Automation in Construction 33 (2013) 123–136

Contents lists available at SciVerse ScienceDirect

Automation in Construction

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

3D AR-based modeling for discrete-event simulation of transport operations in construction

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ARTICLE INFO

Article history:
Accepted 29 September 2012
Available online 23 October 2012

Keywords:
3D modeling
Discrete-event simulation
Transport operations
Augmented Reality
3D animation

ABSTRACT

This study proposes a 3D visualized modeling method for DES of transport operations in construction. The 3D simulation model built is a virtual field scene with property settings. AR technology was further applied to allow the use of a real-world image as the modeling background, which pictorially presents the current status of the real site as a visual basis for modeling. A typical transport operation was analyzed to determine the component classes for modeling. Then the visual representation and attributes of each modeling component class were proposed, along with modeling rules to build the 3D simulation model. A prototype system with STROBOSCOPE as the simulation engine was developed for presenting the proposed modeling method. A set of transformation rules was proposed for converting a 3D simulation model to a STROBOSCOPE input file. The system automatically extracts the simulation output and animates the 3D model to visually demonstrate the simulation result.

1. Introduction

Discrete-event simulation (DES) is a simulation method that models operation processes by arranging a series of events in time sequence. This method is applicable in the pre-planning activities of construction projects, such as modeling a construction process for a project that is yet to be executed or modeling productivity and operation processes during construction for further improvement. Research concerning the application of DES in construction project management is cited in references [1,2]. The current integrated application of discrete event-based simulation of construction operations and 3D visual technology is mostly used at the post-processing stage [3–8]. Simulated results are visually presented as 3D animations by using animation modules in the simulation system or by using other commercial animation programs.

However, 3D visual technology has yet to be effectively integrated into pre-processing modeling of construction simulation. There are two main modeling methods adopted in construction operation simulation systems for building the process model. The first method uses text input files to define commands and data. Based on the input file's commands and format requirements, modelers must write a text input file that is readable by the simulation program, as shown in Fig. 1(a). The other method of constructing a process model is based on a flow chart. Modelers can drag components in a flow chart to build model components and to set model parameters. The on-site operation screen is abstractly presented in 2D, as shown in Fig. 1(b) [9].

From the above background analysis, it is clear that present pre-processing simulation modeling of construction operations does not facilitate an intuitive understanding and introduction due to the absence of 3D visual technology. 3D visualized models and animations are at present still the most intuitive presentations of information. In addition, non-3D pre-processing modeling is not compatible with 3D animated presentation at the post-processing phase, which leads to separate pre-processing and post-processing operations within the simulation system. This lack of integration results in a waste of resources due to repetition, decreased efficiency, and a low level of automation. In light of this, we proposed a 3D visualized simulation model of construction operations and its modeling methods. The model will provide a more detailed and intuitive presentation of model information and simulated results, and improve interactivity of the system interface. Integration of pre- and post-processing stages can also be achieved.

DES has been applied to simulate various types of problems in construction such as material transportation, lifting construction, paving, and excavation. Since the goal of this study is to propose a 3D modeling method for DES, it is desirable to choose a particular construction operation to illustrate this idea and demonstrate the feasibility of the proposed method with similar and unified applications. According to Lu and Wong [10], construction is a project-oriented business that

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0926-5805/$ – see front matter
http://dx.doi.org/10.1016/j.autcon.2012.09.015

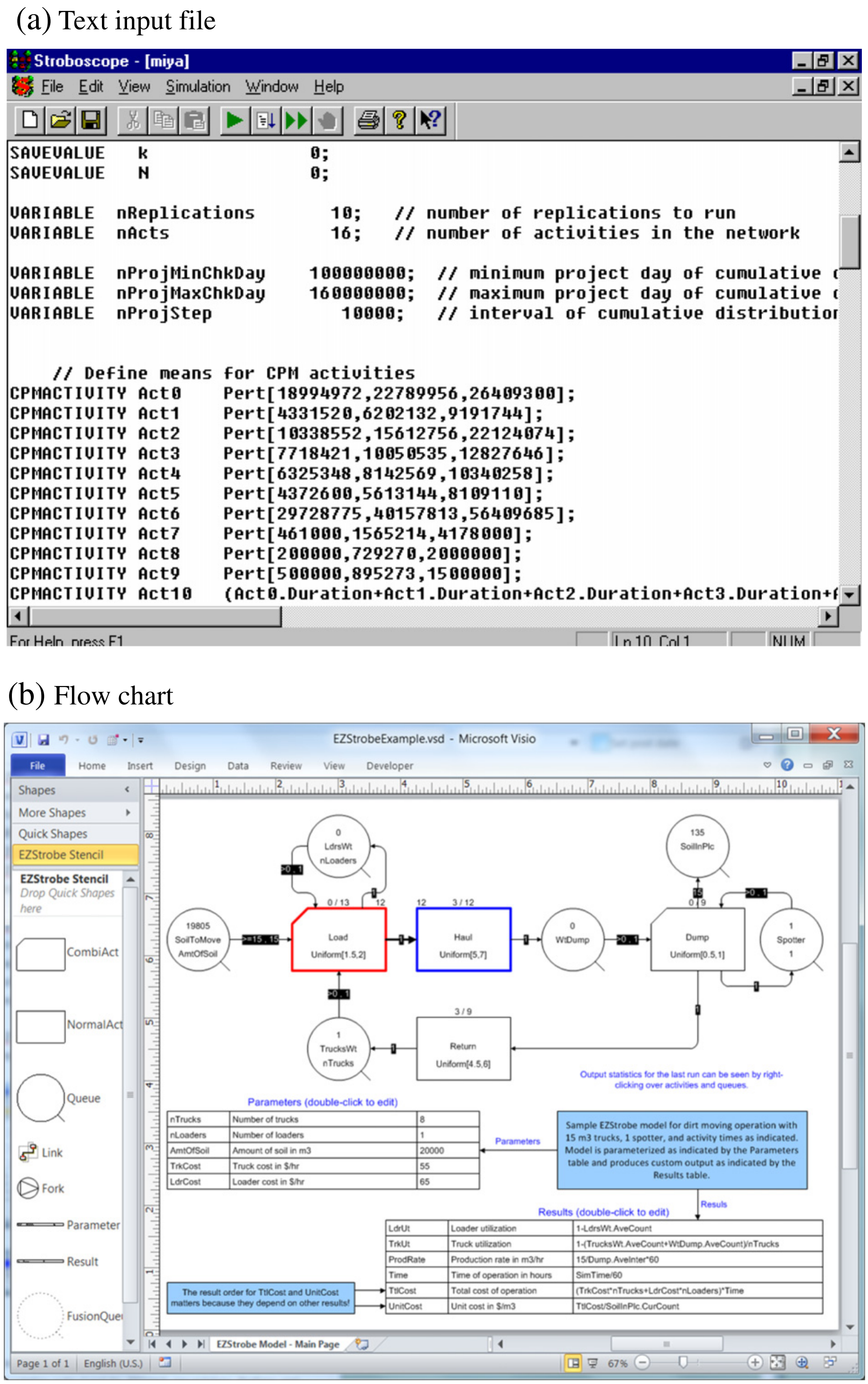


Fig. 1. The two main modeling methods for process models of construction operation simulation [9].

produces unique products; the products resulting from construction are stationary, while, the production facilities are mobile. A construction system generally happens in an open-air, outdoor environment (site) and consists of multiple interrelated workflows in cyclic or linear form. It is noted that in comparison with manufacturing, working processes in construction involve more vehicle-loop operations, where the vehicle can be broadly defined as a movable material-carrying resource. Each vehicle-loop workflow contains cyclical activities, which are arranged in a loop, and are connected with arrows following the precedence relationships imposed mainly by construction technology. Material transportation is a common in-site operation, which possesses the above characteristics of construction, thus it is chosen as a case study in this research. Since the DES applications have common features, the 3D modeling method presented in this paper for transport operations can be modified and extended for simulations of other types of construction operations.

On the other hand, during the pre-processing stage of the modeling process, modelers must have sufficient knowledge of current conditions on the construction site, and consider factors including environmental constraints, materials, positions of machinery, and accessible paths. If a 3D simulation model can be constructed directly on the actual site scene, these conditions can be dealt with visually in real time during the modeling process. Augmented Reality (AR) is an example of such a technology. It utilizes computer visualization to superimpose virtual objects on real world images for user interaction. It features three main elements — a combination of virtual objects and real field settings, interactivity in real time, and a 3D atmosphere. AR technology has been previously applied in construction [11–13]. Previous studies have applied and integrated AR technology with DES tools. Behzadan and Kamat [14,15] utilized the display of DES animations in a 3D outdoor AR environment. An AR animation authoring language was developed as the system interface that enables modelers to create AR animation of constructions simulated with a DES tool. In addition, Vitascope [16], a 3D animation system, can also allow the use of aerial photos and digital elevation models to provide a much more realistic view of the animation of the simulation by displaying virtual objects in a real-world background. However, these existing AR applications for DES are only focused on the animation of simulated operations at post-processing stage.

