Automation in Construction 37 (2014) 68–80

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Integrating building information models with construction process simulations for project scheduling support

Wei-Chih Wang [a,*], Shao-Wei Weng [a], Shih-Hsu Wang [b], Cheng-Yi Chen [a]

[a] Department of Civil Engineering, National Chiao Tung University, 1001, University Road, Hsin-Chu, Taiwan
[b] Department of Civil Engineering, R.O.C Military Academy, Taiwan

ARTICLE INFO

Article history:
Accepted 17 October 2013
Available online 12 November 2013

Keywords:
Building information modeling
Operations simulation
Quantity takeoffs
Stroboscope
Scheduling

ABSTRACT

Many construction practitioners and researchers have developed four-dimensional (4D) models by linking the three-dimensional (3D) components of a building information model (BIM) with the network activities of a project schedule. In such a 4D model, the BIM provides limited information, except for the 3D components. To enhance the benefits of using BIM in 4D applications, this study proposes an interface system that uses the BIMs ability with regard to quantity takeoffs of required materials (such as steel, forms, and concrete) to support site-level operations simulation, ultimately leading to the generation of a project schedule. Our proposed system includes mechanisms that collect, store, and transfer information among various software packages. Facilitated by the BIM's quantity takeoffs, the operations simulation is able to consider uncertain durations of work tasks, which allows it to consider the competing needs for resources among multiple work tasks, and to evaluate various resource allocation strategies in order to create a suitable construction plan. Finally, the resulting project schedule is also linked to the BIM 3D components, thus producing an improved BIM-based 4D model.

1. Introduction

As a construction project grows increasingly complex and involves numerous building elements, two-dimensional (2D) drawings are often unable to adequately express design ideas or resolve the conflicting problems that interfere with the construction. Three-dimensional (3D) computer-aided design provides a solution that resolves these problems [1]. A number of researchers, though, have indicated that a four-dimensional (4D) model, which integrates 3D building components with time as the fourth dimension, can further facilitate construction management by discovering inappropriate schedule sequences, evaluating issues of constructability, and identifying potential time–space conflicts [1–7].

Recently, building information model (BIM), which is a 3D framework that can digitize a great amount of building information, has received much attention in the field of construction project management [7–11]. In particular, combining a BIM-based 3D model and a project schedule (which represents the fourth dimension of time) into a 4D model has been highlighted as one of the great merits of using BIM [10].

Currently, to develop a BIM-based 4D model of a construction project, several steps must be performed [2,6,11]. First, a BIM-based 3D model using commercial software (such as Bentley MicroStation or Autodesk Revit) and a project schedule (using MS Project or Primavera software) are developed separately. Second, a schedule simulator (such as SmartPlant Review or Navisworks) is utilized to link the 3D components with the related scheduling activities. Third, the resulting 4D model displays the construction sequence by showing consecutive 3D components as a progression over the time-span of the project.

However, the current 4D models are limited in that they do not effectively employ the BIM information to support construction scheduling [12,13]. That is, their BIM model mainly provides information regarding the 3D components, and thus offers little advantage over other 3D models used in 4D applications.

To improve the BIM's effectiveness in 4D applications, this work develops an interface system that applies the BIM's quantity takeoffs of a reinforced concrete (RC) structure to facilitate a site-level operations simulation, and consequently, to generate a construction schedule. Unlike current 4D models in which the schedule is developed separately, the proposed system generates a construction schedule according to the results of a BIM-facilitated operations simulation, and the resulting schedule is then linked to the BIM-based 3D components for 4D animation.

2. Review of current studies

This section reviews current studies of 4D and 3D models that address issues regarding the simulation of construction operations. It is worth noting that in most 4D models, the term "simulation" is similar to "visualization" or "animation," because it graphically views scheduling activities forwards or backwards temporally during any period of

* Corresponding author. Tel.: +886 3 5712121x54952; fax: +886 3 5716257.
E-mail addresses: weichih@mail.nctu.edu.tw (W.-C. Wang), m09716005@chu.edu.tw (S.-W. Weng), wss.cv91g@nctu.edu.tw (S.-H. Wang), 494310021@s94.tku.edu.tw (C.-Y. Chen).

0926-5805/$ – see front matter
http://dx.doi.org/10.1016/j.autcon.2013.10.009

time, thus supporting the project participants (e.g., owners, designers, and contractors) in more effectively understanding the sequences of construction work [2,6,14]. On the other hand, the term "operations simulation," as used in the present study, is related to the performance of site-level construction processes, which are cyclic in nature, for several iterations, and is concerned with the competing needs for resources [15,16].

2.1. 4D models

According to Sheppard [3], although the development of 4D models began in 1973, it was not until 1984 that the first construction simulation software (Construction Systems Associates' PM-version) was introduced in the market. The major merit of such 4D models is the visual enhancements they provide. In addition to the 3D geometric data, BIM, which is capable of storing and computing large amounts of data, has been incorporated into the development of 4D models [4,7,8]. Moreover, the availability of commercial 4D management software, such as Bentley's Navigator and Intergraph's SmartPlant Review have made 4D applications increasingly popular [14].

Besides the visualization of construction schedules, researchers have developed numerous 4D applications, which include the detection of construction conflicts [7], optimization of site layouts [17], analysis of workspace congestion [18], discovery of inconsistencies among scheduling activities [2], planning of resource utilization [19], monitoring of progress discrepancies [5], detection of structural safety problems [7], discovery of spatial-related hazards [20], and generation of construction schedules [21].

For example, to facilitate the monitoring of a project's progress, Golparvar-Fard et al. [5] proposed the visualization of performance metrics that represent deviations in a project's progress. This is achieved through the superimposition of a 4D as-planned model over time-lapse photographs to produce comprehensive visual images that offer new insights. In their study, the augmented photographs provide a consistent platform for representing as-planned, as-built, and progress discrepancy information that facilitates communication and reporting processes. As another example, which involves an application that supports construction safety management, Benjaoran and Bhokha [20] applied a 4D CAD model together with rule-based algorithms in order to automatically detect spatial-related hazards (working-at-height) and to visualize the required safety measures, together with the optimal construction sequence.

Furthermore, Mikulakova et al. [21] integrated a knowledge-based approach and the BIM to generate automatically construction schedules and evaluate the schedules. In their study, an Industry Foundation Classes (IFC)-based BIM provides data for building components (i.e., objects with attributes) that are modeled as constraints during the planning process. A constraint describes the situation related to an execution problem resulting from construction conditions. A case-based reasoning system was applied to acquire a suitable construction process (including a certain number of tasks) with a similar execution problem. The obtained construction processes are then ordered to generate a schedule. This schedule can be visualized in CAD environments with IFC interfaces.

2.2. 3D models with operations simulation

With the objective of reducing resource idling time and improving site productivity, operations simulations have been applied to construction modeling processes in order to investigate time conflicts in allocating the utilization of resources [15,16]. Since the time and effort required to build simulation models are known weaknesses of operations simulations, numerous studies have been proposed that use 2D graphical symbols to represent the elements of construction operations [22–24]. These models of operations simulations, which have become known as activity-cycle diagram-based models, include CYCLONE (CYCLic Operation NEtwork) [15], RESQUE [25], COOPS (Construction Objective-Oriented Process Simulation) [26], and Stroboscope (State and Resource Based Simulation of Construction Process) [24]. Stroboscope, which is adopted in the present research, is a general-purpose simulation language that can dynamically access the state of the simulation and the properties of the resources involved in construction operations [24].

With the advancements in computer technologies, the three dimensions of building components have been added to operations simulation models in order to obtain valuable insight into the details of construction operations that are difficult to represent [23,27–29]. For example, Lu et al. [12] proposed a "zoom" interface between two computer system in a Critical-Path-Method (CPM)-based 4D CAD platform called 4D-GCPSU (graphics for construction planning and resource utilization) [19,30] and an operations simulation platform called SDESA (simplified discrete event simulation approach) [31,32]. This zooming into the processes of a CPM activity for operations simulation modeling enables one to assess the impact of the activity constraints (such as resource utilization, site layout, and alternative installation sequences) upon activity durations. How information generated by BIMs can be applied to support 4D development or operations simulation is not addressed in their study.

As the preparation of inputs for simulation is time-consuming, Wu et al. [33] proposed a 3D methodology that allows interactive assignment of construction methods to individual building elements. When reaching the finest detail level in the interaction process, activities and constraints (requirements to execute an activity) are created and used as inputs for a constraint-based simulation. This simulation is applied to overcome the limitation of pre-specified activity sequences in such a way that whenever an activity is completed, all activities that have not yet begun are checked to determine whether their resource constraints are fulfilled. From the resulting set of executable activities, one activity is chosen randomly for execution and the required resources are allocated. Monte Carlo simulation with activities selected randomly supports constraint-based simulation and is repeated several times. A suitable solution with acceptable project duration is obtained and simulation results are then imported into a standard scheduling system, such as MS Project, for further modification. Finally, an improved 4D model is obtained. Notably, they assume the quantities of required materials, such as concrete, reinforcing steel, and forms, for each activity are derived from the geometry of a 3D model.

König and Habenicht [34] proposed an intelligent approach to automatically assign process patterns and define activity interdependencies to provide inputs for constraint-based simulation of construction operations. They adopted a BIM-based multi-model approach that links several models, including the quantity takeoff model, to obtain required input data for construction simulation and scheduling. In addition to a bar chart representation, the resulted schedule can be visualized.

