i^n \times D_{i(0)} + \left(l_{i(n)} \times \frac{\mathrm{IntraD}_i}{2^{n-1}}\right) + \left(m_{i(n)} \times \frac{\mathrm{InterD}_i}{2^{n-1}}\right) + \left(r_{i(n)} \times \frac{\mathrm{MultiD}_i}{2^{n-1}}\right) \tag{7}$$

where IterDR_i is the fraction of the developed drawings associated with activity i that must be reworked at each iteration. For example, IterDR_i can be 20%, 40% or 80%. $D_{i(0)}$ is the time taken to complete an activity i without iterations; that is, $D_{i(0)} = d_i + \mathrm{dd}_i$. (See Eq. (4).) $l_{i(n)} = 1$ 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. $\mathrm{IntraD}_i/2^{n-1}$, $\mathrm{InterD}_i/2^{n-1}$ or $\mathrm{MultiD}_i/2^{n-1}$ 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, $\mathrm{IntraD}_i < \mathrm{InterD}_i <$ MultiD$_i$ is expected. Additionally, using IntraD$_i$/2^{n-1} assumes that the time required for communication for the second intra-iteration (n=2) is half of the time for the first intra-iteration (n=1). This is similar to the InterD$_i$/2^{n-1} and MultiD$_i$/2^{n-1} cases. Using the value of 2^{n-1} (instead of 3^{n-1} or others) is suggested based on the field experience of the aforementioned two architects. Future research should accumulate field data to verify the value of 2^{n-1}.

4.3.3.4. Example of calculations of $D_{i(n)}$. For the aforementioned activity (wall section design), suppose that an intra-iteration occurs and this iteration is repeated twice. Assume that dd_i=4 h; IterDR_i=80%, and IntraD_i=4 h. Notably, $l_{i(1)}$ = 1 and $m_{i(1)}$=$r_{i(1)}$ =0 in this example. Also, the previous example reveals that d_i=16.66 h. $D_{i(0)}$=d_i+dd_i=16.66+4=20.66 h. Hence, the duration required for reworking due to the first iteration (n=1) associated with the activity, $\mathrm{IterD}_{i(1)}$, is

$$\mathrm{IterD}_{i(1)} = \mathrm{IterDR}_i^1 \times D_{i(0)} + \left(l_{i(1)} \times \frac{\mathrm{IntraD}_i}{2^{n-1}}\right) + \left(m_{i(1)} \times \frac{\mathrm{InterD}_i}{2^{l-1}}\right) + \left(r_{i(1)} \times \frac{\mathrm{MultiD}_i}{2^{l-1}}\right) \tag{8a}$$

$$= 0.8^1 \times 20.66 + \left(1 \times \frac{4}{2^0}\right) + \left(0 \times \frac{\mathrm{InterD}_i}{2^0}\right) + \left(0 \times \frac{\mathrm{MultiD}_i}{2^0}\right) \tag{8b}$$

$$= 0.8 \times 20.66 + (1 \times 4) = 20.53 \text{ h}. \tag{8c}$$

Then, the time taken to complete the activity with one iteration is $D_{i(1)}$=d_i+dd_i+$\mathrm{IterD}_{i(1)}$ =$D_{i(0)}$ +$\mathrm{IterD}_{i(1)}$ =20.66+20.53=41.19 h. The time required to rework in the second iteration (n=2) for the activity, $\mathrm{IterD}_{i(2)}$, is

$$\mathrm{IterD}_{i(2)} = \mathrm{IterD}R_i^2 \times D_{i(0)} + \left(l_{i(2)} \times \frac{\mathrm{IntraD}_i}{2^{2-1}}\right) + \left(m_{i(2)} \times \frac{\mathrm{InterD}_i}{2^{2-1}}\right) + \left(r_{i(2)} \times \frac{\mathrm{MultiD}_i}{2^{2-1}}\right) \tag{9a}$$

$$= 0.8^2 \times 20.66 + \left(1 \times \frac{4}{2^1}\right) + \left(0 \times \frac{\mathrm{InterD}_i}{2^1}\right) + \left(0 \times \frac{\mathrm{MultiD}_i}{2^1}\right) \tag{9b}$$

$$= 0.8^2 \times 20.66 + (1 \times 2) = 15.22 \text{ h}. \tag{9c}$$

Then, the time taken to complete the activity with two iterations using Eq. (4) is $D_{i(2)}$=d_i+dd_i+$\mathrm{IterD}_{i(1)}$+$\mathrm{IterD}_{i(2)}$=20.66+20.53+15.22=56.41 h.

4.4. Phase IV: selecting output variables and running the simulation

All the above-mentioned input parameters and derived equations must be suitably coded using Stroboscope statements. Stroboscope automatically generates most of the output variables (called system-maintained variables) [26]. 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 1 min for the example project.

5. Example

5.1. Project description

The example project is to design an auxiliary space next to an existing factory building in the science-based industrial park in northern Taiwan. According to the A/E's schematic plans, this auxiliary space includes a cafeteria, a mechanical room, an electrical room and a rest room. Fig. 3 presents the floor plan for the project. Fig. 4 shows the sections of the mechanical room and the cafeteria. The project involves four design disciplines—architectural, structural, HVAC and electrical. The A/E designs the architectural part and subcontracts out the rest of the work to three outside professional design firms.