The application of AR in this study does not just provide a real site picture as the background of the animation of the simulation result at post-processing stage. In fact, the main purpose of applying AR in this study is to enhance the ease and precision of modeling at the pre-processing stage. By integrating AR, the proposed system allows the proposed 3D simulation model be built and superimposed directly on a real-world background, which pictorially presents the current status of the real site as a visual basis for modeling. If the system does not provide a real-world image as the modeling background, the real site and the 3D modeling world are two separated spaces. Thus, the modeler would need to manually convert the necessary geographical information including layouts or constraints of the real site to the corresponding coordinates in the virtual modeling space as the basis for modeling. Therefore, this proposed system adopts AR to solve the mapping issues caused by the separation of the real world and the virtual modeling space. AR technology is introduced into system development in order to construct an AR modeling space that provides a real site image as the modeling background. Through the AR modeling interface, the proposed 3D simulation model can be built by directly superimposing 3D model components onto the site image. In this manner, modelers can accurately position components by directly selecting the locations on the real-world background image; thus, environmental constraints at the site can be avoided in route planning. Therefore, direct integration of virtual model components and the actual field status in a model can be achieved.

2. Background

Various visualization techniques have been developed to facilitate the verification and validation of DES simulation models. Initial work used a visual diagram to represent the modeled operation as a graphical simulation model. A schematic process model, which represents the modeled process in graphic notation as a symbolic flow chart, was proposed to visualize DES. In computer-aided modeling of such graphic models, DISCO [17] and COOPS [18] provide graphical interfaces that allow the user to construct a simulation model by manipulating graphical symbols on a computer screen. These simulation systems achieve symbolic and visual modeling of DES at pre-processing stage.

Based on the graphical representation of the schematic process model, schematic visualization techniques were developed for visualizing the simulation result by overlaying information or symbols on the model diagram. Examples of these schematic visualization techniques include dynamic statistics and iconic animation. Dynamic statistics overlay run-time statistical data, such as the simulation time, resource utilization rates, productivity etc., on the graphical diagram of the simulation model. Iconic animation, on the other hand, animates the flow of resources during a simulation run by moving icons on the schematic process model background. The icons that represent model resources change position on the model's network during a simulation run in order to reflect their flow in the simulated system. Schematic visualization techniques are usually provided as added functionality in simulation tools. Previous works in schematic process models overlaid with dynamic statistics include EZStrobe [19]; and schematic process models overlaid with iconic animation include COOPS-R [20] and ABC [21]. Schematic visualization techniques achieve the integration of the pre-processing and post-processing of DES in schematic process model representation.

Schematic visualization techniques focus on highlighting important events that occur within the simulation as opposed to visualizing the process represented by activities. Therefore, they provide no sense of realistic resource motions, nor can they adequately represent the processes occurring within activities. There is also no notion of physical space and therefore cases dealing with spatial conflicts or congestion cannot be studied in such visualizations. This has been a major incentive in the introduction of animation in the validation and verification of the simulation models.

Simulation-independent animation systems allow for very realistic animations of simulated operations that can depict processes within activities effectively. Smooth and continuous animation can provide a more accurate representation of a simulated operation. It can also help overcome the inadequacies of traditional schematic visualization techniques. Examples include Vita2D [22] and SDESA [10] for 2D animation, and Vitascope [16] for 3D animation. Behzadan and Kamat [14,15] further explored the use of the display of DES animations in a 3D outdoor AR environment in order to provide a more realistic view of the animation. However, these applications are post-processed in nature. The animations are obtained in a post-processed fashion where simulation models are “instrumented” to generate animation trace files during their execution, which are later processed by the visualization system. 3D visualization techniques have not yet been applied in DES modeling at the pre-processing stage. Subsequently, modeling at the pre-processing stage and the resulting animation at the post-processing cannot be integrated due the inconsistency in their visual representations (schematic diagram vs. 2D/3D animation).

To provide a more intuitive and realistic representation of simulated operations, this study proposes a 3D visualized model along with a modeling method for discrete-event simulation of transport operations in construction. The proposed 3D simulation model is a virtual 3D field scene with property settings for each modeling component. In addition, AR technology is further applied in the prototype system development to allow the 3D model to be built by superimposing modeling components onto images of the construction site. Furthermore, the integration of pre-processing and post-processing of the simulation is achieved by animating the 3D simulation model directly to show the simulation result. Table 1 summarizes and compares previous work in the application of visualization techniques for DES together with the proposed system, thus highlighting the differences between the proposed method and previous studies in the field. First, this study achieved the application of 3D visualization techniques in DES modeling at the pre-processing stage. Second, AR technology is further applied in the prototype system development to achieve the use of a real-world image as the modeling background, which pictorially presents the current status of the real site as a visual basis for modeling. Third, the integration of pre-processing and post-processing of the simulation is achieved due to the consistency in their visual representations (3D).

3. The proposed 3D modeling for des of transport operations in construction

This study proposes 3D visualized modeling for simulation of transport operations in construction. The proposed construction simulation model is a 3D field model with integrated simulation information as the model components attributes. Further integration with AR

Table 1
Summary of previous work in the application of visualization techniques for DES.

	Pre-processing	Post-processing	Integration of pre-processing and post-processing
DISCO [17]	Schematic process model	Text file	N/A
COOPS [18]	Schematic process model	Text file	N/A
EZStrobe [19]	Schematic process model	Dynamic statics	Schematic visualization
COOPS-R [20]	Schematic process model	Iconic animation	Schematic visualization
ABC [21]	Schematic process model	Iconic animation	Schematic visualization
Vita2D [22]	Schematic process model	2D animation	N/A
SDESA [10]	Schematic process model	2D animation	N/A
Vitascope [16]	N/A	3D animation	N/A
Behzadan and Kamat [14,15]	N/A	3D AR animation	N/A
The proposed system	3D model	3D AR animation	3D visualization

technology allows the 3D model to be superimposed onto photos or real-time images of the construction site, thus producing an intuitive simulation model that matches with actual field status through the integration of virtual and real 3D field settings. For the 3D visualized simulation model of the construction site, we investigated the integration of data required in modeling the operation process with the 3D model by setting the data as attributes of the model components. This study also proposes constitutive components of the parametric model and its modeling method. After simulation modeling, attributes contained in the 3D model are automatically formatted into a text input file of an existing simulation program, according to transformation rules. The simulation program can then complete the simulation analysis.

The integration of the 3D model and modeling information allows three-dimensional representation of the simulated construction operation process model, and a 3D modeling method for constructing the model. Moreover, 3D visualization of the pre-processing simulation model enables it to be integrated with post-processing operations. Animation of simulated outputs from post-processing no longer demands additional customized modeling. Simulated results are automatically captured by the program and integrated into the 3D visualized simulation model built in the pre-processing stage. Simulated results are also presented as dynamic animations.

To achieve integrated modeling with real and virtual objects, the 3D simulation model is combined with field images by introducing AR technology. When modeling the simulated construction site, designers can import current photos or real-time images of the construction site by using the system's image capture device. AR technology enables the 3D model to be directly constructed on the photos or real-time images of the site so that modelers can deploy the model structures as if they were actually on site.

Modelers can obtain modeling information intuitively and accurately from the imported field images. For example, without taking any measurements, simply by making selections on images, modelers can obtain the current or expected positions of machinery or materials on site. When planning moving paths for machinery, environmental constraints can be avoided since paths are superimposed onto field images. The system can dynamically present simulated results in AR mode. Through the combination of real and virtual objects, users can gain an intuitive understanding of the simulated construction operation in the field scene.

In this study, a prototype system was developed for the proposed modeling method. The development involved integration of STROBOSCOPE [23] simulation software as the simulation engine of the system. ARToolKit [24] was used for the introduction of AR technology. The operation process is shown in Fig. 2. The system imports field photos or images to the AR interface using image capture devices, and modelers can then directly place 3D model components on the field scene through the interface to achieve integration of real and virtual fields. They can also set material properties and machinery properties using the interface. A synchronization mechanism for the system coordinates in the simulated construction fields for the 3D and AR interfaces is utilized to ensure consistency. Depending on the requirements of the operation, modelers can switch between the two interfaces, choosing the proper one to perform the modeling. Modelers can use model components stored in the component library to populate the model. Once the simulation model is complete, model components are formatted as a STROBOSCOPE text input file according to transformation rules proposed in this study. Attributes of the model components will be set as parameters for corresponding commands. The system can then perform simulation using the text input file for STROBOSCOPE, and results are extracted automatically and fed back to the system. The automatically extracting and returning simulated results to model components, and presenting them as a 3D animation gives modelers an intuitive view of the simulated results.

4. 3D visualized simulation model of the construction operation

Aimed at 3D visualization of the construction operation site and integration of modeling information, model components and modeling procedures for the 3D visualized simulation model are proposed in this study. Based on the requirement of 3D visual presentation of the site, we proposed model component classes that constitute the simulation model, as well as 3D presentation methods for each class. Modeling information or parameters are assigned as attributes of the relevant model component classes. Based on these model component classes with assigned attributes, relationships among the attributes and their time sequences are analyzed and examined. Modeling rules, parameter setting, and the modeling procedure are subsequently proposed.