In addition, many visual reality (VR) techniques have also been proposed that support construction simulation in a manner that allows interactions with the animation to define very realistic construction operations [35–37]. For instance, considering that construction engineers must be convinced of a model's accuracy (i.e., model credibility) before they will rely upon any simulation results, Rekapalli and Martinez [35] developed a discrete-event-based VR method to test the effectiveness of user interaction capabilities in validating complicated simulation models. Considering that 3D technology is not effectively combined with the pre-processing modeling of construction simulations, Chen and Hung [37] developed a 3D augmented-reality (AR)-based model that supports define inputs to run simulations. They devised 3D modeling components that virtually represent the areas, paths, machinery, and resources of material transportation operations, and also defined rules for transforming the modeling components into the required inputs. Simulation results were retrieved automatically for 3D, not 4D, animation. Furthermore, their study is not related to BIM.

2.3. Summary of previous studies

BIM-based 4D models that can support construction scheduling are considered to be one of the popular uses of BIM [10,38]. Despite this popularity, several studies have indicated the weaknesses of current 4D models. For example, Tanyer and Aouad [4] identified the inability of current 4D models to incorporate the details of the construction site and the procedures taking place there. Furthermore, Lu at al. [12] pointed out that in general, 4D CAD does not realize the visualization of construction operations in a way that features the dynamic interactions among various resources as the product is being built. Moreover, Chen [11] suggested that BIM should provide additional information beyond just 3D geometric data in 4D scheduling applications.

To improve the effectiveness of BIM in 4D applications, this work aims to use quantity takeoffs data provided by the BIM to support probabilistic duration estimations for work tasks involved in a site-level operations simulation, eventually yielding a construction schedule. Table 1 compares the most relevant studies and this study. Although most studies have similar objectives (i.e., improving 4D models or combining visualization with operations simulation), no study focused on how BIM's material quantities can be derived to support automatic operations simulations.

3. Proposed system

The key to developing the proposed system was to devise mechanisms that can collect, store, and transfer data (including the material quantities, task durations, and simulation inputs/outputs) among various software packages. Fig. 1 presents the framework of the proposed system, which is comprised of five modules: (1) development of the BIM model; (2) a duration estimation interface (DEI) module; (3) an operations simulation; (4) generation of project schedules; and (5) 4D animation. The following sections provide a brief explanation of each module. The details of each module are provided in our case study in Section 4.

3.1. Development of the BIM model

The proposed system applies Autodesk Revit Architecture [39] to establish the BIM model of a construction project. This BIM model provides geometric data (i.e., length, width, and height) of each building component (i.e., columns, beams, walls, and slabs) to support quantity takeoffs for concrete. However, most current BIM software cannot automatically extract the quantity of reinforcing steel embedded in the concrete without access to additional design data [10]. Moreover, the quantity of column forms that likely intersect with walls/slabs and the quantity of wall forms that could possess either one or two sides of forms cannot be derived automatically; thus, additional design details are needed. This work adds quantity-related attributes or mathematical equations (based on design documents of the construction project of interest) to each building component to extract the quantities of reinforcing steel, column forms, and wall forms.

As a result, the developed BIM model stores the quantities of materials (including reinforcing steel, forms, and concrete) required for erecting columns, beams, walls, and slabs. Fig. 2 presents a screenshot that shows an example of material quantities taken off from a BIM model. When the proposed system is activated for a particular building project, the developed BIM model exports the material quantities in .txt files (by each work zone and each floor of the building), which can then be retrieved using MS Access.

3.2. Duration estimation interface module

The proposed duration estimation interface (DEI) module is the core of the entire system, and is developed using Visual Basic language. The DEI module integrates the BIM model, the MS Access database, the Stroboscope simulation language, MS Excel, and MS Project. The DEI module consists of two components: a log-in component and a main functions component. The log-in component captures the BIM's material quantities from MS Access. The material quantities stored in MS Access are then used to estimate the durations of work tasks.

Fig. 3 displays the main functions component, which performs three functions: inputting of construction conditions, activation of operations simulation, and outputting of simulation results to generate a project schedule. These three functions are described as follows:

- *Inputting of construction conditions*: The required inputs for the proposed system include the task productivity values (such as kg/man-hour for steel work and m^2/man-hour for formwork), number of sets of forms, number of workers, number of cranes, and whether

Table 1
Comparisons of the most relevant studies and this study.

Characteristics	Mikulakova et al. [21]	Lu et al. [12]	Wu et al. [33]	König et al. [34]	Chen and Huang [37]	This study
Focused problem	Using knowledge-based CBR for scheduling	Integrating 4D and 3D simulation	Interactively building the inputs for simulation	Intelligently defining simulation network	Using AR to define inputs for simulation	Integrating BIM's QTO and Stroboscope
Significance	Integrating with the BIM	Using a zooming interface	Using process patterns	Using process patterns and a multi-model	Using AR	Developing interface system
3D visualization	Yes	Yes	Yes	Yes	Yes	Yes
An improved 4D model	Yes	Yes	Yes	Yes	Not a 4D model	Yes
Integration with BIM	Yes; IFC-based	Can be extended	No; but can be extended	Yes; a multi-model	No	Yes
Focus on quantity takeoffs (QTO)	No	No	No; but QTO data are included in a 3D model	No; but QTO data are provided by the multi-model	No	Yes; developing QTO equations in the BIM model
Constraint-based or discrete event simulation	No	DES	Constraint-based	Constraint-based	DES (Stroboscope)	DES (Stroboscope)
Simulation network	No	Pre-defined	Generated	Generated	Generated	Pre-defined
Consider resource competitions	No	Yes	Resource constraint	Resource constraint	Yes	Yes
Consider different construction methods	Yes; case based	Can be extended	Yes; using process patterns	Yes; using process patterns	Can be extended	Can be extended with templates
Consider uncertain task durations	No	Yes (included in simulation)	No	No	Yes (included in simulation)	Yes (using QTO and productivity)
Calculate probabilistic project durations	No	Can be extended	Can be extended	Can be extended	Can be extended	Yes

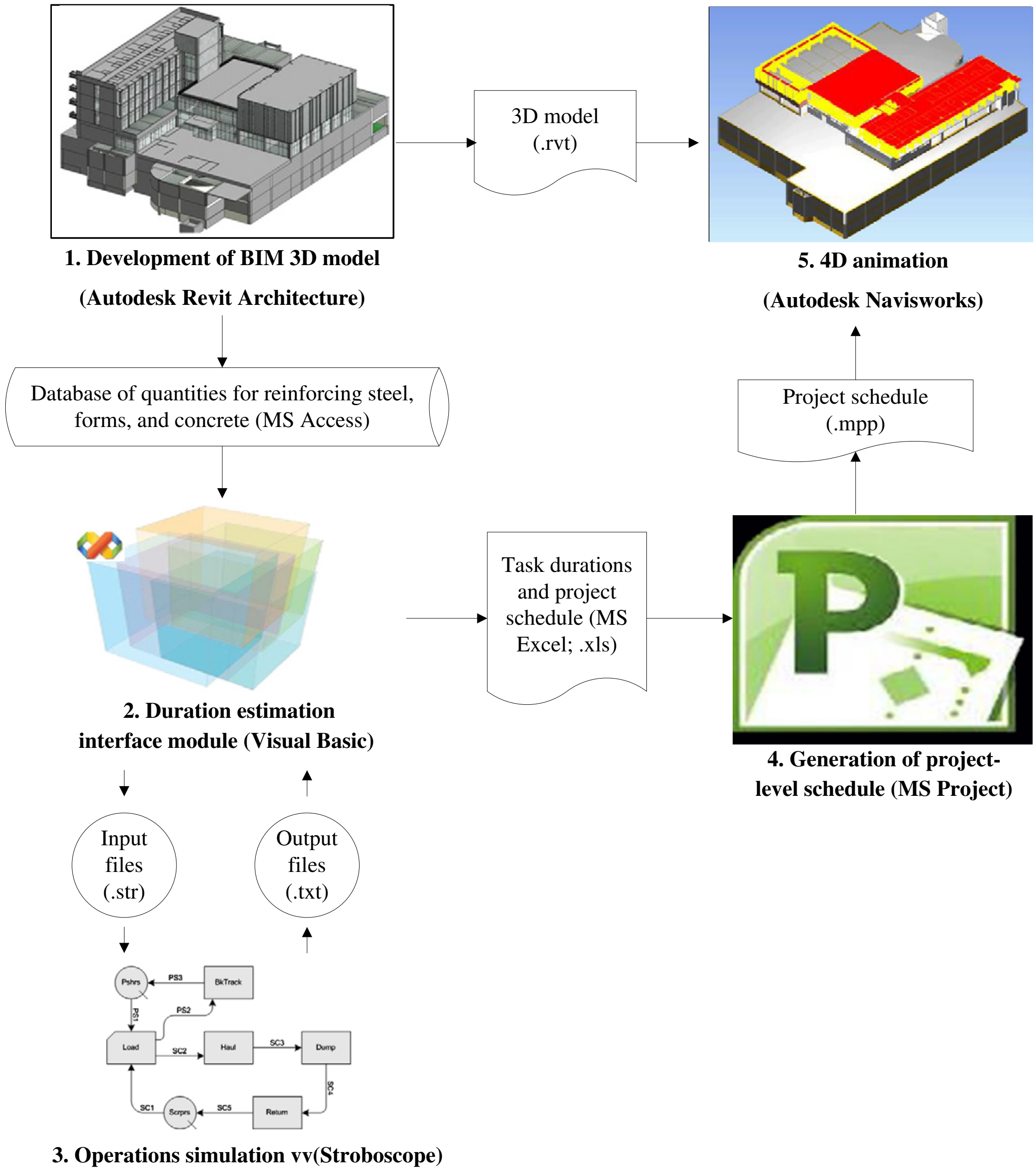


Fig. 1. Framework of the proposed system.

or not there will be overtime work. The productivity data of each construction task include three values: optimistic, most likely, and pessimistic levels of productivity. Steps 1 to 5 shown in Fig. 3 are used to guide the system user to provide these inputs to the system. See the case study for further illustrations.