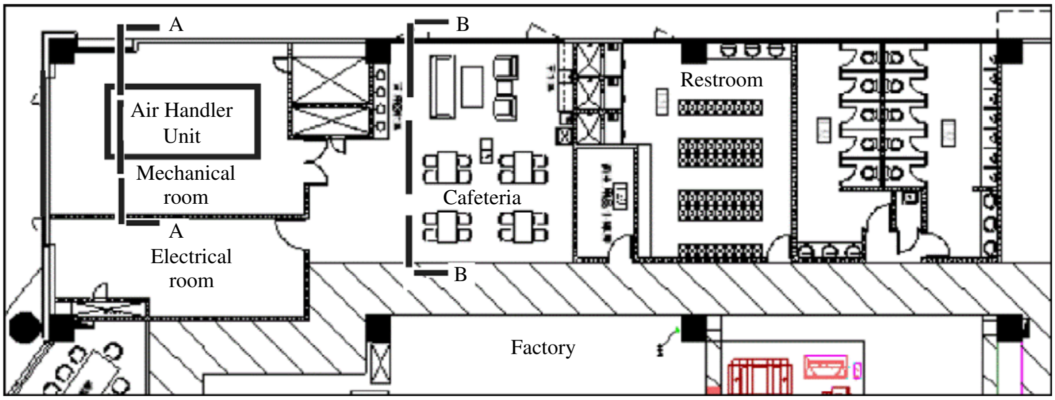


Fig. 3. Floor plan of the example project.

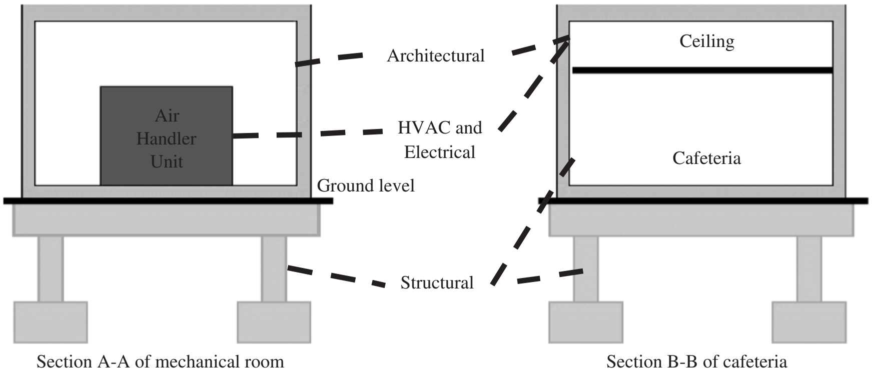


Fig. 4. Sections of mechanical room and cafeteria in the example project.

The architectural design involves developing a floor plan, door and window plans, furniture details and other interiors. The structural design involves structural calculations for designing columns, beams and slabs. The HVAC design involves HVAC calculations and the design of AHU (Air Handler Unit) equipment and supply and return water piping. The electrical design involves switchgear calculations and the design of light fixtures, smoke detectors and emergency exhaust ducts. The A/E who controls the entire design duration designs the floor plan and exterior elevations (activities A1 and A2) first, such that the design deliverables of activities A1 and A2 can be used in the subsequent activities (including those subcontracted to external firms). When all the activities have been completed, the A/E will require around 8 h to complete all of the design work (the end of which is represented by an End activity). The following sections detail the inputs, evaluations and results of generating the design schedule for the example project.

5.2. Inputs

Table 3 lists the 31 identified design activities, including 11 activities (A1–A10 and End) of architectural design, seven activities (A11–A17) of structural design, six (A18–A23) of HVAC design, and seven (A24–A30) of electrical design. The right of Table 3 presents the predecessors of each activity.

Table 4 presents the required model inputs for scheduling the design project. These inputs include the type of deliverable, the number of transferred drawings (TQ_i), the conversion factor (CF_i), the participation ratio ($Ratio_{i(p)}$) and the time required to process the deliverables (dd_i) for each activity. For instance, the types of deliverables, TQ_i, CF_i and dd_i for activity A3 (wall sections design) are SEC (section), 1.52 sheets, 0.97, and 4 h, respectively. Also, the $Ratio_{i(p)}$ values for the architect, the designer and the assistant designer, who are responsible for A3 are 10%, 60% and 30% respectively. Table 5 lists the 12 participants involved in the four disciplines. An architect, a designer and an assistant designer are responsible for performing the architectural work. Table 5 also shows the unit rate ($UR_{i(p)}$) per person for each type of participant.