4.1. Determination of model components

To determine the 3D visual presentation of model components, one must analyze common modeling requirements of various 3D models in the construction operation field. Transport operation is a common and typical construction operation simulated using DES. Examples can be found in [1,8–10,19,21,23]. Typical transport operation in construction can be defined as construction vehicles (movable material-carrying resources) transport or move materials in a workflow of looping structure (vehicle-loop) at a construction site. It possesses the key characteristic of construction operation, which involves multiple interrelated workflows in vehicle-loop, and each vehicle-loop workflow contains cyclical activities. Therefore, this study adopts a typical example of material transport in construction, which is shown in Fig. 3, to describe the analysis process. This example is a transport operation involving trucks transporting steel bars. Trucks depart from two places; they pass through a bridge to arrive at the steel bar storage location, and transport them back to their respective origin. Since there is a river, the transport route has roads and a bridge spanning over the river. The goal of this operation is to choose appropriate routes for trucks to transport steel bars from (B) to (A) and (D), and unload them there. In the end, steel bars at (B) are all moved to (A) and (D) after many

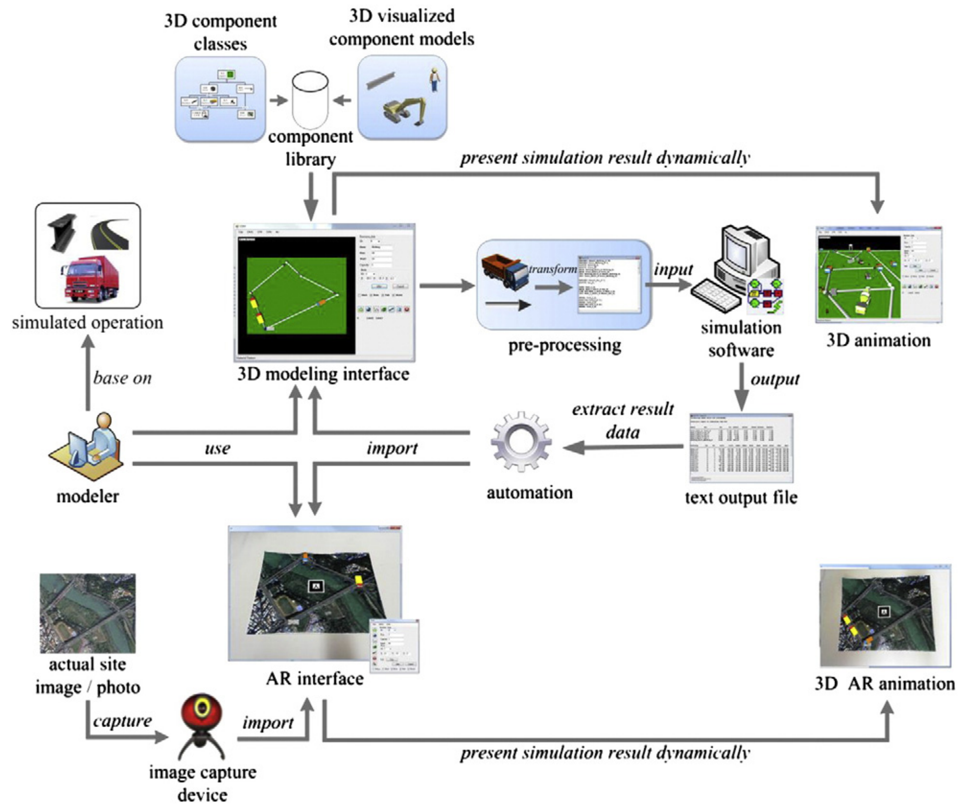


Fig. 2. The operation process of the proposed 3D visualized modeling and simulation for construction operation.

transportation runs. If this operation is described as a model, it comprises the following units:

1. Area (construction field): Fig. 3.
2. Node (position): (A), (B), (C), (D), (E).
3. Machinery: truck 1, truck 2.
4. Resource (material): steel bar.
5. Path: (1): (A) → (B), (2): (B) → (C), (3): (C) → (D), (4): (D) → (E), (5): (E) → (A).
6. Route: truck 1: (1) → (2) → (3) → (4) → (5), truck 2: (4) → (5) → (1) → (2) → (3).

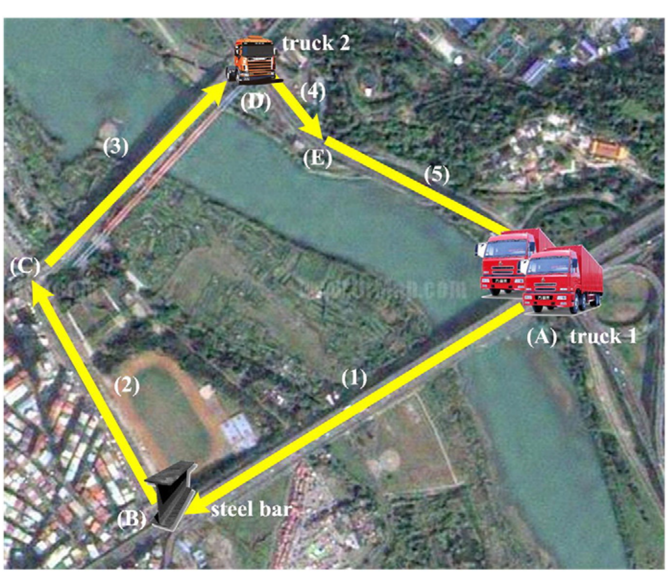


Fig. 3. A typical example of transport operations in construction.

The steel transportation problem described in this section is a simple but typical case used as an example to identify modeling elements, as well as illustrating the following method for 3D modeling. The proposed system can be used for simulating all kinds of transport operations in construction involving complex interactions, such as earthmoving, material logistics, etc. Steel transportation is not the only application of the proposed method and system.

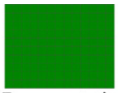
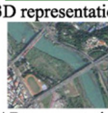
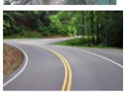
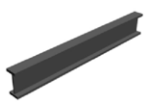
4.2. 3D visualization and parameterization of model components

The purpose of this study is to propose a 3D visualized simulation model for construction operations. On the basis of model component classes determined from the example in Fig. 3, appropriate 3D visual representations for these component classes must be proposed first, as summarized in Table 2. 3D representations of the model components enable modelers to intuitively construct the operation field, as shown in Fig. 3, by placing and arranging model components in the virtual space.

The model built from the proposed classes of model components is a pure 3D visualized field model. It requires further integration of simulation information, as model attributes, in order to become a complete simulation model. Therefore, this study analyzes information required in model simulation, and determines various parameters such as quantity, type, distance, and velocity. The information is then assigned to relevant classes of model components as their attributes. The values of the attributes describe details of the 3D construction operation model.

The proposed attributes of the 3D model component classes are summarized in Table 2. The integration of required simulation information as attributes of classes not only allows 3D visualization of model components but also their parameterization. A simulation model that is built from visualized and parameterized model components can present field operations using 3D model components of various classes, and the attributes contained in each model component can be provided to construction operation simulation software for computation.

Table 2
3D visual representations and attributes of model components.

Model component class	Corresponding field element	3D visual representation	Component attributes
Area		 3D representation  AR representation	Length, width, height
Node			Coordinate (x、 y、 z)
Path			Starting node, ending node, distance
Machinery			Amount, node, type, speed, capacity, route
Resource			Node, amount, type, operating time

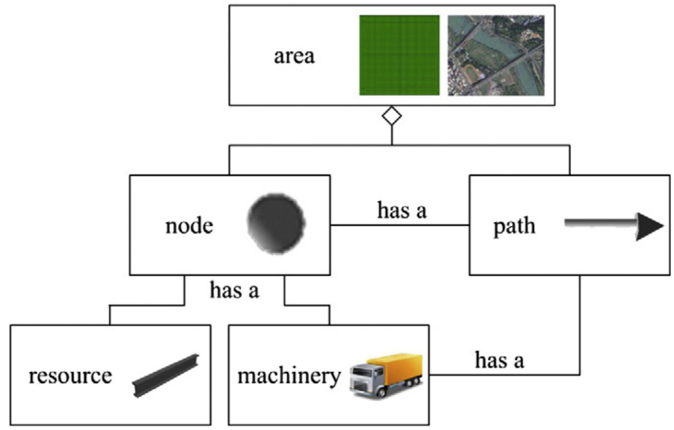


Fig. 4. The relationships between model components (in class diagram UML).

4.3. Relationships between model components

Parameterized model components are proposed based on the requirements of 3D visual presentation and simulation calculations. Due to the inter-dependency of the model components in constructing the simulated field scene, their relationships must be examined, and modeling procedures should be proposed accordingly. The relationships between model components are demonstrated in Fig. 4. The top level of the structure is 'Area', and components can be placed on other model components through this class. 'Node' is used in positioning other classes of components, and 'Path' can only be modeled using 'Node' as its referential attributes. 'Resource' and 'Machinery' also use 'Node' as reference attributes for their positions, and therefore both component classes use 'Node' either directly or by referencing. In addition, 'Machinery' must obtain path components by referencing to select its route.