- *Activation of the operations simulation*: This DEI module then can transfer the provided construction conditions to a pre-defined coding program (a template), which is a .str file and an input file, in order to run the Stroboscope simulation. (See Step 6 in Fig. 3.) During the simulation activation process, the three-point durations (i.e., the optimistic, most likely, and pessimistic durations) of each task are obtained by multiplying the aforementioned three productivity values by the quantity of material that needs to be erected for the task. These three-point durations of each task capture the uncertainties involved in construction operations.
- *Outputting of simulation results to generate a project schedule*: After 1000 simulation runs, this module can transfer the simulation results to an MS Excel file. This Excel file is also pre-formatted so that it can be retrieved by MS Project for further scheduling analyses. (See Steps 7 and 8 in Fig. 3.)

3.3. Operations simulation

The proposed system employs Stroboscope in order to conduct the site-level simulation of construction operations. This kind of simulation can be used to evaluate problems related to uncertainties that are encountered and competition among resources [16]. As indicated earlier, this study considers the influence that uncertainties have on the productivity of construction tasks, and is thus able to generate probabilistic durations of tasks. Moreover, there is competition among resources; for instance, cranes are shared for the tasks of hoisting reinforcing steels for columns, walls, and beams, and crews of ironworkers are considered competitive for these same tasks. The rule governing such competition is that the first need receives the highest priority for being served.

The system focuses on the structure part of RC construction. A Stroboscope input file (formatted in a str. file) that reflects RC construction

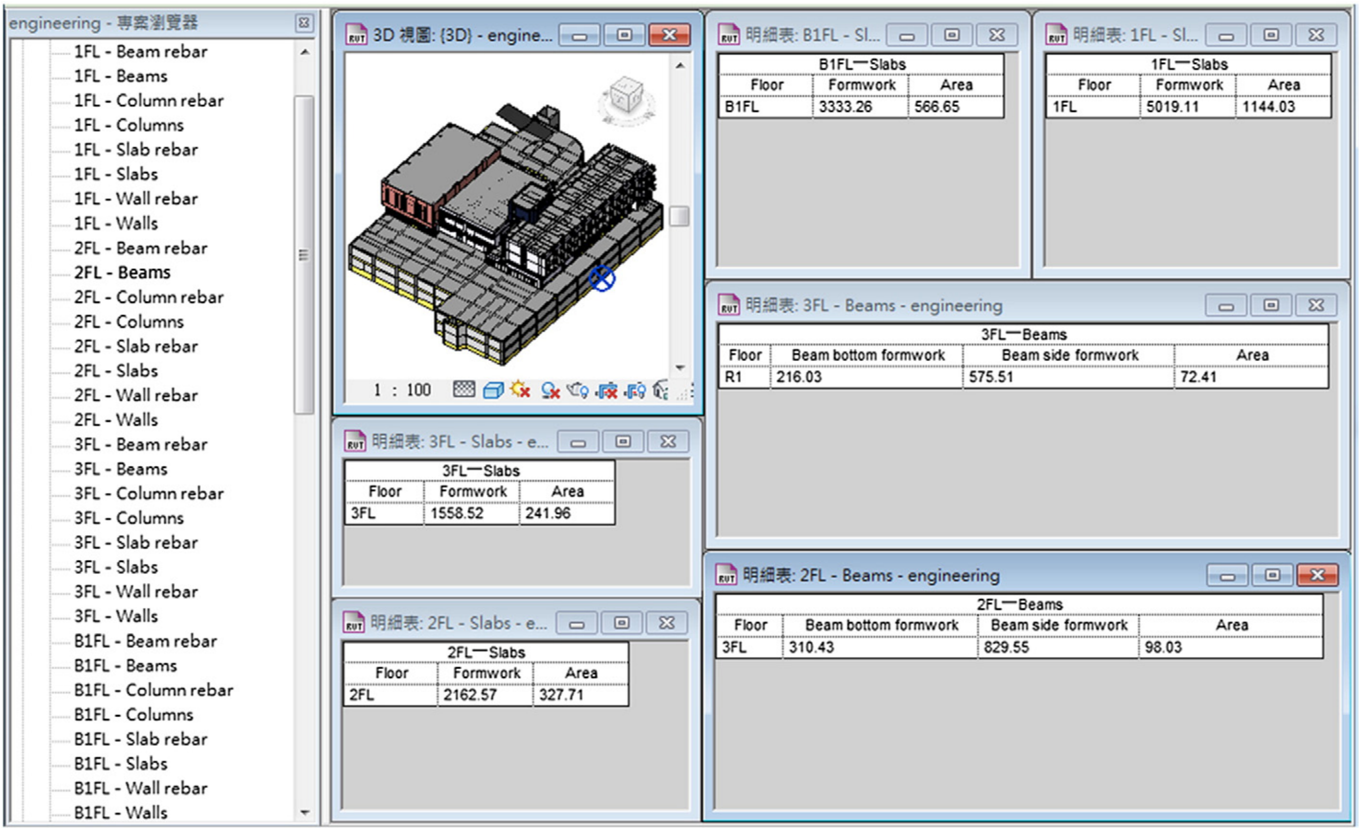


Fig. 2. Screenshot of quantity data stored in the BIM model.

operations has been pre-written and incorporated into the proposed system. Notably, this pre-written file acts as a template. The proposed system also allows for the inclusion of additional templates that reflect various types of construction operations (for example, steel-reinforced-concrete construction and pre-assembled construction).

Another benefit of using Stroboscope is that a simulation can be run for several iterations and will generate the corresponding times of the duration of a project's completion. The resulting project duration and the probability of the project being completed by the contractual deadline can thus be found, offering helpful support to schedule control. The case study presented in Section 4 illustrates further details of the operations simulation that is applied in this work.

3.4. Generation of project-level schedule and 4D animation

After Stroboscope completes a simulation, the generated results of the site-level simulation are stored in an MS Excel (.xls) file, where they can be exported to MS Project. The system user can then operate MS Project in order to produce a project-level schedule (in the form of bar charts and network schedules). Notably, the construction tasks defined in the Stroboscope simulation are also the activities of the project-level schedule in MS Project. The user can generate a higher-level schedule (such as a milestone schedule) by grouping related activities into a milestone activity (such as the completion of work zone A on the first floor). Finally, a 4D animation of the construction project can be presented by linking the schedule activities with the corresponding BIM's 3D components.

4. Case study

As a case study, we applied the proposed system to a building project located in northern Taiwan. This building built with RC has three upper-structure floors and two underground-structure floors. The total building floor area is 14,966 m^2, and the construction budget is approximately US $7.4 million. The contractual duration of the project for this RC structure is 186 days. The following subsections present the evaluation results of this case study.

4.1. Development of a BIM model

First, a 3D BIM-based model was built using Autodesk Revit Architecture, as shown in Fig. 4. This BIM 3D model provides the relevant parameters (such as length, width, height, area, and volume) needed to perform the quantity takeoffs of the weight (in tons) of steel, the area (m^2) of the forms, and the volume (m^3) of concrete for each construction element (i.e., column, beam, wall, and slab). As indicated earlier, the quantity take-off process is performed using mathematical equations that are already built into Autodesk Revit, or are provided by the proposed system. For example, the built-in equation $volume = length \times width \times height$ can be used to calculate the volume of concrete needed for a column. Details of the quantity take-off process can be found in Chen [11].

Through the data-exporting function of Revit, the calculated material quantities of each building element are exported to .txt files, where they can then be retrieved by MS Access. Fig. 5 presents a quantity table that summarizes the quantities of materials that will be needed for the tasks in construction zone B. For instance, Fig. 5 indicates that the calculated quantity of the steel for all the columns in zone B on the foundation floor (FF) is 2237.96 kg.

4.2. Development of a Stroboscope network for RC construction

By working with the contractors and subcontractors of this case project, a Stroboscope network for RC construction was built, as shown in Fig. 6. This network indicates the construction tasks, the logical links