5.3. Evaluations

Fig. 5 presents the partitioned matrix for the example project obtained by applying the DSM algorithms. Each "X" in the matrix indicates that the activity on the left-hand side depends

Table 3
Description and predecessors of each activity in the example project

ID	Activity	Predecessors
Architectural design		
A1	Floor plan design	
A2	Exterior elevations design	A1,A3
A3	Wall sections design	A2
A4	Ceiling plan design	A2,A21,A26
A5	Restroom details design	A3
A6	Door and window details design	A5
A7	Cafeteria furniture design	A3
A8	Interior elevation design	A4, A5, A7
A9	Construction details design	A8
A10	Architectural design review	A6, A9
Structural design		
A11	Structural calculations	A2,A19
A12	Foundation design	A11,A17
A13	Floor framing design	A12
A14	Beam details design	A13
A15	Column details design	A13
A16	Slab details design	A13
A17	Structural design review	A14, A15, A16
HVAC design		
A18	HVAC calculations	A2
A19	AHU equipment design	A18
A20	Piping system design	A19
A21	Air duct plan design	A19
A22	AHU ductwork details design	A20, A21
A23	HVAC design review	A22
Electrical design		
A24	Electrical switchgear calculations	A2
A25	Electrical switchgear design	A24
A26	Light fixture and wiring design	A25,A27,A28
A27	Emergency light design	A26
A28	Smoke detector design	A26
A29	Emergency exhaust duct design	A26
A30	Electrical design review	A27, A28, A29
End	Design completed	A10, A17, A23, A30

Table 4
Input data of each activity in the example project

ID	Type of deliverable	Transferred drawing amount (TQ)	Conversion Factor (CF)	Participation ratio (Ratio$_{i(p)}$, %)			Time required to process deliverables (dd$_i$, h)
Architectural design				Architect (%)	Designer (%)	Assistant designer (%)	
A1	PLA	1.00	1.2	100	–	–	4
A2	ELE	1.20	0.85	40	60	–	4
A3	SEC	1.52	0.97	10	60	30	4
A4	PLA	1.83	1.2	–	100	–	4
A5	DET-A	2.11	1	–	–	100	4
A6	DET-A	2.00	1	–	–	100	4
A7	DET-A	3.00	1	70	–	30	4
A8	ELE	1.17	0.85	–	30	70	4
A9	DET-A	2.00	1	–	100	–	4
A10	REP	2.00	0.6	20	80	–	4
Structural design				Structural consultant (%)	Structural engineer (%)	Structural assistant engineer (%)	
A11	CAL-S	3.00	1.25	100	–	–	8
A12	CAL-S	2.00	1.25	50	50	–	4
A13	FRA	2.00	0.85	20	50	30	4
A14	BEA	1.00	0.8	–	–	100	4
A15	COL	1.00	1	–	50	50	4
A16	SLA	2.00	0.8	–	100	–	4
A17	CAL-S	2.00	1.25	50	–	50	4
HVAC design				HVAC consultant (%)	HVAC engineer (%)	HVAC assistant engineer (%)	
A18	CAL-H	3.00	1.15	50	50	–	8
A19	CAL-H	2.00	1.15	50	50	–	4
A20	WAT	2.00	0.85	–	–	100	4
A21	AIR	1.00	0.80	–	50	50	4
A22	DET-H	2.00	0.8	–	–	100	4
A23	CAL-H	2.00	1.15	30	50	20	4
Electrical design				Electrical consultant (%)	Electrical engineer (%)	Electrical assistant engineer (%)	
A24	CAL-E	3.00	1.15	100	–	–	8
A25	CAL-E	3.00	1.15	60	40	–	4
A26	LIG	3.00	0.60	–	60	40	4
A27	EME	3.00	0.8	–	60	40	4
A28	DET-E	3.00	0.7	–	–	100	4
A29	EXH	2.00	0.7	–	60	40	4
A30	CAL-E	2.00	1.15	100	–	–	4
End	–	–	–	–	–	–	8

on the activity at the top of the matrix. This partitioned matrix demonstrates that 31 activities contribute to three iterative loops (iterations A, D, and E with complete loops). Furthermore, two incomplete iterative loops (B and C) are identified. Table 6 presents the description, characteristics, initiating activities, iterated activities and input parameters (IterDR$_i$, IntraD$_i$, InterD$_i$, or MultiD$_i$) for each iteration.

For example, in Table 6, iteration A is of Type 1 (a simple intra-iteration with a complete loop) and is identified by DSM. The practical implication of iteration A is that the downstream activity A3 (wall sections design) must confirm the size and height of exterior openings of an upstream activity A2. Therefore, A3 initiates the iteration and A2 is reworked in the iteration. Also, the values of IterDR$_i$ and IntraD$_i$ for the iteration are assumed to be 80% and 4 h, respectively. Fig. 6 displays a bar chart that helps to represent the dependencies among activities for these iterations.

Fig. 7 depicts the established simulation-based network for this example project. The network incorporates the 31 activities (represented by Combi nodes), 12 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 five iterations. Moreover, all small Queues shown in the network are used only to control the resource flows. Liao described some of the simulation codes of this network [25].