4.4. Modeling procedure of assembling model components

On the basis of proposed relationships between model component classes, this study has derived some basic modeling rules: (1) 'Node' must be placed within the 'Area', and cannot be outside the defined region; (2) 'Path' cannot exist independently at the construction operation field scene — it must be defined between existing start and end nodes; (3) 'Machinery' must be placed on 'Node', and its moving path must be an existing 'Path'; (4) 'Resource' must be placed on 'Node'. In principle, if all four rules are satisfied, modelers can freely place and connect components to build the 3D simulation model. However, in order to have a systematic modeling procedure in place, the modeling procedure shown in Fig. 5 is suggested based on the aforementioned rules. Modelers must first set the length and width of the 'Area' to define the model base. 'Node' is created next by selecting a point in the 'Area', and positions of various model components and points on their paths are marked for modelers to use as references for placing other components. After this step, 'Path' is created by selecting start and end nodes, and connecting them. 'Path' specifies machinery routes and directions. After routes are planned, 'Machinery' can be placed on a corresponding 'Node', and an existing route can be set as its referential attribute. Finally, 'Resources' to be transported by machinery can be placed on a selected 'Node'. After the placement of model components, models are chosen from the component library with the appearance of various machinery and materials to represent the simulated field scene. As shown in Fig. 5, accurate positioning for various modeling components can be achieved by selecting the locations directly on the field image through the AR modeling interface.

5. Formatted output of the stroboscope text input file based on model attributes

The prototype system of the 3D visualized simulation model proposed in this study uses STROBOSCOPE as the engine to perform its simulation calculations. For the adopted engine to be able to perform simulation on the 3D model, model attributes must be automatically formatted as a text input file for STROBOSCOPE. To define the transformation rules, one must interpret command keywords and grammar rules of the STROBOSCOPE text input file, and analyze its various types of command structures. For each model component, the corresponding command structure is determined. A format transformation rule for each component is derived, and component attributes are set as parameters required by corresponding commands. The analysis and derivation procedure of the transformation rules are presented in Fig. 6.

5.1. Modeling commands for STROBOSCOPE

To automatically transform the 3D simulation model to a text input file for STROBOSCOPE, commands and grammar structure of the text input file must be analyzed. A STROBOSCOPE input file is shown in Fig. 7. There are three main types of commands: component command, attribute command, and control command. A component command generates various constitutive components during the simulation process. Simulated construction operations in the system are mainly constructed using this type of command. An attribute command sets the attribute value of a component command, such as construction duration of normal work item (NORMAL) and how far resource waiting nodes (QUEUE) need to be shifted. A control command governs the corresponding component command and system operation of the simulation, such as connecting work items. The modeling commands and their descriptions are tabulated in Table 3.

Based on all possible relationships between component commands and control commands in the STROBOSCOPE text input file, this study proposes flow charts of all types of command structures, as tabulated in Table 4. The following is a description of the structures:

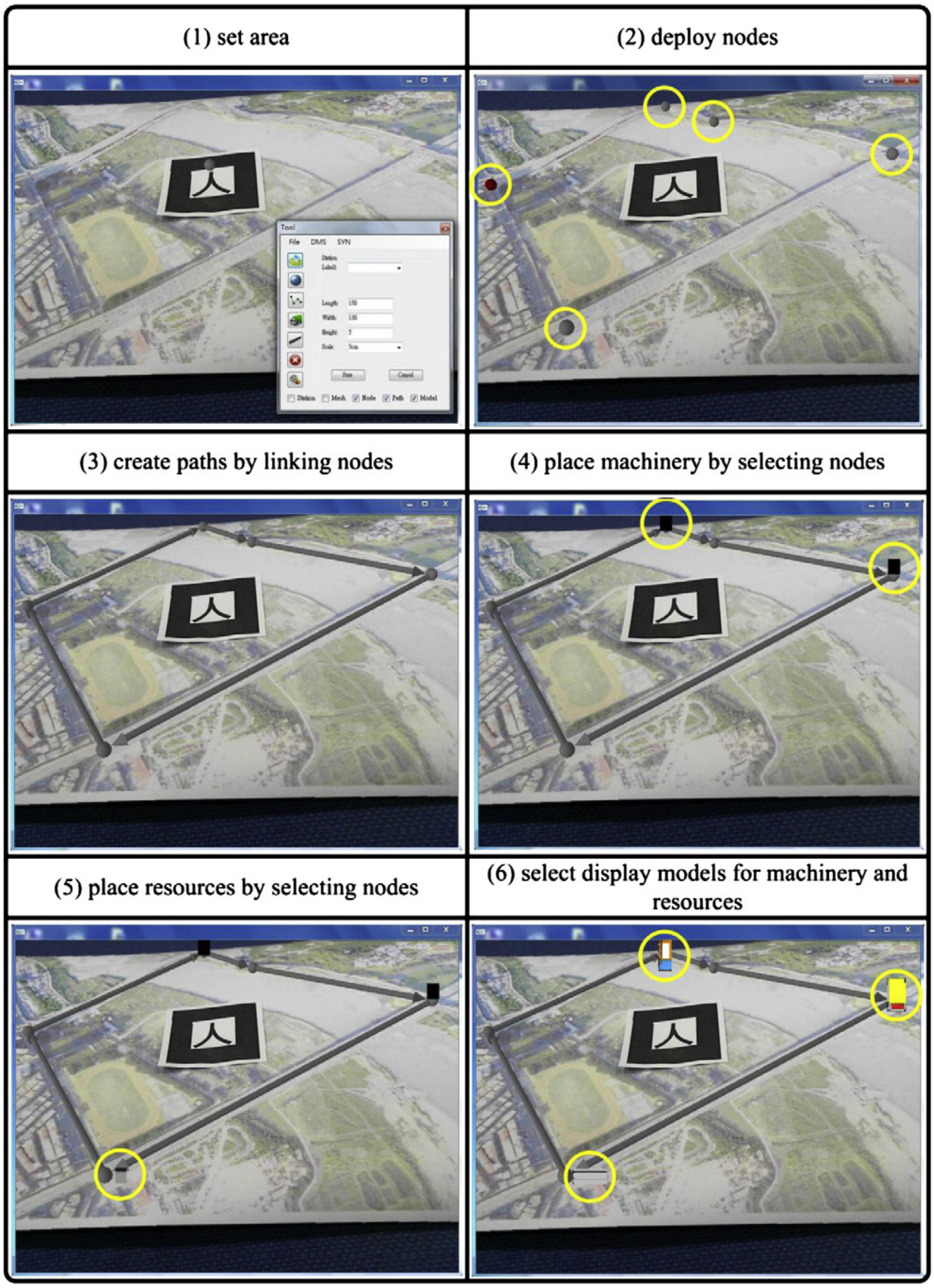


Fig. 5. The suggested modeling procedure.

Type (1): Consists of two normal work items (NORMAL). This structure mainly deals with construction items that do not need to wait, such as a truck driving from location A to B.

Type (2): Consists of a constrained work item (COMBI), a normal work item (NORMAL), and a waiting node (QUEUE). It is mainly used in work items that can be executed once a certain condition is satisfied, e.g. a truck needs to wait for the excavator to remove the soil before it can transport it.

Type (3): Consists of a constrained work item (COMBI), a normal work item (NORMAL), and two waiting nodes (QUEUE). It is primarily used in work items with a limited number of items and can only be carried out once a certain condition is satisfied. Therefore, the next item can be started only when the preceding item is finished. Once an item is completed, it can move to other work items. An example is when a patient visits a doctor; only the patient or families of the patient are allowed to enter. The next patient can only enter once the current session ends.

Type (4): Consists of a constrained work item (COMBI), a normal work item (NORMAL), and two waiting nodes (QUEUE). It processes different events due to a differing sequence compared to the previous structure. For example, in a concrete coring test, a certain number of test specimens must be drawn for testing, and operators must wait for the test report.