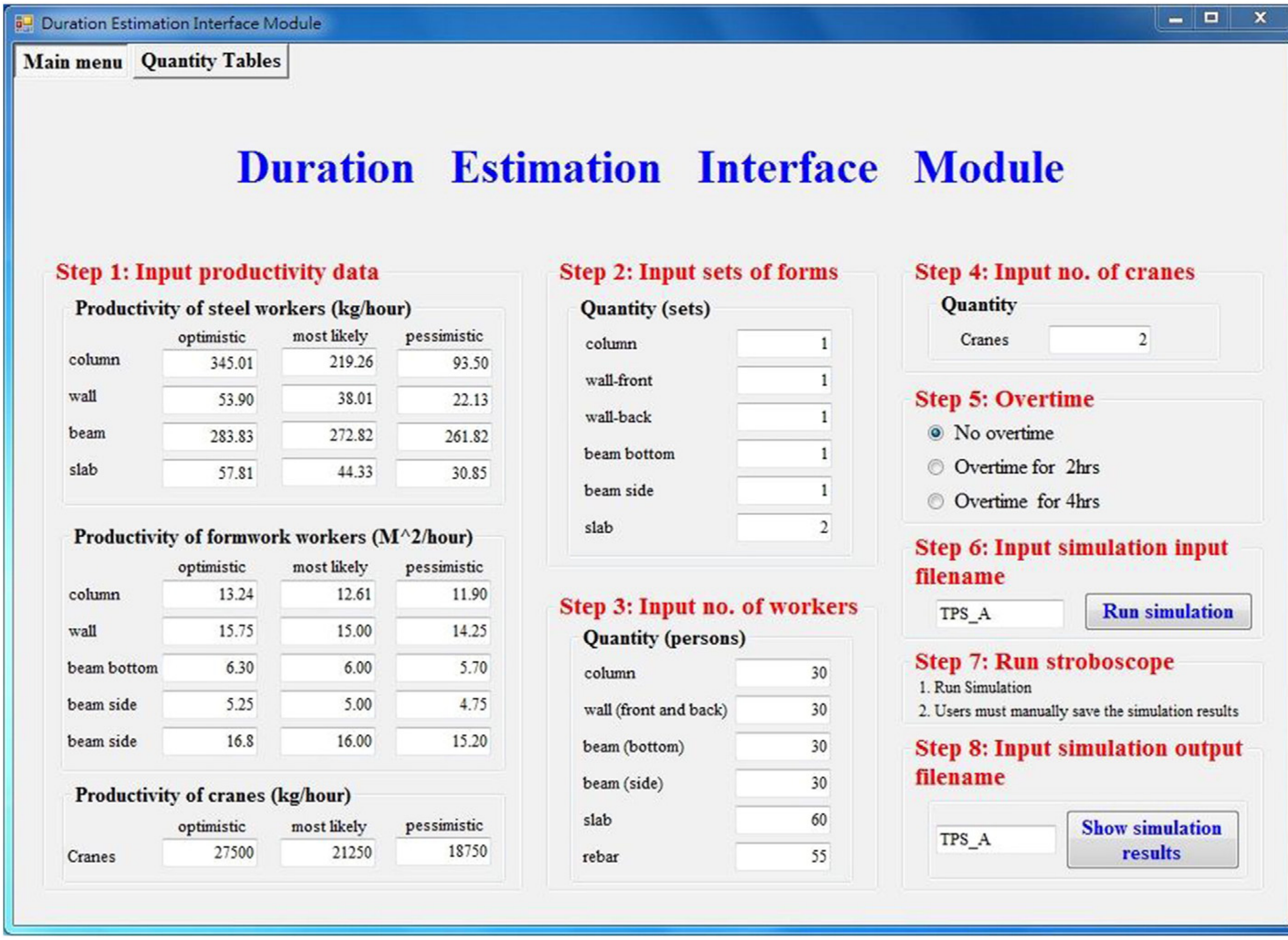


Fig. 3. Home page of the duration estimation interface module.

between tasks, and the resources required for the project. Specifically, the following 18 construction tasks are involved in each work zone of the RC construction operations: layout, hoisting of column steel, setting of column steel, setting of column forms, setting of wall forms (front), hoisting of wall steel, setting of wall steel, setting of beam forms (bottom), setting of beam forms (side), setting of slab forms, hoisting of beam and slab steel, setting of beam steel, setting of slab steel, installation of mechanical/electrical/plumbing (MEP) systems, inspection, pouring of concrete, and curing of concrete.

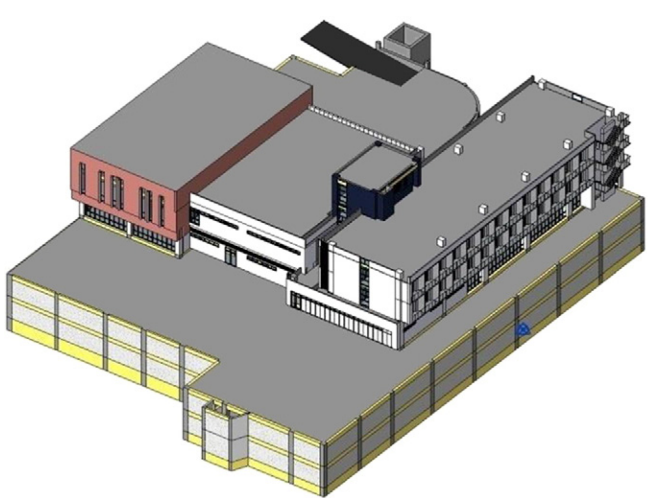


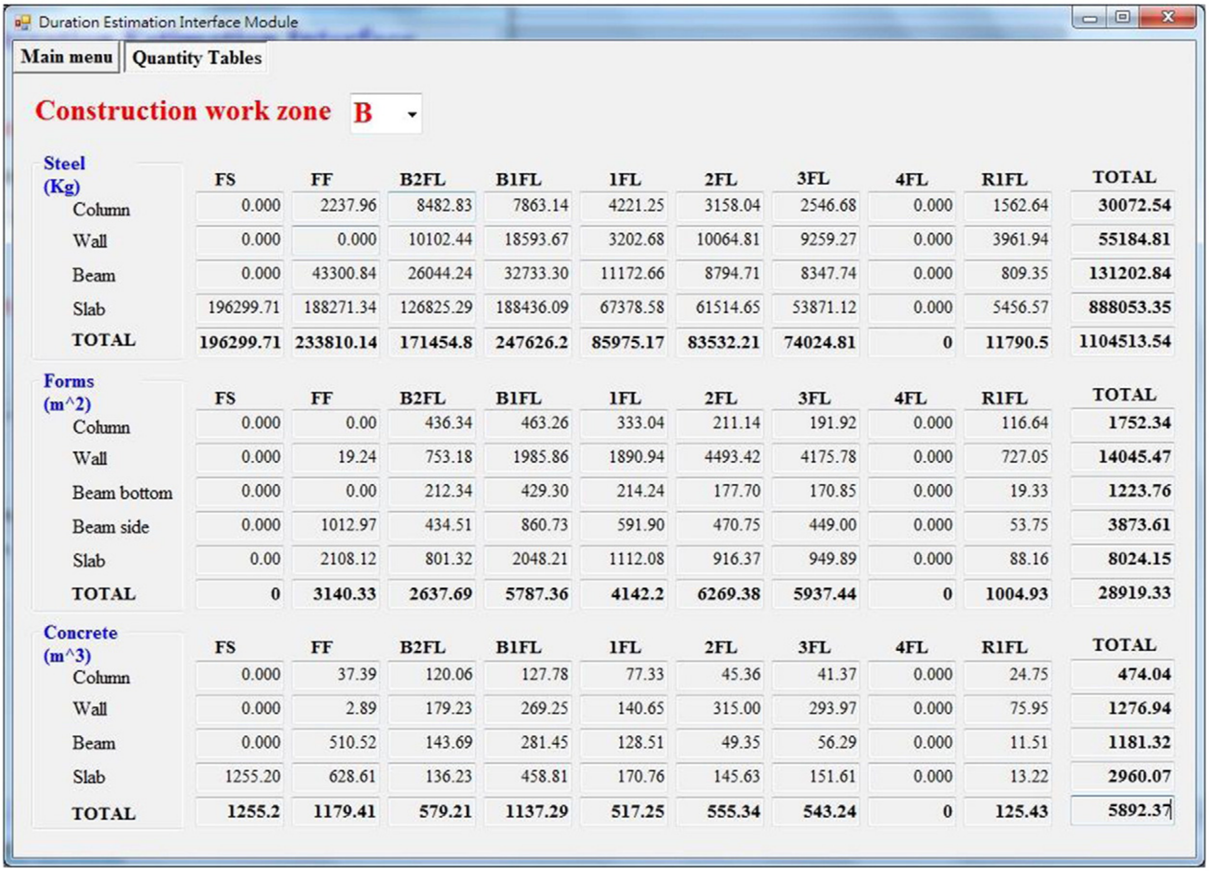
Fig. 4. 3D BIM model of the case study.

In addition, six formwork crews are involved: crew 1 handles column formwork, crew 2 and crew 3 handle wall formwork (front and back), crew 4 is responsible for beam bottom formwork, crew 5 handles beam side formwork, and crew 6 handles slab formwork. Steel work is handled by a single crew. The construction operations shown in Fig. 6 are written using the Stroboscope language.

4.3. Execution of the system

Based on the material quantities exported from the BIM model to the MS Access database, one can start the DEI system by logging in the name of the project (which is also the filename of the project). The system will then go to the main functions page of the project, as shown in Fig. 3.

Next, users can input the three point values of productivity (Step 1 in Fig. 3), the number of the sets of forms (Step 2), and the number of workers (Step 3) for each task. These productivity data were provided by the contractor's supervisor of this case project. For instance, the optimistic, most likely, and the pessimistic productivity levels for placing the reinforcing steel for the column work are 345.01, 219.26, and 93.50 kg/man-hour, respectively. In addition, the number of cranes (Step 4) and whether or not the project involves overtime work (Step 5) can also be considered. Table 2 presents some of these input data (Steps 1–5) for the case project.



Duration Estimation Interface Module

Main menu | Quantity Tables

Construction work zone B

Steel (Kg)	FS	FF	B2FL	B1FL	1FL	2FL	3FL	4FL	R1FL	TOTAL
Column	0.000	2237.96	8482.83	7863.14	4221.25	3158.04	2546.68	0.000	1562.64	30072.54
Wall	0.000	0.000	10102.44	18593.67	3202.68	10064.81	9259.27	0.000	3961.94	55184.81
Beam	0.000	43300.84	26044.24	32733.30	11172.66	8794.71	8347.74	0.000	809.35	131202.84
Slab	196299.71	188271.34	126825.29	188436.09	67378.58	61514.65	53871.12	0.000	5456.57	888053.35
TOTAL	196299.71	233810.14	171454.8	247626.2	85975.17	83532.21	74024.81	0	11790.5	1104513.54
Forms (m^2)	**FS**	**FF**	**B2FL**	**B1FL**	**1FL**	**2FL**	**3FL**	**4FL**	**R1FL**	**TOTAL**
Column	0.000	0.00	436.34	463.26	333.04	211.14	191.92	0.000	116.64	1752.34
Wall	0.000	19.24	753.18	1985.86	1890.94	4493.42	4175.78	0.000	727.05	14045.47
Beam bottom	0.000	0.00	212.34	429.30	214.24	177.70	170.85	0.000	19.33	1223.76
Beam side	0.000	1012.97	434.51	860.73	591.90	470.75	449.00	0.000	53.75	3873.61
Slab	0.00	2108.12	801.32	2048.21	1112.08	916.37	949.89	0.000	88.16	8024.15
TOTAL	0	3140.33	2637.69	5787.36	4142.2	6269.38	5937.44	0	1004.93	28919.33
Concrete (m^3)	**FS**	**FF**	**B2FL**	**B1FL**	**1FL**	**2FL**	**3FL**	**4FL**	**R1FL**	**TOTAL**
Column	0.000	37.39	120.06	127.78	77.33	45.36	41.37	0.000	24.75	474.04
Wall	0.000	2.89	179.23	269.25	140.65	315.00	293.97	0.000	75.95	1276.94
Beam	0.000	510.52	143.69	281.45	128.51	49.35	56.29	0.000	11.51	1181.32
Slab	1255.20	628.61	136.23	458.81	170.76	145.63	151.61	0.000	13.22	2960.07
TOTAL	1255.2	1179.41	579.21	1137.29	517.25	555.34	543.24	0	125.43	5892.37

Fig. 5. Summary of material quantities for construction zone B of the case project.