Table 5
Productivity (unit rate) of each design participant

Participants	Unit rate (h/sheet) per person
Architectural discipline	
Architect	8
Designer	10
Assistant designer	15
Structural discipline	
Structural consultant	8
Structural engineer	10
Structural assistant engineer	12
HVAC discipline	
HVAC consultant	6.5
HVAC engineer	9
HVAC assistant engineer	14
Electrical discipline	
Electrical consultant	8
Electrical engineer	10
Electrical assistant engineer	14

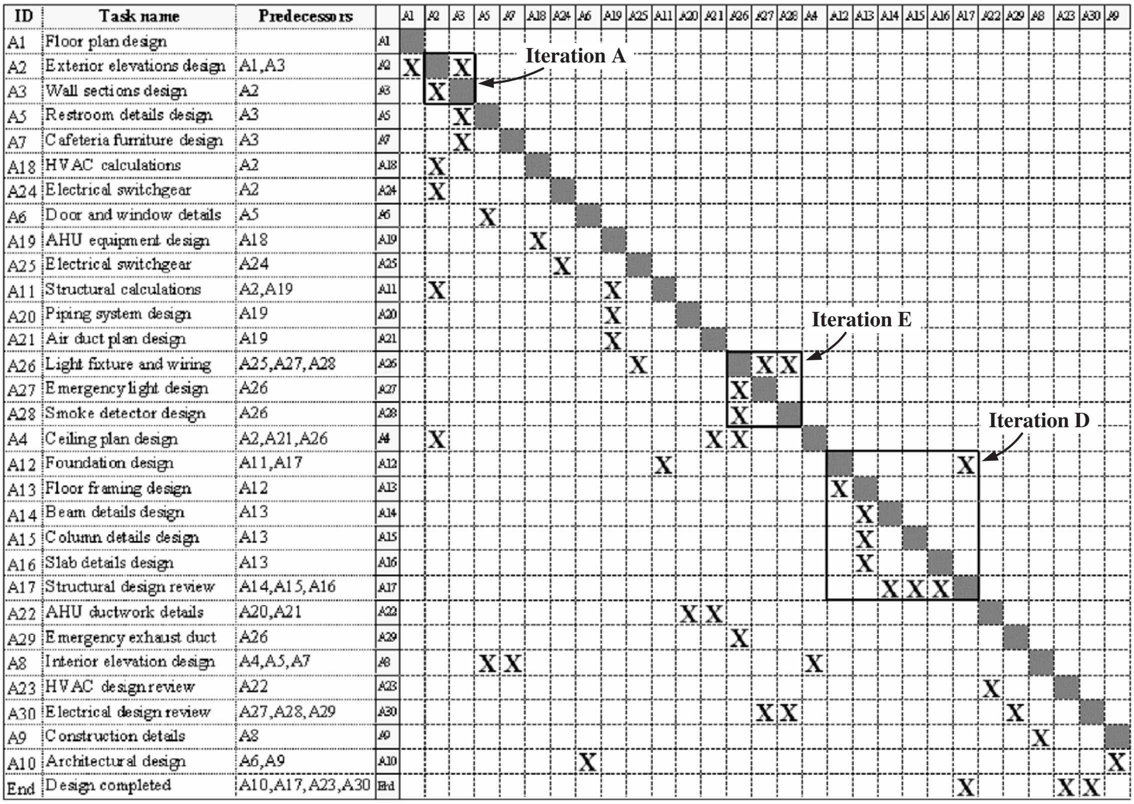
5.4. Results

5.4.1. Base case analysis

A base case is analyzed by assuming that each iteration (iterations A–E) arises for only one time. Also, this base case includes 12 persons, one of each type of participant. In this base case, the duration of the entire design project is 285.75 h (approximately 35.72 working days, 8 h per day). Table 7 lists the results of the simulation for each activity. For instance, in activity A3, the equivalent quantity (EQ_i), the weighted unit rate ($\mathrm{WeightUR}_i$), the estimated duration without iterations ($D_{i(0)}$), the time required for reworking related to a single iteration ($\mathrm{IterD}_{i(1)}$), and the duration due to a single iteration ($D_{i(1)} = D_{i(0)} + \mathrm{IterD}_{i(1)}$) are 1.47 sheets, 11.30 h per sheet, 20.66 h, 20.53 h and 41.19 h, respectively. The start time, the finish time, the start time of iteration A, and the finish time after the iteration for activity A3 are 26.98, 47.64, 62.35 and 82.88, respectively.