Type (5): Consists of two constrained work items (COMBI) and three waiting nodes (QUEUE). It is mainly used in continuous trigger events. Only when a condition is satisfied can the next restriction be executed, and there is a limitation on the number of items for the succeeding work. For example, construction workers must wait for a manager's order to start work, and

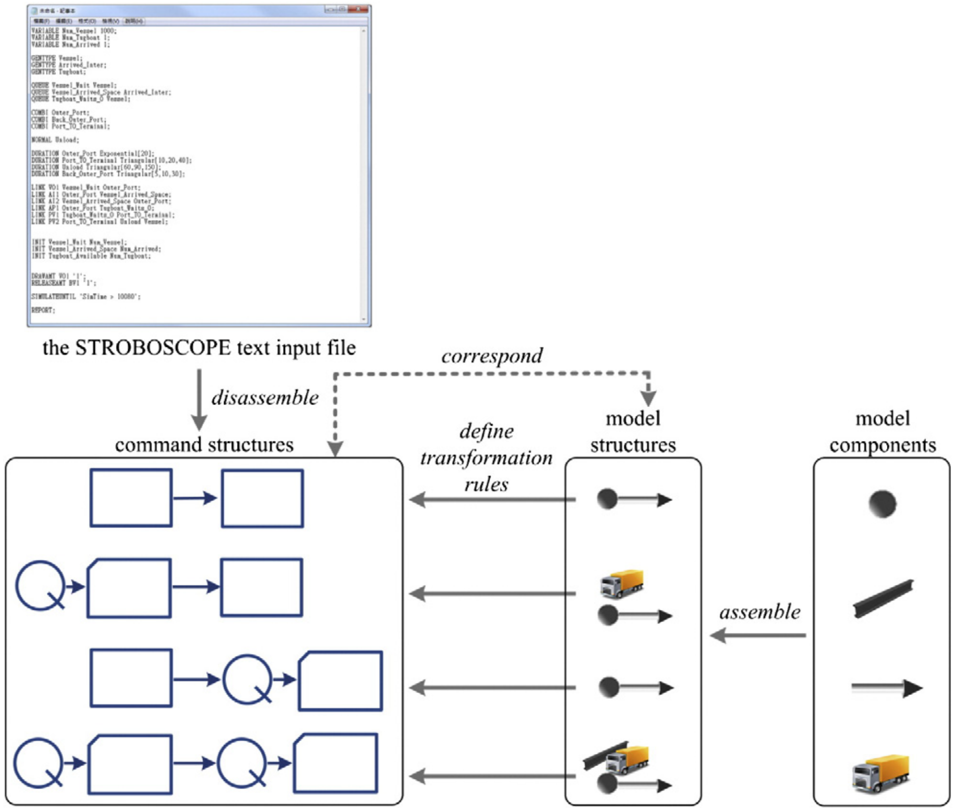
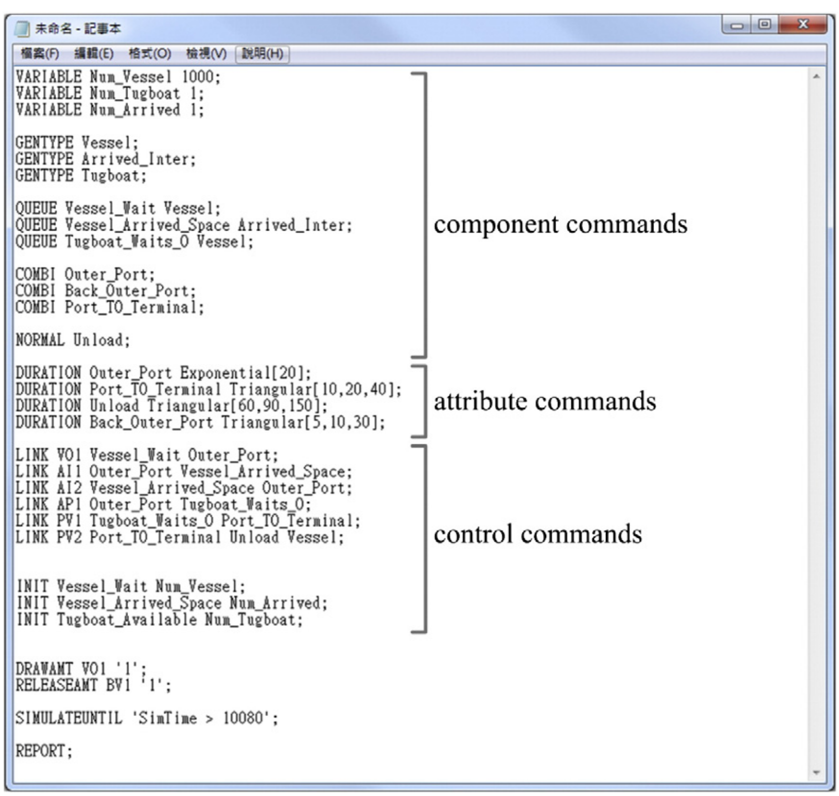


Fig. 6. The analysis and derivation procedure of the transformation rules.

the number of workers on a task is specified by the manager.

Type (6): Consists of two constrained work items (COMBI) and four waiting nodes (QUEUE). It is mostly used for a series of trigger events with limited quantities. Only a number of work items can be processed, and finished work items are still affected by limited numbers of the next work item. For example,




```
VARIABLE Num_Vessel 1000;
VARIABLE Num_Tugboat 1;
VARIABLE Num_Arrived 1;

GENTYPE Vessel;
GENTYPE Arrived_Inter;
GENTYPE Tugboat;

QUEUE Vessel_Wait Vessel;
QUEUE Vessel_Arrived_Space Arrived_Inter;
QUEUE Tugboat_Waits_0 Vessel;

COMBI Outer_Port;
COMBI Back_Outer_Port;
COMBI Port_TO_Terminal;

NORMAL Unload;

DURATION Outer_Port Exponential[20];
DURATION Port_TO_Terminal Triangular[10,20,40];
DURATION Unload Triangular[60,90,150];
DURATION Back_Outer_Port Triangular[5,10,30];

LINK VO1 Vessel_Wait Outer_Port;
LINK AI1 Outer_Port Vessel_Arrived_Space;
LINK AI2 Vessel_Arrived_Space Outer_Port;
LINK AP1 Outer_Port Tugboat_Waits_0;
LINK PV1 Tugboat_Waits_0 Port_TO_Terminal;
LINK PV2 Port_TO_Terminal Unload Vessel;

INIT Vessel_Wait Num_Vessel;
INIT Vessel_Arrived_Space Num_Arrived;
INIT Tugboat_Available Num_Tugboat;

DRAWAMT VO1 '1';
RELEASEAMT BV1 '1';

SIMULATEUNTIL 'SimTime > 10080';

REPORT;
```

Fig. 7. A STROBOSCOPE input file example.

Table 3
The modeling commands of STROBOSCOPE.

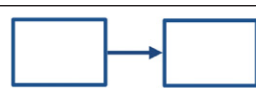
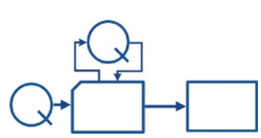
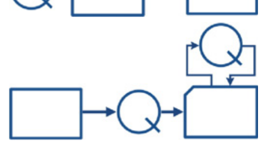
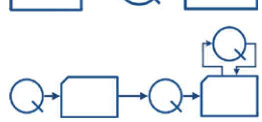
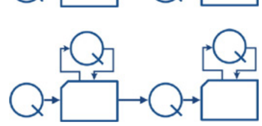
Category	Command	Description	Flowchart element	Usage for settings
Component commands	VARIABLE	Define variables and numerical values		
	GENTYPE	Define resource types and names		
	QUEUE	Define resource waiting nodes		
	COMBI	Define constrained work item		
	NORMAL	Define normal work item		
Attribute commands	DRAWAMT	Set quantity of resources transported every time		QUEUE
	DRAWDUR	Set time spent in moving resources		QUEUE
	DURATION	Set time spent on the work item		COMBI, NORMAL
	RELEASEAMT	Set quantity of resources released every time		QUEUE
Control commands	INIT	Specify on which resource waiting node resource is to be placed		VARIABLE/GENTYPE ➔ QUEUE
	LINK	Specify linked work items and their sequences		QUEUE ➔ COMBI NORMAL ➔ NORMAL NORMAL ➔ QUEUE COMBI ➔ NORMAL COMBI ➔ QUEUE
	COLLECT	Collect required information		
	SIMULATE	Stop the simulation when resource is exhausted		
	REPORT	Display relevant information after the simulation is complete		

when buying train tickets, only after the person in front finishes buying the ticket can the next person in line buy his. Later on at the entry, the person behind can only enter the station after the person in front enters.

5.2. Transformation rule for formatted output of model attributes

Adopting the various types of command structures for STROBOSCOPE text input files listed in Table 4 as unit for analysis, transformation rules for formatting the output of attributes of the 3D simulation model are proposed. Correspondence between model structures in the 3D model and command structures are first identified. Automatic transformation rules between the model structures and their corresponding command structures are derived. According to these transformation rules, the 3D simulation model is disassembled into model structures, which are subsequently converted to command structures to compose the STROBOSCOPE text input file. This transformation mechanism is presented in Fig. 8. To achieve automatic transformation, we propose transformation rules between each model structure and its corresponding command structure.

Table 4
The command structures of STROBOSCOPE.

Type	Elements	Flowchart presentation
(1)	2 NORMAL	
(2)	1 QUEUE, 1 COMBI, 1 NORMAL	
(3)	2 QUEUE, 1 COMBI, 1 NORMAL	
(4)	1 NORMAL, 2 QUEUE, 1 COMBI	
(5)	3 QUEUE, 2 COMBI	
(6)	4 QUEUE, 2 COMBI	

By analyzing command structures, it can be found that they basically correspond to a node and a path, with this node as its starting point in the 3D model. The differences lie in the choice of connecting components such as machinery and materials, and attribute settings. The basic structure of model structures mainly consists of a node and the path that starts from it. There are also machinery and materials components. Table 5 contains model structures corresponding to command structures in the STROBOSCOPE input file listed in Table 4. The command structures chiefly include two construction work items and different numbers of waiting nodes. According to constraint attributes of path components and those of the model components which are attached to the node in each model structure, various types of model structures are transformed to command structures, and command parameters are set on the basis of attributes contained in the model components.