Next, the system user needs to provide the simulation input filename (Step 6 in Fig. 3) before executing the simulation. After *Run Simulation* (Step 7) is activated on the main functions page, the system automatically estimates the three point durations of each work task by multiplying the quantities required to be completed (such as Fig. 5) by the productivity data (Table 2) for the task. The task durations are then automatically transferred into a pre-written file of Stroboscope programming codes.

As an example, Fig. 7 shows the conversion of the input conditions (Steps 1–5) into a Stroboscope input file for performing construction operations (Fig. 6). Namely, as soon as a system user provides construction conditions, such as productivity data and number of workers (the top of Fig. 7), these conditions are mapped automatically to pre-defined Visual Basic coding statements in the DEI module (middle of Fig. 7). Furthermore, when *Run Simulation* (Step 7) is selected, the DEI module is activated to transfer all input conditions and estimated three-point durations of each work task to produce a Stroboscope input file (bottom of Fig. 7).

In this case study, Stroboscope took approximately 15.53 s to run 1000 simulation iterations. After this, the user needs to enter the output filename in order to store the simulation results in .txt format (Step 8 in Fig. 3), which allows the system to read and extract the results. Next, the user can click *Show Simulation Results* to examine a summary of the simulation results, as shown in Fig. 8. For instance, minimum duration, average duration, and maximum duration of this RC construction project are about 230, 240.5, and 251 days, respectively (top right of Fig. 8).

4.4. Simulation results

48 simulation alternatives associated with various resource allocation strategies were produced. Table 3 presents the results of a number of these alternatives. Alternative No. Base was the initial plan prepared by the contractor. The simulation results predicted that the project duration of this Base alternative would be 240.5 days, which is much longer than the contractual duration (186 days). Thus, different strategies needed to be explored. The effects of adopting various strategies for the project duration are summarized as follows:

(1) *More work zones help shorten the project duration*. The project duration could be expected to be shortened by about 7 days (i.e., Alternative No. 1; project duration = 233.4 days) by creating one additional work zone, given that all other working conditions (such as the number of laborers and the sets of available forms) are the same. The effect of such an addition could even be amplified by combining it with other strategies. For instance, Alternative No. 3 (Table 3) could generate project duration of 158.3 days if two work zones were applied and the number of sets of forms was doubled.
(2) *Additional forms help shorten the project duration.* Alternative No. 3 is an example of this case. However, just adding many sets of forms cannot shorten the project duration any further unless workers are asked to work overtime. In the case project, using two sets of forms for the column, walls, beams (bottom), and beams (side), as well as four sets of forms for the slab is suggested.
(3) *Acquiring additional cranes contributes less to shortening the project duration.* For example, Alternative No. 15 (with three cranes) generates project duration of 157.4 days, which is only about 1 day shorter than Alternative No. 3 (with two cranes).
(4) *Allocating more laborers can shorten the project duration.* For example, the project duration of Alternative No. 15 (which employs 55 steel workers) is 157.4 days, which is shorter than the

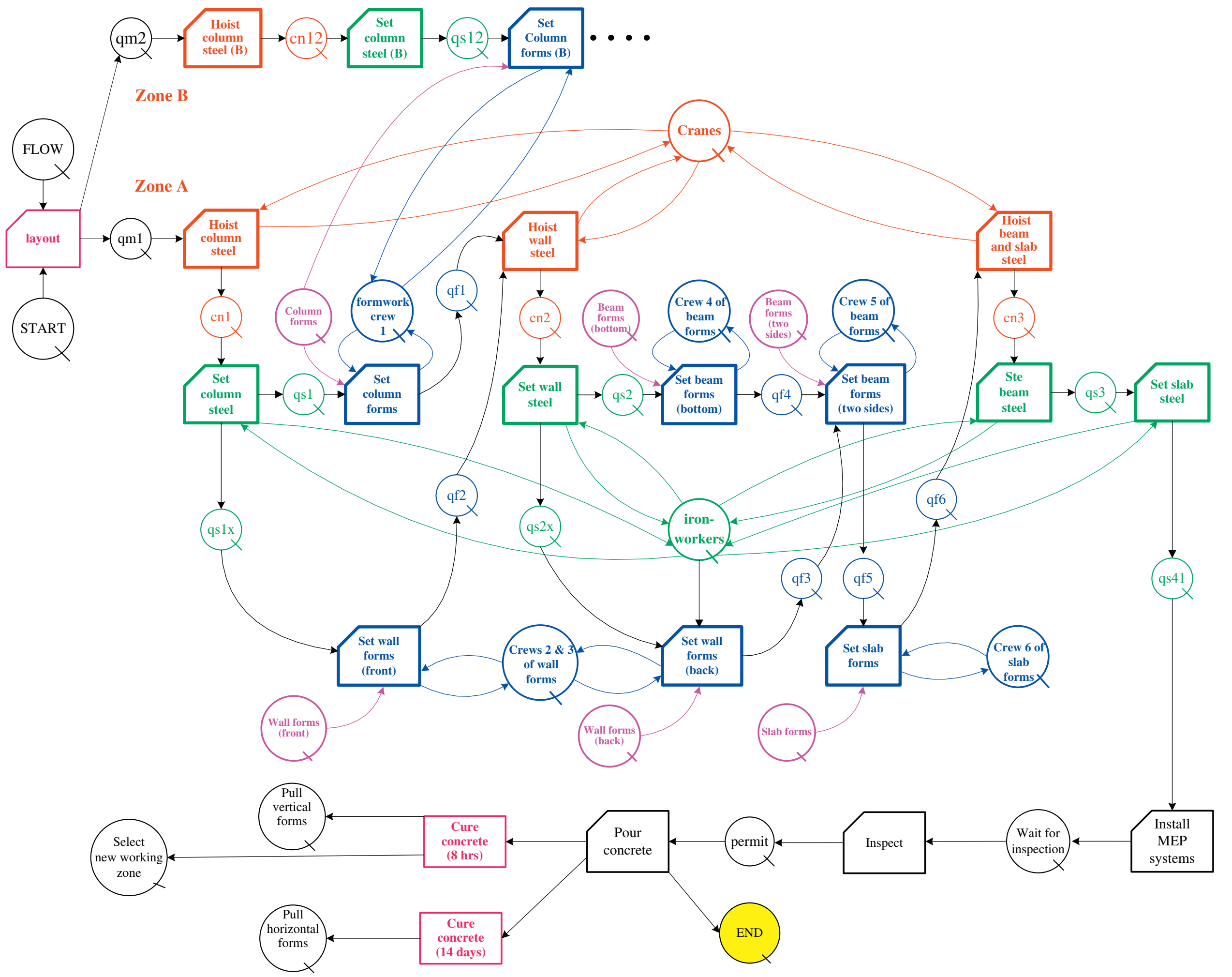


Fig. 6. Construction operations of a work zone of the case project.

duration (186.0 days) of Alternative No. 25 (with 41 steel workers), provided that all other conditions of the two alternatives are the same. Moreover, Alternative No. 15, which has three times as many formwork workers as Alternative No. 37, results in shorter project duration, that is, 157.4 days versus 181.8 days.

(5) *Overtime work can shorten the project duration.* For instance, compared with Alternative No. 37 (without overtime work; duration = 181.8 days), Alternative No. 41, which assigns all workers (for all steel work and formwork) two hours of overtime every day, has a much shorter project duration of 158.1 days.

Table 2
Productivity data for steel workers and formwork workers for the case project.

Resource	Persons	Productivity	Productivity		
		Unit	Optimistic	Most likely	Pessimistic
Steel workers					
Column	55	kg/man-hour	345.01	219.26	93.50
Wall	55	kg/man-hour	53.90	38.01	22.13
Beam	55	kg/man-hour	283.83	272.82	261.82
Slab	55	kg/man-hour	57.81	44.33	30.85
Formwork workers					
Column	30	M^2/man-hour	13.24	12.61	11.90
Wall	30	M^2/man-hour	15.75	15.00	14.25
Bottom of beam	30	M^2/man-hour	6.30	6.00	5.70
Two sides of beam	30	M^2/man-hour	5.25	5.00	4.75
Slab	60	M^2/man-hour	16.80	16.00	15.20

Among the analyses of 48 alternatives, Alternative No. 25 is suggested because it meets the contractual duration without spending too much (i.e., using fewer steel workers and without overtime work).

4.5. BIM-facilitated schedule and 4D animation

Based on the 1000 simulated project completion durations, the proposed system can generate a cumulative probability curve of the project completion time, as shown in Fig. 9. This figure shows clearly that the chance of completing the project (using Alternative No. 25) by the contractual deadline (186 days) is about 48.4%.

Next, the proposed system can convert simulation results into an MS Project schedule for Alternative No. 25 (the adopted resource allocation strategy) (Fig. 10). The user first can click the button "Output simulation results to MS Project and open MS Project" (top left of Fig. 10; the simulation results screen), to instruct the DEI module to pass simulation results to an MS Excel file (bottom right of Fig. 10). Then, the user must operate MS Project to open this Excel file and set a starting calendar date for the construction project to generate a network (or bar chart) schedule. Notably, at this moment, name, duration, and the predecessors of each work task in the Excel file are retrieved automatically by MS Project. Fig. 10 (bottom left) presents the generated schedule as viewed in MS Project.