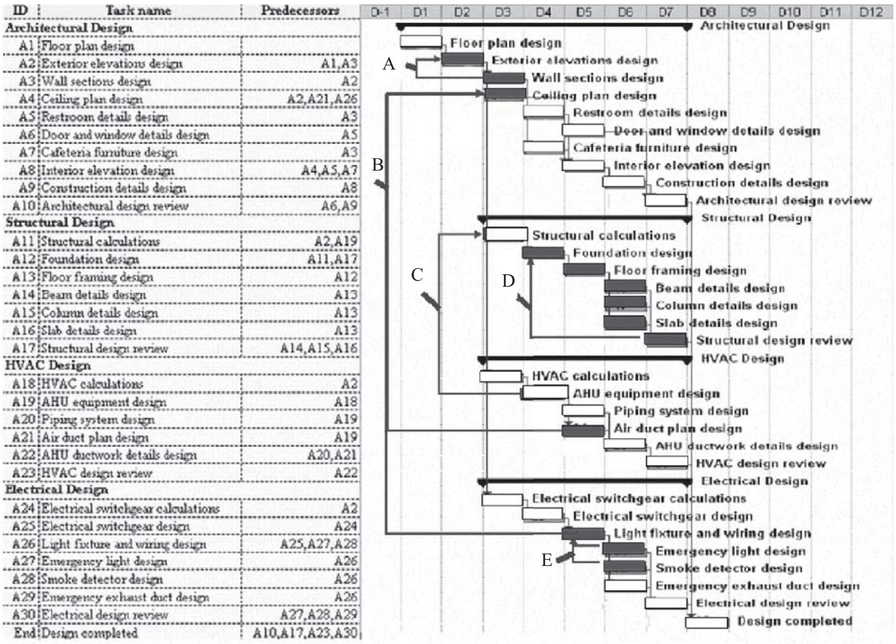
Table 7 also reveals that 13 activities (architectural A2–A4, structural A11–A17, and electrical A26–A28) must be reworked because of the iterations. The iteration affects no HVAC activity. The times spent on architectural, structural, HVAC and electrical tasks are 243.78, 232.13, 152.12 and 250.77 h, respectively. (The 243.78 h spent on architectural tasks excludes the 8 h required by the End activity.) Furthermore, Table 7 provides the start time and finish time of each design discipline. For instance, the electrical discipline starts at 26.98 h and finishes at 277.75 h. Overall, after architectural activity A1 is completed and A2 is finished at 26.98 h (before starting the iteration of A2), the other three disciplines start; then the electrical discipline takes the longest duration to complete activities A24–A30, and the End activity closes the design work for this example project. Notably, Table 7 can easily be represented by a bar chart similar to that presented in Fig. 6.

The simulation enables the model to evaluate the utilization rates of the participants (stored in Queues). Table 8 provides the working and idle times of each participant involved in the



ID	Task name	Predecessors		A1	A2	A3	A5	A7	A18	A24	A6	A19	A25	A11	A20	A21	A26	A27	A28	A4	A12	A13	A14	A15	A16	A17	A22	A29	A8	A23	A30	A9
A1	Floor plan design		A1	▨																												
A2	Exterior elevations design	A1,A3	A2	X	▨	X																										
A3	Wall sections design	A2	A3		X	▨																											
A5	Restroom details design	A3	A5			X	▨																										
A7	Cafeteria furniture design	A3	A7			X		▨																									
A18	HVAC calculations	A2	A18		X				▨																									
A24	Electrical switchgear	A2	A24		X					▨																								
A6	Door and window details	A5	A6				X				▨																							
A19	AHU equipment design	A18	A19						X			▨																					
A25	Electrical switchgear	A24	A25							X			▨																				
A11	Structural calculations	A2,A19	A11		X							X		▨																			
A20	Piping system design	A19	A20									X			▨																		
A21	Air duct plan design	A19	A21									X				▨																	
A26	Light fixture and wiring	A25,A27,A28	A26										X				▨	X	X														
A27	Emergency light design	A26	A27														X	▨															
A28	Smoke detector design	A26	A28														X		▨														
A4	Ceiling plan design	A2,A21,A26	A4		X										X	X			▨													
A12	Foundation design	A11,A17	A12											X							▨				X								
A13	Floor framing design	A12	A13																		X	▨											
A14	Beam details design	A13	A14																			X	▨										
A15	Column details design	A13	A15																			X		▨									
A16	Slab details design	A13	A16																			X			▨								
A17	Structural design review	A14,A15,A16	A17																				X	X	X	▨						
A22	AHU ductwork details	A20,A21	A22												X	X											▨					
A29	Emergency exhaust duct	A26	A29														X											▨				
A8	Interior elevation design	A4,A5,A7	A8				X	X												X									▨			
A23	HVAC design review	A22	A23																								X			▨		
A30	Electrical design review	A27,A28,A29	A30															X	X									X			▨	
A9	Construction details	A8	A9																										X			▨
A10	Architectural design	A6,A9	A10								X																					X
End	Design completed	A10,A17,A23,A30	End																							X				X	X	

Fig. 5. Three iterations identified by DSM in the example project.



ID	Task name	Predecessors
Architectural Design		
A1	Floor plan design	
A2	Exterior elevations design	A1,A3
A3	Wall sections design	A2
A4	Ceiling plan design	A2,A21,A26
A5	Restroom details design	A3
A6	Door and window details design	A5
A7	Cafeteria furniture design	A3
A8	Interior elevation design	A4,A5,A7
A9	Construction details design	A8
A10	Architectural design review	A6,A9
Structural Design		
A11	Structural calculations	A2,A19
A12	Foundation design	A11,A17
A13	Floor framing design	A12
A14	Beam details design	A13
A15	Column details design	A13
A16	Slab details design	A13
A17	Structural design review	A14,A15,A16
HVAC Design		
A18	HVAC calculations	A2
A19	AHU equipment design	A18
A20	Piping system design	A19
A21	Air duct plan design	A19
A22	AHU ductwork details design	A20,A21
A23	HVAC design review	A22
Electrical Design		
A24	Electrical switchgear calculations	A2
A25	Electrical switchgear design	A24
A26	Light fixture and wiring design	A25,A27,A28
A27	Emergency light design	A26
A28	Smoke detector design	A26
A29	Emergency exhaust duct design	A26
A30	Electrical design review	A27,A28,A29
End	Design completed	A10,A17,A23,A30

Fig. 6. Representation of iterations using bar charts.

example project. For instance, the idle times of the architect, the designer and the assistant designer in performing the architectural activities are 92.30, 49.62 and 81.21 h, respectively. Thus, a design manager can assign additional design tasks (of the same project or other projects) to the architect who is very idle.