Taking type (2) of the model structures as an example, the command structure that this model structure corresponds to consists of a constrained work item (COMBI), a normal work item (NORMAL), and a waiting node (QUEUE). Defining the machinery using resource command component (GENTYPE), and defining the waiting node (QUEUE) that the machinery is to be placed on, the link following the resource waiting node (QUEUE) must be constrained item (COMBI); therefore, constrained item must be defined to be linked to the waiting node (QUEUE). The INIT command is then used to place the machinery at the resource waiting node. Transformation of the connected path is done by defining normal items based on the state of the path component. Travel time is calculated by dividing the machinery's distance traveled by its speed attribute. The calculated time is set as operation

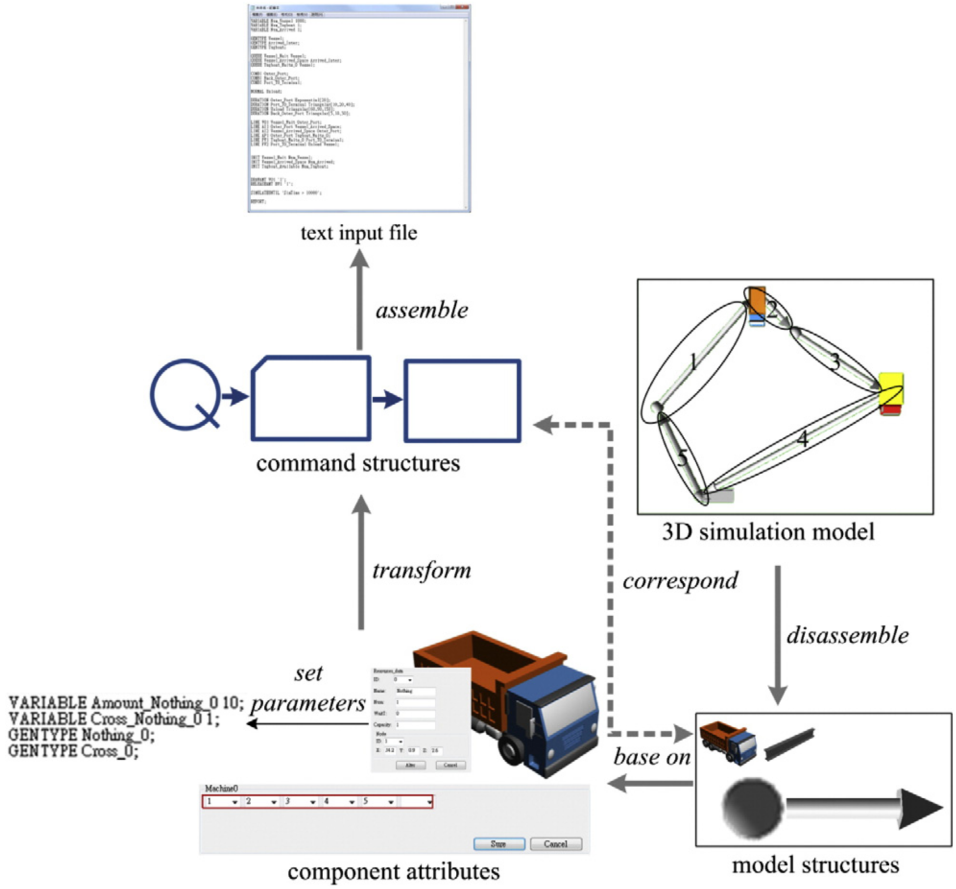
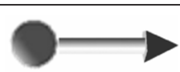
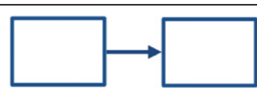
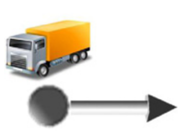
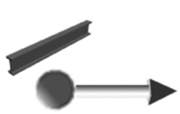
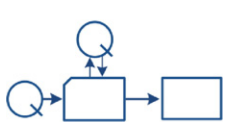
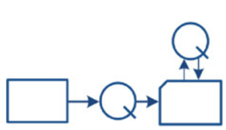
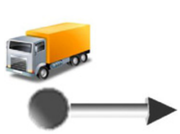
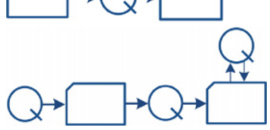
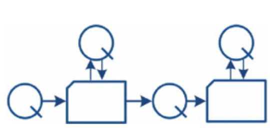


Fig. 8. The proposed automatic transformation mechanism from a 3D simulation model to a STROBOSCOPE input file.

Table 5
Correspondence between model structures and command structures.

Type	Model structures	Command structures
(1)		
(2)		
(3)		
(4)		
(5)		
(6)		

duration, and finally the nodes are connected through LINK. The formatted output of this model structure, according to the procedure described above, is shown in Fig. 9.

6. Mechanism for automatic retrieval of simulated results

After the system automatically transforms the 3D simulation model to a STROBOSCOPE text input file and feeds it to the simulation software, an automatic results retrieval mechanism must be developed in order to present simulated results as a 3D animation, using the 3D visualized model built in the pre-processing phase. Representation of the results as a 3D animation requires the system to automatically interpret text commands in the output file containing the results, extract the results, set them as data in the animation script of the model components in the field, and visually show the sequence of operation.

This study has analyzed simulated results contained in the output file, including machinery identification numbers, node, path, and start and end time of operations. The flow chart of the proposed automatic retrieval mechanism is shown in Fig. 10. A complete record of routes taken by the machinery corresponds to the same identification number being retrieved from the file. From nodes and paths in the travel record, work items executed by this piece of machinery during the simulation process can be obtained. Work items could include transporting resources when passing by the storage place, or waiting for a constraint to be removed. Following this step, time spent at each node and on each path in the travel record, such as travel time,

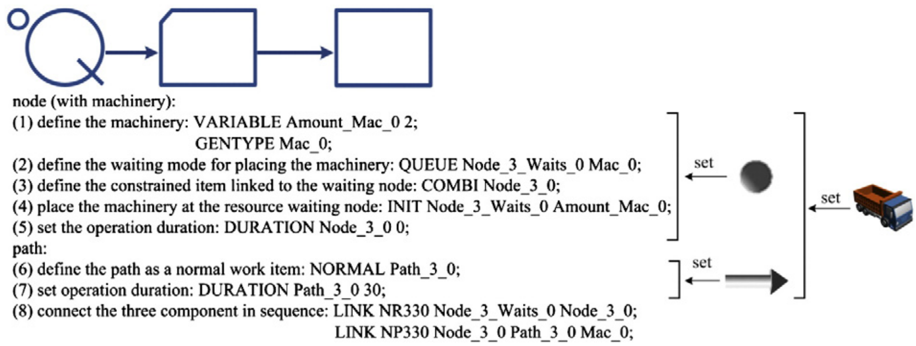


Fig. 9. The transformation rule for type (2) of the model structures.

working time, and waiting time, is calculated from the start time (S) and end time (E) recorded in the analysis results. From time spent in a series of work items by this piece of machinery, the system can put them in order using a pre-set timer to form continuous animation. Actions such as driving, waiting, and transporting can be presented on the interface. 3D animation of simulated results relevant to this machinery is thus accomplished.