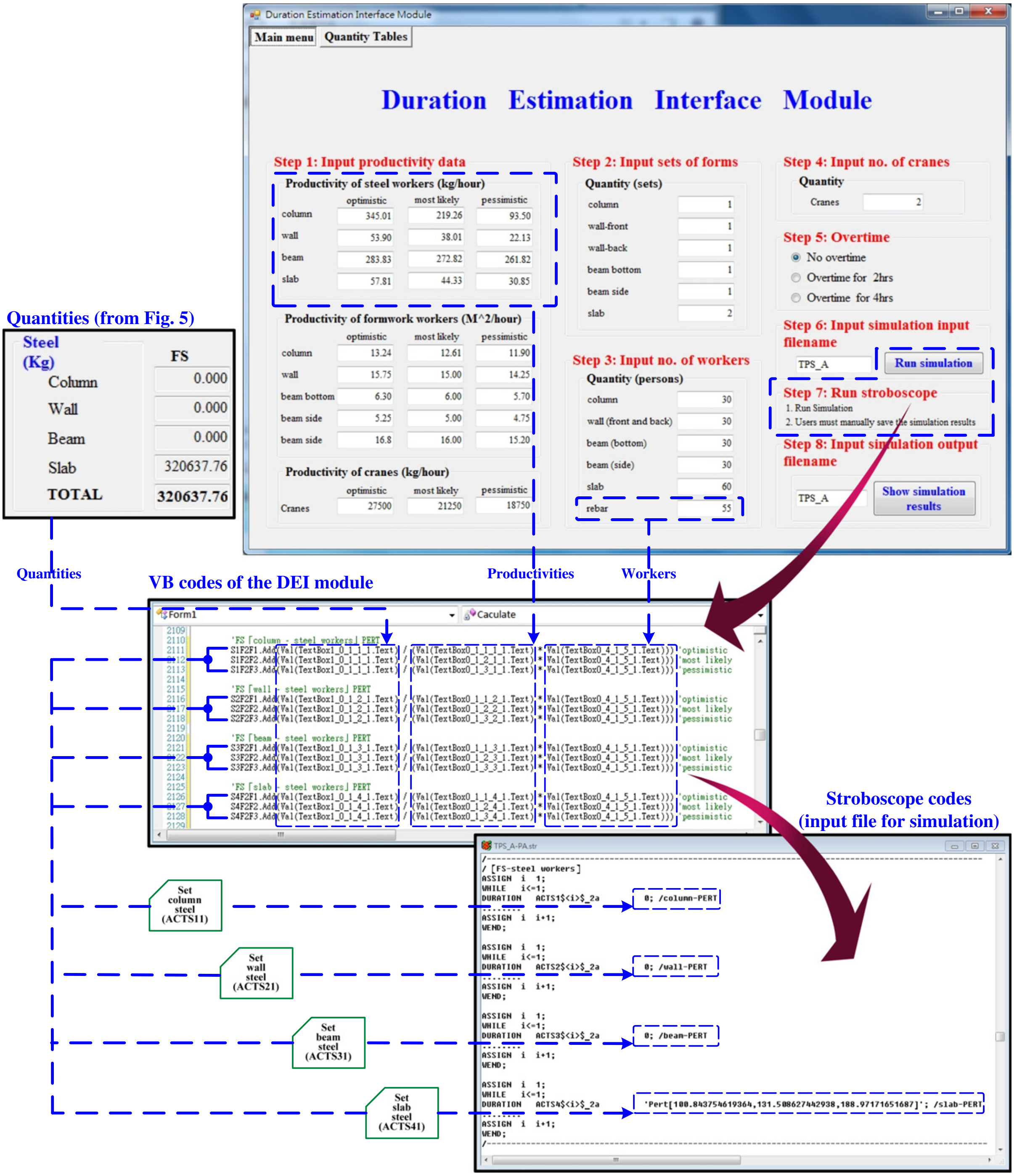


Fig. 7. Example of converting input conditions into a Stroboscope input file.

Finally, the user can combine the schedule and the BIM model in Navisworks to generate a BIM-based 4D model to obtain animated activity sequences as time passes. For example, Fig. 11 shows a screenshot of a 4D animation for the case project, in which the upper left corner of the figure displays the percentage of project time elapsed to date and the corresponding proportion of work completed.

5. Significances and discussions

As demonstrated, the proposed DEI module is the core for successfully integrating the BIM quantity takeoffs and operations simulation. Moreover, a significant programming mechanism is designed in this module that generates automatically Stroboscope simulation input files. Fig. 12 compares programming mechanisms between a manual and an automatic DEI module.

In a manual system (top of Fig. 12), when a user selects a particular number of work zones (can be 1 to N zones) for analysis, construction conditions, such as the number of laborers for formwork and number of cranes, and the estimated three-point durations of tasks must be input into a predefined simulation input file. However, data input and duration-estimating processes must be repeated and simulation codes may be revised for a new analysis with a different number of work

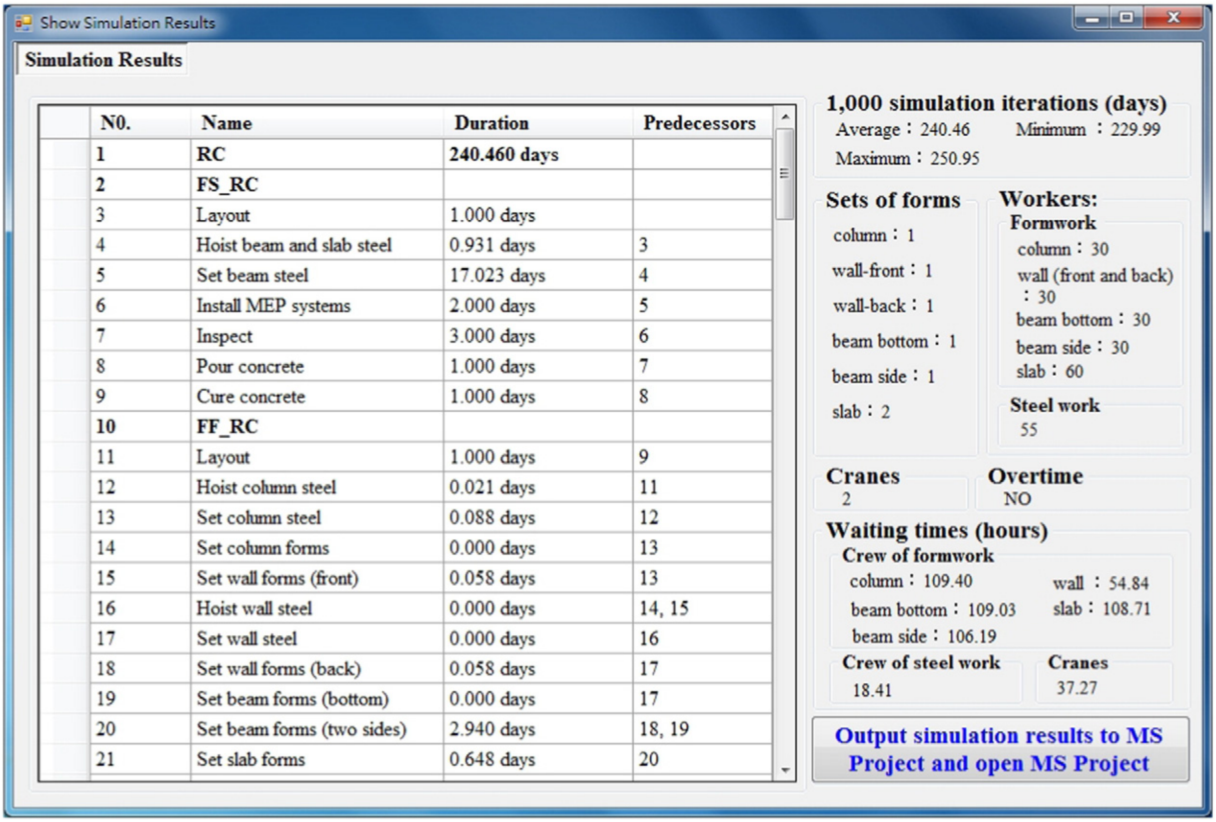


Fig. 8. Screenshot of "show simulation results".

zones. Consequently, this manual approach is time-consuming and can easily cause errors due to typos.

Conversely, the proposed DEI module (bottom of Fig. 12) uses various templates of simulation input files to respond automatically to decision alternatives (with different number of work zones). When a particular number of work zones are considered, a corresponding template for the simulation input file will be applied to execute the above manual processes, thereby saving time and increasing input data accuracy.

In addition, after presenting the proposed system and the application results to several participants in the case project, their feedback can be summarized as follows:

- Combining the BIM's quantity takeoffs and the site-level operations simulation for assessing various resource allocation strategies (and zoning alternatives) should support schedule control and site planning.

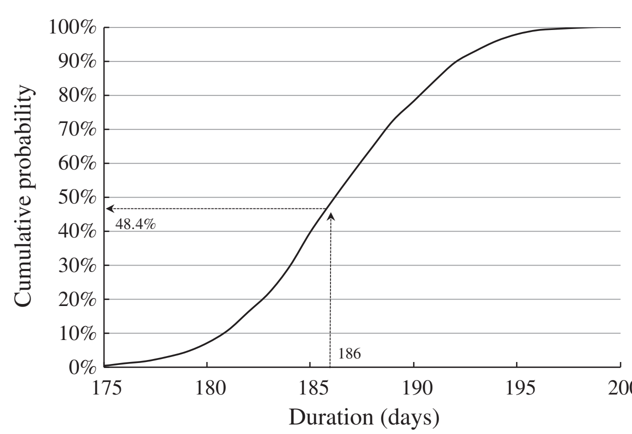


Fig. 9. Cumulative probabilities of the completion time of the case project.