5.4.2. Effect of design iteration on duration

The times required for reworking due to iterations A, B, C, D and E in the base case are 35.24, 23.19, 19.60, 68.69 and 48.05 h, respectively. For example, activities A2 and A3 must be reworked because of iteration A. The rework durations ($\mathrm{IterD}_{i(1)}$) of A2 and A3 are 14.71 and 20.53 h, respectively. Therefore, the rework duration associated with iteration A is 35.24 h (=14.71+20.53). Of these five iterations, iteration D most strongly affects the duration. Accordingly, the control of activity A17 (the activity of initiating the iteration) should be improved.

Fig. 8 indicates that the total duration of the example project increases with the number (n) of iterations from

Table 6
Five identified iterations in the example project

Iteration	Description	Characteristics	Initiating activities	Iterated activities	Input parameters
A (Type 1)	The downstream activity A3 (wall sections design) is to confirm the size and height of exterior openings of an upstream activity A2. Hence, part of A2 must be reworked.	• Identified by DSM • Simple intra-iteration • Complete loop	A3	A2	$\mathrm{IterDR}_i=80\%$ $\mathrm{IntraD}_i=4$ h
B (Type 6)	Those who perform architectural tasks commonly fail to consider the locations of the air ducts (A21) and light fixtures (A26) in the ceiling plan design (A4). Therefore, downstream activities (A21 and A26) often require A4 to be reworked.	• Identified by model user • Multi-iteration N-to-1 • Incomplete loop	A21, A26	A4	$\mathrm{IterDR}_i=20\%$ $\mathrm{MultiD}_i=18$ h
C (Type 3)	The AHU equipment design (A19) causes the structural calculations (A11) to be reworked because the equipment loading exceeds the structural loading capacity.	• Identified by model user • Simple inter-iteration • Incomplete loop	A19	A11	$\mathrm{IterDR}_i=20\%$ $\mathrm{InterD}_i=12$ h
D (Type 2)	The structural design review (A17) forces the foundation design (A12) to be reworked. Accordingly, the design of the floor framing (A13), the details of the beams (A14), the details of the column (A15), and the details of the slabs (A16) are iterated.	• Identified by DSM • Complex intra-iteration • Complete loop	A17	A12, A13, A14, A15, A16	$\mathrm{IterDR}_i=20\%$ $\mathrm{IntraD}_i=4$ h
E (Type 2)	The designed locations of emergency lights (A27) and smoke detectors (A28) do not meet the design standards for light fixtures and wiring (A26). Thus, A26 is reworked.	• Identified by DSM • Complex intra-iteration • Complete loop	A27, A28	A26	$\mathrm{IterDR}_i=40\%$ $\mathrm{IntraD}_i=4$ h