7. Operating mode of modeling various types of model components

The nature of the proposed prototype system is a modeling program with dual 3D and AR interfaces. To effectively assist users in modeling and to serve as basis for system development, modes of operation and interaction of the system interface must be properly designed. Operating modes for modeling each type of model component are proposed below:

1. Area: The main function of 'Area' is to provide modelers with a base for constructing the simulated field. Therefore its operating mode enables users to select any point and to place model components of all types in the area. Users can also remove model components in the area.
2. Node: Users need to be able to freely place and move nodes in the modeling field. This operating mode involves clicking the mouse or dragging the nodes. 3D coordinates in the modeling space can be set as node position attributes, or they can be used to modify position attributes of existing nodes.
3. Path: The 'Path' modeling operation must be based on nodes deployed in the field. Modelers select start and end nodes to create a path, and modify a path by moving its start and/or end node(s). Users can also click on a path to show positions of its reference nodes.
4. Machinery: The 'Machinery' modeling operation allows users to place pieces of machinery by selecting a node in the field. The machinery route can be specified on the route interface. Modelers can select the component to open the attribute setting interface and set its material attributes such as quantity and capacity. They can also choose the appearance model of the machinery from the component library, and switch the visual presentation between

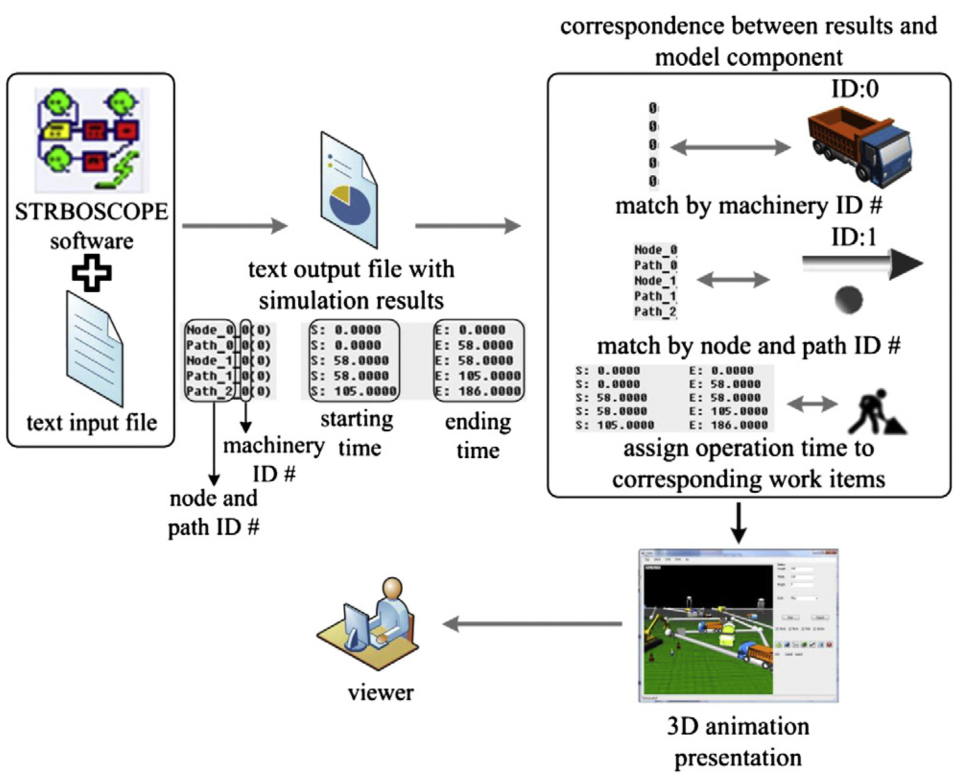


Fig. 10. The proposed automatic retrieval mechanism for STROBOSCOPE simulation results.

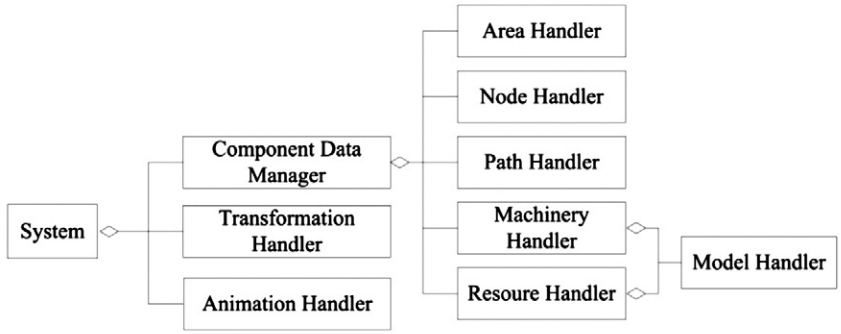


Fig. 11. The system architecture.

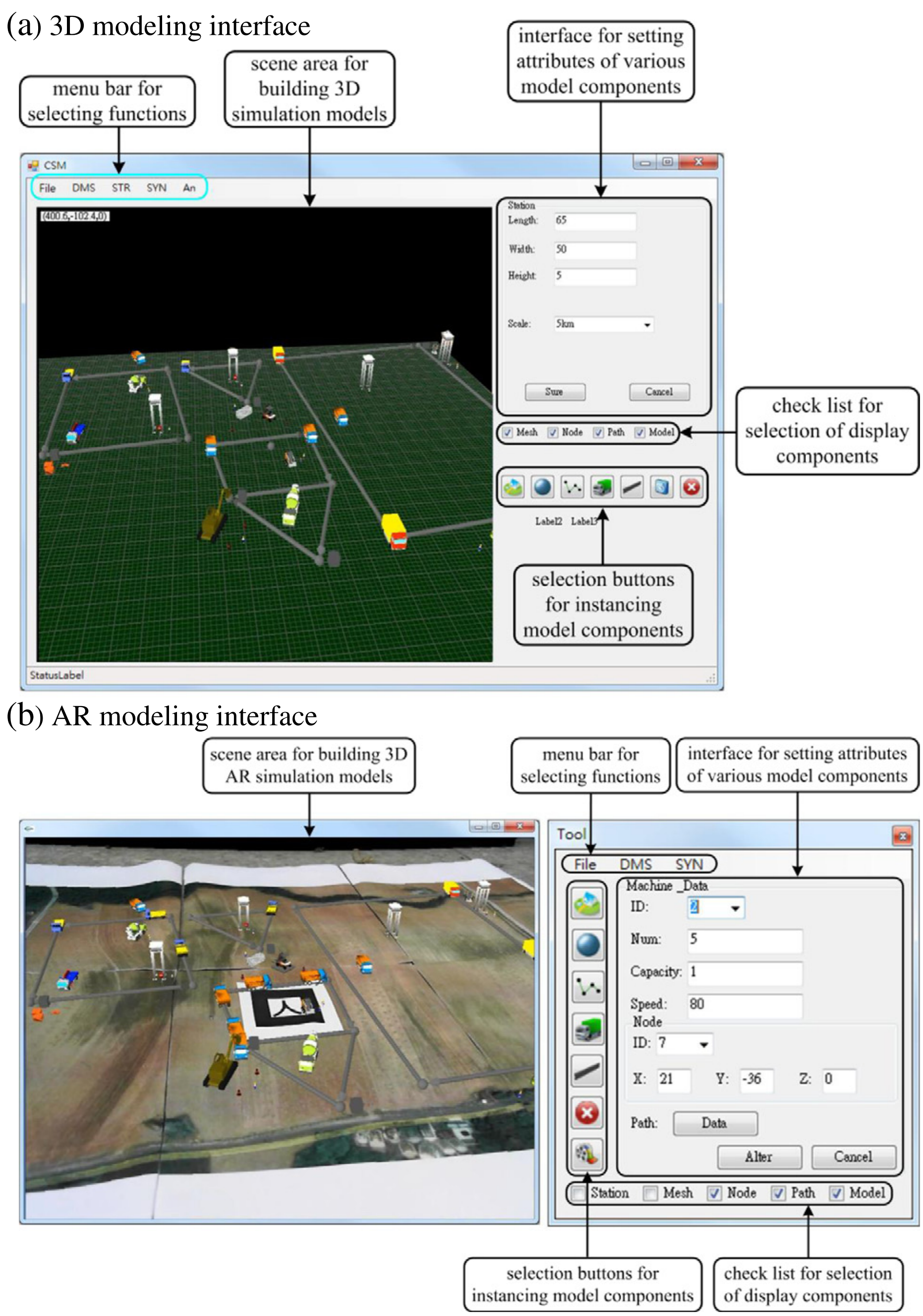


Fig. 12. The system interfaces.

simplified 3D cube and realistic rendering using the selected appearance model.

5. Resource: The ‘Resource’ modeling operation resembles the ‘Machinery’ operation. It must also be placed by selecting a node in the field. Its appearance can be chosen from the component library, and presentation can be switched between the simplified cube and selected appearance model. Attributes of the model component can be set on the attribute setting interface which appears when the component is selected.

8. System design and implementation

The proposed prototype system platform integrates AR technology, a 3D component library, a visual interface, and a 3D model. AR technology utilizes video equipment to capture images or photos of the field, imports them into the system, and then presents them on the visual interface. The 3D component library uses the format of 3D models, and employs 3D drawing technology on the visual interface. The system development adopts and integrates VB.NET, ARToolKit, and OPENGL for implementing the function interface.

The class diagram of the system is displayed in Fig. 11. The top level, system class, represents the entire program, and is the aggregation of objects of the component manager class, transformation handler class, and animation handler class. The component manager class contains objects of six classes: Area handler class, node handler class, path handler class, machinery handler class, resource handler class, and model handler class. The system class uses a 3D modeling interface and AR interface as the operating windows, as shown in Fig. 12(a) and (b), respectively. The prototype system developed in this study is capable of simulating general material transportation problem in construction, which can involve various construction vehicles (such as trailer truck, mixer truck, forklift truck, excavator, or crane) transport or move various materials (such as earth, concrete, or steel) in a workflow of looping structure (vehicle-loop) at a construction site. The scene areas in Fig. 12 show an example of such application.