Table 3
Simulation results of some construction alternatives.

Alternative no.	No. of zones	Sets of forms	Labor for formwork	Labor for steel work	No of cranes	Over-time	Duration (days)
Base (original plan)	1	1 set for column, wall, beam (bottom), and beam (side); 2 sets for slab	30 laborers for columns, walls, beams (bottom), and beams (side); 60 laborers for slab	55 laborers	2	No	240.5
1 (additional zones)	2	Same	Same	55 laborers	2	No	233.4
3 (additional forms)	2	2 sets; 4 sets	Same	55 laborers	2	No	158.3
15 (additional cranes)	2	2 sets; 4 sets	Same	55 laborers	3	No	157.4
25 (few steel workers)	2	2 sets; 4 sets	Same	41 laborers	2	No	186.0
37 (few form workers)	2	2 sets; 4 sets	10 laborers for columns, walls, beams (bottom), and beams (side); 20 laborers for slabs	55 laborers	2	No	181.8
41 (Overtime)	2	2 sets; 4 sets	Same as Alternative 37	55 laborers	2	2 h	158.1

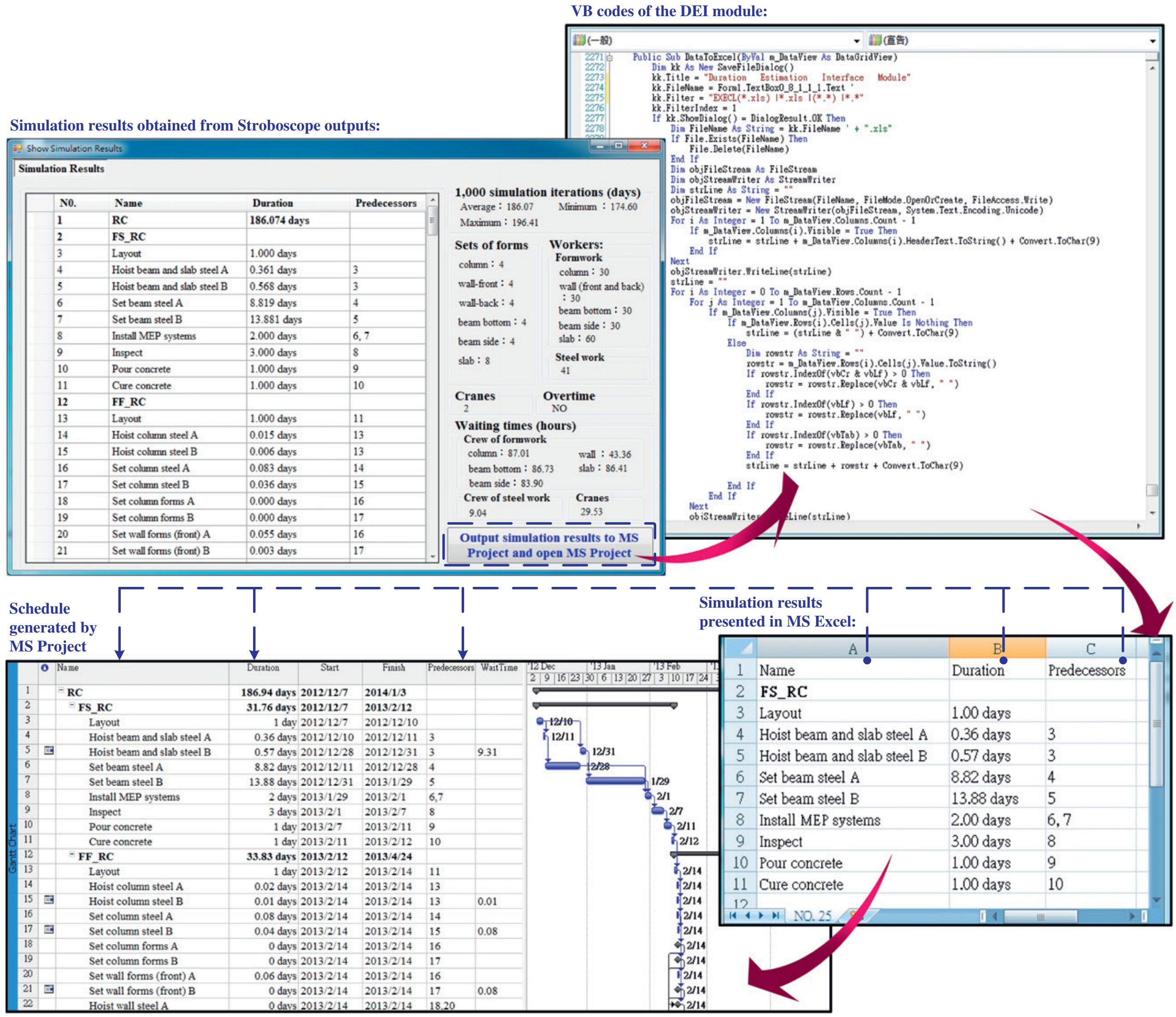


Fig. 10. Converting simulation results into an MS Project schedule for Alternative No. 25.

- Current 4D models develop 3D components and the schedule separately. Using current 4D models to animate scheduling activities forwards or backwards at any point in time to detect impossible activity sequences is difficult, because practitioners still need to image the resource availabilities and the competition among activities. The proposed system utilizes resource-oriented construction operations

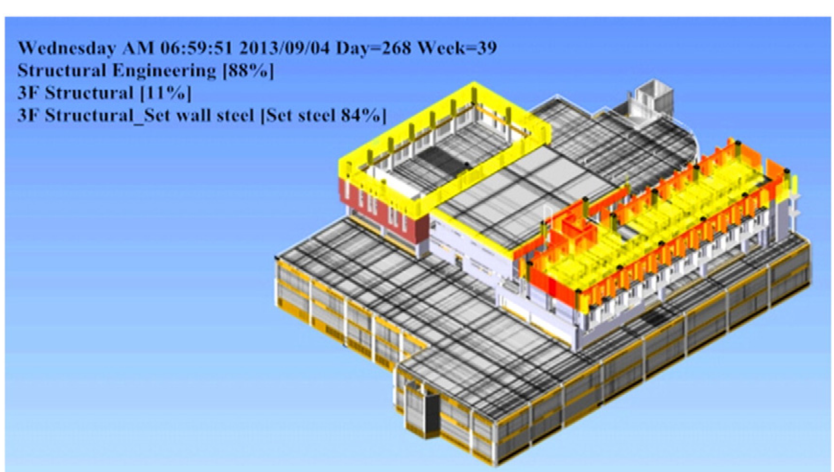


Fig. 11. Screenshot of 4D animation of the case project.

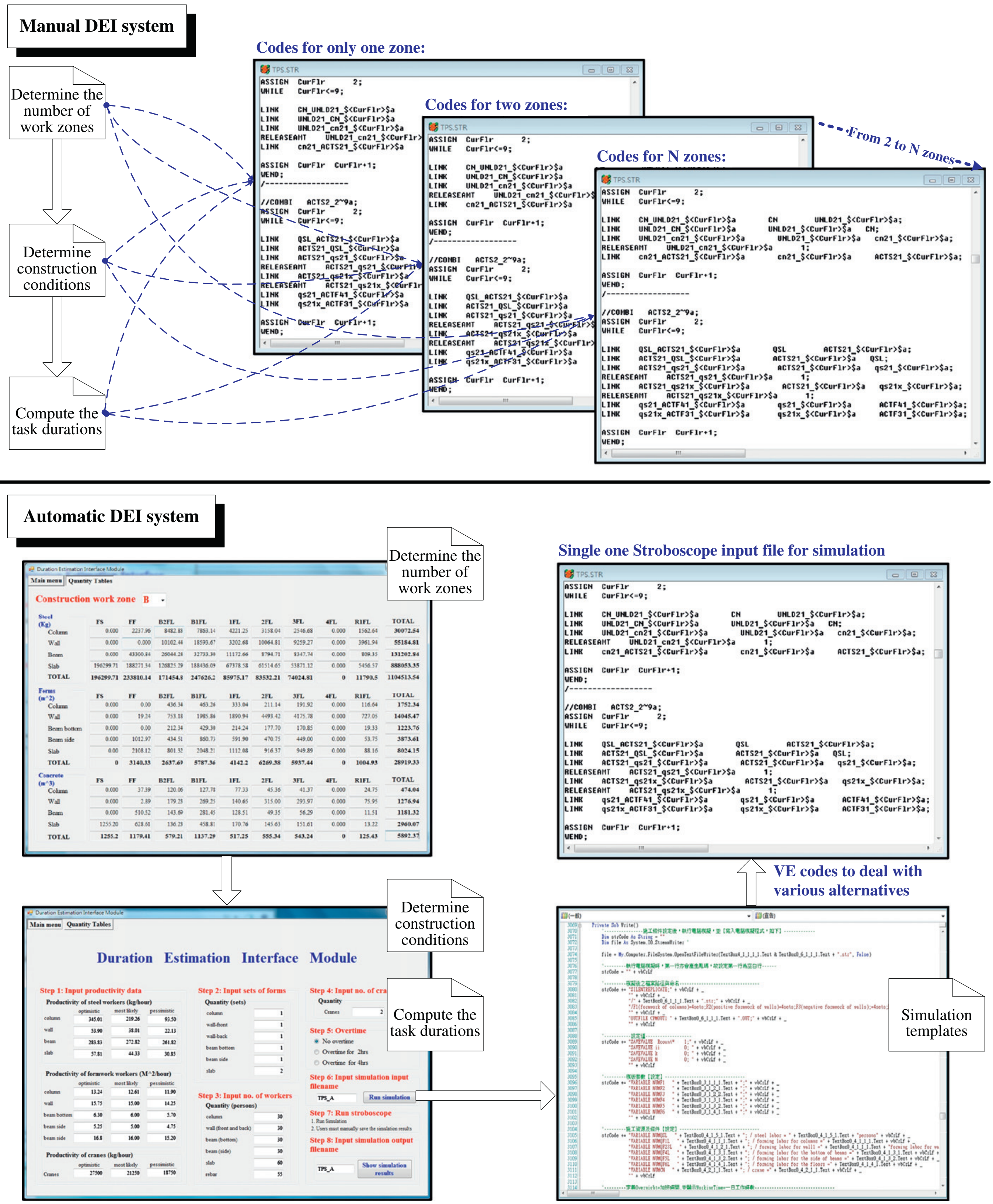


Fig. 12. Comparison of manual and automatic DEI modules.