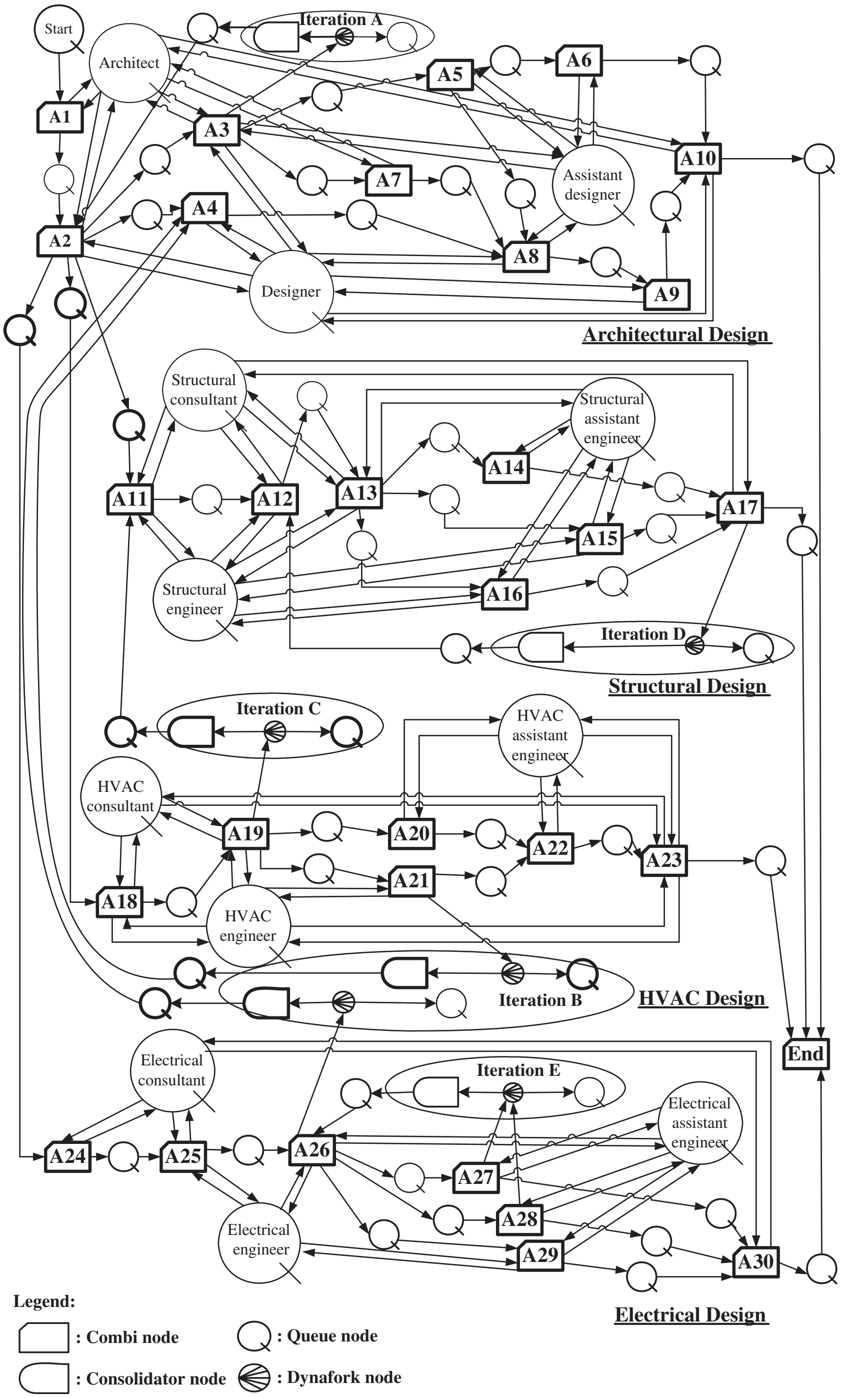


Fig. 7. Simulation-based network of the example project.

zero to four. However, the impact of the number of iterations on the duration falls as n increases. For instance, the total duration increases only by about 2.86% (=(314.94 − 306.17)/306.17) as n is increased from two to three. The total duration increases by only around 1.21% (=(318.75 − 314.94)/314.94) as n changes from three to four. The effect of additional design iterations on duration becomes smaller because less design reworking is required following several iterations. IterDR_i^n decreases as n rises.

5.4.3. Effect of design teams on duration

The original design team has 12 participants (three for each discipline). Three other scenarios are considered to improve resource allocation strategies. Scenario-1 involves 24 persons, two of each type of participant. Similarly, scenario-2 and scenario-3 involve 36 and 48 persons, respectively; in each case, the numbers of participants of the various types are equal. Fig. 9 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

Table 7
Simulation results for base case in the example project (one time of iteration)

Activity	Equivalent Quantity (EQ_i)	$WeightUR_i$ (h/sheet)	$D_{i(0)}$ (h)	$IterD_{i(1)}$ (h)	$D_{i(1)}$ (h)	Start time	Finish time	Start time of iteration	Finish time after iteration
Architectural design (Duration = 243.78 h)						0.00			243.78
A1	1.20	8.00	13.60	–	13.60	0.00	13.60	–	–
A2	1.02	9.20	13.38	14.71	28.09	13.60	26.98	47.64	62.35
A3	1.47	11.30	20.66	20.53	41.19	26.98	47.64	62.35	82.88
A4	2.20	10.00	25.96	23.19	49.15	82.88	108.84	124.55	148.74
A5	2.11	15.00	35.65	–	35.65	82.88	118.53	–	–
A6	2.00	15.00	34.00	–	34.00	118.53	152.53	–	–
A7	3.00	10.10	34.30	–	34.30	152.53	186.83	–	–
A8	0.99	13.50	17.43	–	17.43	186.83	204.26	–	–
A9	2.00	10.00	24.00	–	24.00	204.26	228.26	–	–
A10	1.20	9.60	15.52	–	15.52	228.26	243.78	–	–
Structural design (Duration = 232.13 h)						26.98			259.11
A11	3.75	8.00	38.00	19.60	57.60	26.98	64.98	190.42	210.02
A12	2.50	9.00	26.50	9.30	35.80	64.98	91.48	210.02	219.32
A13	1.70	10.20	21.34	8.27	29.61	91.48	112.82	219.32	227.59
A14	0.80	12.00	13.60	6.72	20.32	112.82	126.42	227.59	234.31
A15	1.00	11.00	15.00	7.00	22.00	126.42	141.42	234.31	241.31
A16	1.60	10.00	20.00	8.00	28.00	141.42	161.42	241.31	249.31
A17	2.50	10.00	29.00	9.80	38.80	161.42	190.42	249.31	259.11
HVAC design (Duration = 152.12 h)						26.98			179.10
A18	3.45	7.75	34.74	–	34.74	26.98	61.72	–	–
A19	2.30	7.75	21.83	–	21.83	61.72	83.55	–	–
A20	1.70	14.00	27.80	–	27.80	83.55	111.35	–	–
A21	0.80	11.50	13.20	–	13.20	111.35	124.55	–	–
A22	1.60	14.00	26.40	–	26.40	124.55	150.95	–	–
A23	2.30	10.50	28.15	–	28.15	150.95	179.10	–	–
Electrical design (Duration = 250.77 h)						26.98			277.75
A24	3.45	8.00	35.60	–	35.60	26.98	62.58	–	–
A25	3.45	8.80	34.36	–	34.36	62.58	96.94	–	–
A26	1.80	11.60	24.88	13.95	38.83	96.94	121.82	187.06	201.01
A27	2.40	11.60	31.84	16.74	31.84	121.82	153.66	201.01	217.75
A28	2.10	14.00	33.40	17.36	33.40	153.66	187.06	217.75	235.11
A29	1.40	11.60	20.24	–	20.24	235.11	255.35	–	–
A30	2.30	8.00	22.40	–	22.40	255.35	277.75	–	–
End					8.00	277.75	285.75		