9. Effectiveness evaluation

The effectiveness of the proposed system was evaluated by comparing it with some other DES tools by means of a user survey. The system tools selected to compare with the proposed system include Stroboscope (a text-based simulation system) [23], EZStrobe (a simulation system with schematic visualization) [19], Vita2D (a 2D post-processing animator) [22], and VITASCOPE (a 3D post-processing animator) [16]. All these systems are available free online (http://www.ezstrobe.com/) and have been discussed previously in the background section above. The user group for this test and survey were 32 students who enrolled in a graduate-level course named “Computer-aided Decision Simulation and Analysis” during the fall semester of 2011 at National Taiwan University of Science and Technology. This course focuses on developing a student's skills on using computer simulation to provide information to assist with decision-making in construction engineering. Simulation-related topics of this course include computer simulation model construction, result evaluation and alternative comparison, and software tools. Including the proposed system, all the tools being evaluated were introduced and used by students doing assignments and projects during this course. At the end of the semester, a survey was conducted in order to assess user opinions by comparing various aspects of the performance of these systems. Various performances were evaluated separately for the pre-processing phase (modeling) and post-processing phase (result presentation), except for the integration (of pre-processing and post-processing) aspect. Since the post-processing animators do not support modeling for simulation, their performances are evaluated only in post-processing. The respondents chose an agreement level between 1 (low) and 5 (high) for each evaluation item. The result statistics of this user survey are shown in Table 6. According to user opinion, the proposed system achieved a relatively good performance in all aspects of both the pre-processing and post-processing phase. The results of the survey indicated that the proposed system performed better than traditional schematic visualization systems. In addition, the proposed system was also regarded as successful in achieving the integration of pre-processing and post-processing in 3D mode, while maintaining comparable performances with the post-processing animators in post-processing.

10. Conclusions

In this study, a 3D visualized simulation model of construction operations and its modeling method were proposed for simulating transport operations in construction. AR technology was introduced in the system development to combine virtual objects and real field settings. As required by 3D visual representation of the construction operation, model component classes were proposed to compose the 3D simulation model, and their visual representations and relevant attributes for simulation were then determined through analysis. Modeling rules, details of parameter settings, and the modeling procedure for the simulation model were also presented. For the 3D model to be analyzed by the STROBOSCOPE simulation engine, transformation rules were derived. The output of attributes of the 3D model is automatically formatted as a text input file for

Table 6
The result statistics of a user survey to evaluate the effectiveness of the proposed system.

		Intuitiveness	Interactivity	Reality	Ease	Precision	Integration
Stroboscope	Pre-processing	1.47	1.50	1.53	1.47	1.56	N/A
	Post-processing	N/A	N/A	N/A	N/A	N/A	N/A
EZStrobe	Pre-processing	2.13	2.38	2.25	3.22	1.13	3.88
	Post-processing	2.06	2.03	2.19	3.16	1.13	3.84
Vita2D	Pre-processing	N/A	N/A	N/A	N/A	N/A	N/A
	Post-processing	3.31	3.06	3.03	3.09	2.06	N/A
Vitascope	Pre-processing	N/A	N/A	N/A	N/A	N/A	N/A
	Post-processing	4.47	3.34	4.53	3.06	4.13	N/A
The proposed system	Pre-processing	4.41	4.47	4.44	4.16	4.53	4.53
	Post-processing	4.38	4.31	4.47	4.13	4.56	4.50

Intuitiveness: User can intuitively understand the model and information presented in the system, and associates them with the simulated operation in real world.
Interactivity: User can interactively manipulate the simulation model in the system for various operations, such as model development, model information query, model viewing, and simulation result animation.
Reality: The system can display the simulated operation using realistic visualization.
Ease: The system is easy to learn and use. The requirement on learning authoring language or modeling rules is minimal.
Precision: The system provides functions to assist users in building a model accurately and efficiently.
Integration: The system can automatically integrate the pre-processing and post-processing of a simulation in the same model.

STROBOSCOPE. A mechanism of automatic retrieval of the simulated results was developed, which automatically interprets text commands in the output file and extracts the resulting data. This data is then used in the animation script for model components in the field, thus presenting simulated results in 3D animation.

The proposed modeling method allows 3D representation of the simulation model. The model can be built in 3D space, and, as a result, model information and simulated results can be presented more intuitively. Interactivity of the system interface is enhanced. The integration of pre-processing and post-processing phases is achieved. Furthermore, modelers can directly place 3D model components on the field image through an AR modeling interface. This not only facilitates accurate positioning of model components by directly selecting the placed locations, but also enables modelers to avoid environmental constraints in route planning. Integration of virtual model components and actual construction field status is realized. The user survey results reveal that the proposed system performs better than traditional schematic visualization systems. In addition, the proposed system is also regarded successful in the achievement of the integration of pre-processing and post-processing in 3D mode, while maintaining a comparable performance to the post-processing animators in post-processing.

Acknowledgments

This research was supported by the National Science Council of Taiwan under Project Number NSC100-2628-E-011-023-MY3.

References

[1] J.C. Martinez, Methodology for conducting discrete-event simulation studies in construction engineering and management, Journal of Construction Engineering and Management 136 (1) (2010) 3–16.
[2] A. Alvanchi, S. Lee, S. AbouRizk, Modeling framework and architecture of hybrid System dynamics and discrete event simulation for construction, Computer-Aided Civil and Infrastructure Engineering 26 (2) (2011) 77–91.
[3] V.R. Kamat, J.C. Martinez, Dynamic 3D visualization of articulated construction equipment, Journal of Computing in Civil Engineering 19 (4) (2005) 356–368.
[4] V.R. Kamat, J.C. Martinez, Variable-speed object motion in 3D visualizations of discrete-event construction simulation models, The Electronic Journal of Information Technology in Construction 12 (2007) 293–305.
[5] M. Al-Hussein, M. Athar Niaz, H. Yu, H. Kim, Integrating 3D visualization and simulation for tower crane operations on construction sites, Automation in Construction 15 (5) (2006) 554–562.
[6] J.D. Manrique, M. Al-Hussein, A. Telyas, G. Funston, Constructing a complex precast tilt-up-panel structure utilizing an optimization model, 3D CAD, and animation, Journal of Construction Engineering and Management 133 (3) (2007) 199–207.
[7] A.A. ElNimr, Y. Mohamed, Application of gaming engines in simulation driven visualization of construction operations, The Electronic Journal of Information Technology in Construction 16 (2011) 23–38.
[8] P.V. Rekapalli, J.C. Martinez, Discrete-event simulation-based virtual reality environments for construction operations: technology introduction, Journal of Construction Engineering and Management 137 (3) (2011) 214–224.
[9] http://www.ezstrobe.com EZStrobe.
[10] M. Lu, L.-C. Wong, Comparison of two simulation methodologies in modeling construction systems: manufacturing-oriented PROMODEL vs. construction-oriented SDESA, Automation in Construction 16 (1) (2007) 86–95.
[11] P.S. Dunston, X. Wang, Mixed Reality-based visualization interfaces for architecture, engineering, and construction industry, Journal of Construction Engineering and Management 131 (12) (2005) 1301–1309.
[12] M. Golparvar-Fard, F. Pea-Mora, C.A. Arboleda, S. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, Journal of Computing in Civil Engineering 23 (6) (2009) 391–404.
[13] D.H. Shin, P.S. Dunston, Evaluation of Augmented Reality in steel column inspection, Automation in Construction 18 (2) (2009) 118–129.
[14] A.H. Behzadan, V.R. Kamat, Automated generation of operations level construction animations in outdoor augmented reality, Journal of Computing in Civil Engineering 23 (6) (2009) 405–417.
[15] A.H. Behzadan, V.R. Kamat, Integrated information modeling and visual simulation of engineering operations using dynamic augmented reality scene graphs, The Electronic Journal of Information Technology in Construction 16 (2011) 259–278.
[16] V.R. Kamat, Vitascope: Extensible and scalable 3D visualization of simulated construction operations, Ph.D. dissertation, Virginia Polytechnic Institute and State Univ., Blacksburg, Va., 2003.
[17] R.-Y. Huang, A.M. Grigoriadis, D.W. Halpin, Simulation of cable-stayed bridges using DISCO, Winter Simulation Conference Proceedings (1994) 1130–1136.
[18] L.Y. Liu, P.G. Ioannou, Graphical object-oriented discrete-event simulation system, Winter Simulation Conference Proceedings (1992) 1285–1291.
[19] J.C. Martinez, EZStrobe — general-purpose simulation system based on activity cycle diagrams, Winter Simulation Conference Proceedings 1 (1998) 341–348.
[20] L.Y. Liu, P.G. Ioannou, Graphical resource-based object-oriented simulation for construction process planning, in: Proceedings of the 5th International Conference on Computing in Civil and Building Engineering, 1993, pp. 1390–1397.
[21] J.J. Shi, H. Zhang, Iconic animation of construction simulation, Winter Simulation Conference Proceedings 2 (1999) 992–997.
[22] http://www.ezstrobe.com/2009/10/vita2d.html Vita2D Introduction.
[23] J.C. Martinez, STROBOSCOPE : State and Resource Based Simulation of Construction Process, doctoral dissertation, University of Michigan, Ann Arbor, MI, 1996.
[24] http://www.hitl.washington.edu/artoolkit AR Toolkit.