(e.g., the network shown in Fig. 6) that are assessed by project participants in advance. Thus, its 4D animation, along with a reliable schedule, is already more effective in helping practitioners virtually understand how the project will be built.

- The current system considers only the construction tasks of erecting an RC structure. Other auxiliary tasks, such as excavation, finishing, partitioning, and landscaping, should also be included to develop a complete schedule for a building project.

- The current study focuses on the aspect of duration. Cost criteria may also be added to evaluate various construction strategies.

6. Conclusions

This work demonstrated that integrating BIM's quantity takeoffs and an operations simulation is feasible via the development of an interface system. The integration provided by this system is significant in three aspects. First, BIM can support Stroboscope simulations in providing the material quantities of construction elements to evaluate task durations in a prompt and accurate manner. Second, the operations simulation allows for the evaluation of various resource allocation strategies and considers the competition among resources in generating a suitable schedule. Third, the developed 4D model, which is not intended for animation purposes alone, presents reliable working sequences of construction activities. Overall, the proposed system demonstrated its effectiveness in enhancing the current 4D applications.

Future research in this area may also include the following directions in expanding the proposed system. First, while the current system considers RC construction operations, other types of construction operations, such as steel-reinforced concrete construction and precast construction can be developed as templates for consideration. Second, an interactive mechanism that selects and revises construction methods using rules or process patterns may be considered [33]. Third, the use of 3D symbols to define construction operations has also been suggested [37].

Acknowledgments

The authors would like to thank the reviewers for their careful evaluation and thoughtful suggestions. This research is financially supported by the National Science Council of Taiwan (Contract No. NSC100-2622-E-009-017-CC3). The authors also thank Professor Julio Martinez for making Stroboscope available, and the Concord Tech Taiwan company as well as Autodesk for supporting relevant software. In addition, the valuable assistance and collaboration of several practitioners involved in the case study are greatly appreciated.

References

[1] T. Hartmann, J. Gao, M. Fisher, Areas of application for 3D and 4D models on construction projects, J. Constr. Eng. Manag. 134 (10) (2008) 776–785.
[2] B. Koo, M. Fisher, Feasibility study of 4D CAD in commercial construction, J. Constr. Eng. Manag. 126 (4) (2000) 251–260.
[3] L.M. Sheppard, Virtual building for construction projects, IEEE Comput. Graph. Appl. 24 (1) (2004) 6–12.
[4] A.M. Tanyer, G. Aouad, Moving beyond the fourth dimension with an IFC-based single project, Autom. Constr. 14 (1) (2005) 15–32.
[5] M. Golparvar-Fard, F. Peña-Mora, C.A. Arboleda, S. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, J. Comput. Civ. Eng. 23 (6) (2009) 391–404.
[6] A. Mahalingam, R. Kashyap, C. Mahajan, An evaluation of the applicability of 4D CAD on construction projects, Autom. Constr. 19 (2010) 148–159.
[7] J.P. Zhang, Z.Z. Hu, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies, Autom. Constr. 20 (2011) 155–166.
[8] V. Popov, V. Juocevicius, D. Migilinskas, L. Ustinovichius, S. Mikalauskas, The use of a virtual building design and construction model for developing an effective project concept in 5D environment, Autom. Constr. 19 (1) (2010) 66–72.
[9] C.W. Feng, Y.J. Chen, J.R. Huang, Using the MD CAS model to develop the time-cost integrated schedule for construction projects, Autom. Constr. 19 (2010) 347–356.
[10] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook, a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, second ed. John Wiley & Sons, Inc., New Jersey, 2011.
[11] C.Y. Chen, Applying BIM and Simulation to Schedule Construction Projects, Master's Thesis, Department of Civil Engineering, National Chiao Tung University, Hsinchu, Taiwan, 2011. (in Chinese).
[12] M. Lu, Y. Zhang, J.P. Zhang, Z.Z. Hu, J.L. Li, Integration of four-dimensional computer-aided design modeling and three-dimensional animation of operations simulation for visualizing construction of the main stadium for the Beijing 2008 Olympic games, Can. J. Civ. Eng. 36 (3) (2009) 473–479.
[13] M.T. Lee, C.Y. Chen, S.W. Weng, S.H. Wang, W.C. Wang, J.J. Liu, Y.Y. Cheng, M.F. Yeh, B.Y. Lin, C.J. Kung, Integration of BIM and construction simulation for scheduling, Proceedings of the 12th International Conference on Construction Applications of Virtual Reality, November 1–2, Taipei, Taiwan, 2012.
[14] M.H. Tsai, S.C. Kang, S.H. Hsieh, A three-stage framework for introducing a 4D tool in large consulting firms, Adv. Eng. Inform. 24 (2010) 476–489.
[15] D.W. Halpin, R. Woodhead, Design of Construction and Process Operations, John Wiley & Sons, New York, 1976.
[16] D.W. Halpin, L.S. Riggs, Planning and Analysis of Construction Operations, John Wiley & Sons, New York, 1992.
[17] Z. Ma, Q. Shen, J. Zhang, Application of 4D for dynamic site layout and management of construction projects, Autom. Constr. 14 (3) (2005) 369–381.
[18] Z. Mallasi, Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualization, Autom. Constr. 15 (2006) 640–655.
[19] H.J. Wang, J.P. Zhang, K.W. Chau, M. Anson, 4D dynamic management for construction planning and resource utilization, Autom. Constr. 13 (5) (2004) 575–589.
[20] V. Benjaoran, S. Bhokha, An integrated safety management with construction management, Autom. Constr. 48 (2010) 395–403.
[21] E. Mikulakova, M. König, E. Tauscher, K. Beucke, Knowledge-based schedule generation and evaluation, Adv. Eng. Inform. 24 (4) (2010) 389–403.
[22] D.W. Halpin, An Investigation of the Use of Simulation Networks for Modeling Construction Operations, University of Illinois, Urbana, Champaign, Ill, 1973. (PhD dissertation).
[23] S. AbouRizk, K. Mather, Simplifying simulation modeling through integration with 3D CAD, J. Constr. Eng. Manag. 126 (6) (2000) 475–483.
[24] J.C. Martinez, STROBOSCOPE: State and Resource Based Simulation of Construction Process, Doctoral Dissertation, University of Michigan, Ann Arbor, MI, 1996.
[25] D.Y. Chang, RESQUE: A Resource Based Simulation System for Construction Process Planning, Univ. of Michigan, Ann Arbor, MI, 1986. (Ph.D. dissertation).
[26] L.Y. Liu, COOPS — Construction Objective-Oriented Process Simulation System, Doctoral Dissertation, University of Michigan, Ann Arbor, MI, 1991.
[27] V.R. Kamat, J.C. Martinez, Variable-speed object motion in 3D visualizations of discrete-event construction simulation models, Electron. J. Inf. Technol. Constr. 12 (2007) 293–305.
[28] V.R. Kamat, J.C. Martinez, Generic representation of 3D motion paths in dynamic animations of simulated construction processes, Autom. Constr. 12 (2008) 188–200.
[29] S.C. Kang, H.L. Chi, E. Miranda, Three-dimensional simulation and visualization of crane-assisted construction erection processes, J. Comput. Civ. Eng. 23 (6) (2009) 363–371.
[30] J.P. Zhang, M. Anson, Q. Wang, A new 4D management approach to construction planning and site space utilization, Proceedings of the 8th International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII), Stanford, 2000, pp. 15–22.
[31] M. Lu, Simplified discrete-event simulation approach for construction simulation, J. Constr. Eng. Manag. 129 (5) (2003) 537–546.
[32] M. Lu, W.H. Chan, J.P. Zhang, M. Cao, Generic process mapping and simulation methodology for integrating site layout and operations planning in construction, J. Comput. Civ. Eng. 21 (6) (2007) 453–462.
[33] I.C. Wu, A. Borrmann, U. Beisert, M. König, E. Rank, Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation, Adv. Eng. Inform. 24 (2010) 379–388.
[34] M. König, C. Koch, I. Habenicht, S. Spieckermann, Intelligent BIM-based construction scheduling using discrete event simulation, Proceedings of the 2012 Winter Simulation Conference, 2012.
[35] P.V. Rekapalli, J.C. Martinez, Discrete-event simulation based virtual reality environments for construction operations: a technology introduction, J. Constr. Eng. Manag. 137 (3) (2011) 214–224.
[36] A.H. Behzadan, V.R. Kamat, Integrated information modeling and visual simulation of engineering operations using dynamic augmented reality scene graphs, Electron. J. Inf. Technol. Constr. 16 (2011) 259–278.
[37] H.M. Chen, P.H. Huang, 3D AR-based modeling for discrete-event simulation of transport operations in construction, Autom. Constr. 33 (2013) 123–136.
[38] CIC, Computer Integrated Construction (CIC) Research Program, BIM Project Execution Planning Guide — Version 2.1, Pennsylvania State University, PA, USA, 2011.
[39] Autodesk, http://usa.autodesk.com/2012.