Table 8
Simulated working time and idle time of each design participant

Participants	Working time (h)	Idle time (h)
Architectural discipline		
Architect	151.48	92.30
Designer	194.16	49.62
Assistant designer	162.57	81.21
Structural discipline		
Structural consultant	161.81	1.63
Structural engineer	115.41	48.03
Structural assistant engineer	110.73	52.71
HVAC discipline		
HVAC consultant	84.72	67.40
HVAC engineer	111.12	41.00
HVAC assistant engineer	95.55	56.56
Electrical discipline		
Electrical consultant	92.36	158.41
Electrical engineer	142.01	108.76
Electrical assistant engineer	158.41	92.36

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). Numerous scenarios were tried,

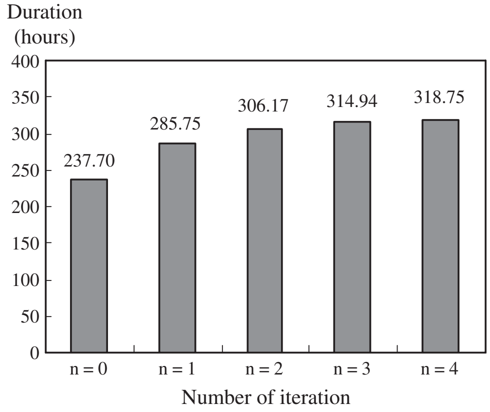


Fig. 8. Project durations given various numbers of iterations.

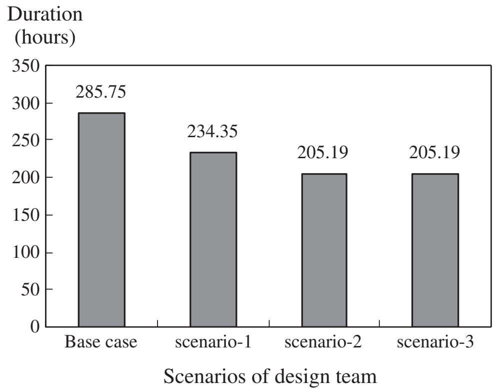


Fig. 9. Project durations under different design teams.

and a design team of 22 persons was to minimize the duration of the project—205.19 h. In order, the numbers of participants listed from the top to the bottom of Table 5 for these 22 persons are 1, 2, 3, 2, 2, 3, 1, 1, 1, 1, 2 and 3, respectively. (Current practice involves allocating participants to various design projects. The model outputs of working time and idle time for each participant can support such allocation when the model is applied to multiple projects.)

6. Other considerations

This study elucidated several practical lessons and suggested future research directions.

- A design project is frequently undertaken in an uncertain environment. The analysis based on the current model can easily incorporate uncertainties (expressed by statistical distributions) of the model inputs (such as those displayed in Table 4). The likelihood that the schedule is overrun can thus be determined to support schedule risk management.
- The current model can be readily extended to offer 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.
- Decisions (such as those on modifying system requirements to satisfy the constraints of a limited budget) made as part of earlier activities may constrain the design search space in later activities. Consequently, iterations across activities can totally alter design. Such iterations often arise during the conceptual and schematic design phases. An experienced designer should carefully produce minimal design deliverables to ensure that the proposed alternative satisfies the client's needs before generating numerous detailed drawings. The model steps must be repeated to generate a new design schedule if such a significant change occurs in the detailed design phase, which is considered herein.
- On many occasions, a downstream activity B may begin when upstream activity A is only partially finished, if B has received sufficient information from A. For instance, when the floor plan design has been 15% completed, both the ceiling design activity and the finish design activity may begin; when the floor plan design has been 25% completed, the structural design activity may be started, and when the floor plan is 35% completed, the mechanical design activity may be started [27]. Future work should extend the current model to model these occasions.
- In this investigation, iterations are assumed to be independent of each other. Consider iterations E and B of the example project for illustration. Downstream activities A27 and A28 cause activity A26 to be reworked due to iteration E. The reworking of A26, which activity is also one of the two (A26 and A21) that activate iteration B, cannot cause the re-activation of iteration B. Future research should relax the assumption of such independence.

7. Conclusions

Bar charts and network analysis are useful in construction. However, their logical relationships among activities are one-way, and cannot be used to handle processes that involve iterations with complete or incomplete loops. This work devises a new simulation-based model that incorporates the DSM algorithm to identify design iterations for generating the schedule of a design project. The model can produce scheduling outputs, including start times, finish times and the durations of each activity, each discipline and the entire design project. Additionally, the model can be used to assess the effects of various iterations on the duration; it addresses the design deliverables required to evaluate activity durations, and helps to select participants in an appropriate design team. The example project illustrates the aforementioned advantages of the model.

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