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

Ming Lu, Yang Zhang, Jianping Zhang, Zhenzhong Hu, and Jiulin Li

Abstract: In this paper, we give a state review of modeling methodologies for four-dimensional computer-aided design (4D CAD) and three-dimensional (3D) animation of operations simulation. We then present our efforts of integrating 4D CAD and 3D animation of operations simulation to facilitate the construction planning of the main stadium for the Beijing 2008 Olympic Games (nicknamed the "Bird's Nest"). We propose a "zoom" interface between 4D CAD and 3D animation of operations simulation to enable a natural synergy of two separate, but organically linked research streams. For concept proving and application demonstration, we seamlessly integrated two computer systems resulting from previous in-house research to plan and visualize the construction of the "Bird's Nest" in close collaboration with the main contractor. The integrated construction planning methodology is found instrumental in visually and intuitively conveying the master project schedule and detailed operations plan for construction of the "Bird's Nest".

Key words: visualization, 3D modeling, computer aided design, animation, simulation, construction management, project management.

Résumé : Cet article présente une revue des méthodes de modélisation des animations 4D « computer-aided design (CAD) » et 3D pour simuler les opérations. Nous soulignons nos efforts d'intégration de l'animation 4D « CAD » et 3D dans la planification de la construction du stade principal des Jeux Olympiques 2008 à Beijing (surnommé le 'Nid d'Oiseau'). Nous proposons une interface de zoom entre l'animation 4D CAD et 3D de la simulation des opérations afin de permettre une synergie naturelle des deux courants de recherche séparés mais liés organiquement. Quant à la vérification du concept et à la démonstration de l'utilisation, nous avons intégré de manière harmonieuse les deux systèmes informatiques provenant d'une recherche interne antérieure afin de planifier et de visualiser la construction du 'Nid d'Oiseau', en étroite coopération avec l'entrepreneur principal. La méthode intégrée de planification de la construction s'est avérée importante pour transmettre visuellement et intuitivement l'échéancier principal du projet et le plan détaillé des opérations pour la construction du 'Nid d'Oiseau'.

Mots-clés : visualisation, modélisation 3D, conception assistée par ordinateur, animation, simulation, gestion de la construction, gestion de projet.

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Introduction

Communication of design details and construction plans is critical to the successful delivery of modern construction projects, which feature bold, unconventional architectural designs, tight schedules, congested site space, and the involvement of multiple stakeholders. Nevertheless, interacting with and making sense of huge amounts of relevant project data would be tedious and overwhelming, if not impossible. This has presented a distinct challenge for engineers and managers to attain cost efficiency in executing large-scale, complex construction projects.

Three-dimensional computer-aided design (3D CAD) technology became available as the predominant means of designing and drafting to the Architecture–Engineering–Construction (AEC) industry in the 1980s. The combination of computer graphics, animation, and 3D computer modeling lends effective visual aid to engineers from conceptual design to construction process (Morad and Beliveau 1994). As a matter of fact, by making better use of human spatial memory, visualization in 3D computer models brings the full power of the human visual system to bear on processing information in tackling highly convoluted problems (Sher-

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M. Lu.[1] Department of Civil & Structural Engineering, Hong Kong Polytechnic University, Hong Kong, China.
Y. Zhang, J. Zhang, and Z. Hu. Department of Civil Engineering, Tsinghua University, Beijing, China.
J. Li. Beijing Urban Construction Ltd. Co., Beijing, China.

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[1]Corresponding author (e-mail: cemlu@polyu.edu.hk).

Fig. 1. Four-dimensional computer-aided design implies the product state changes over time.

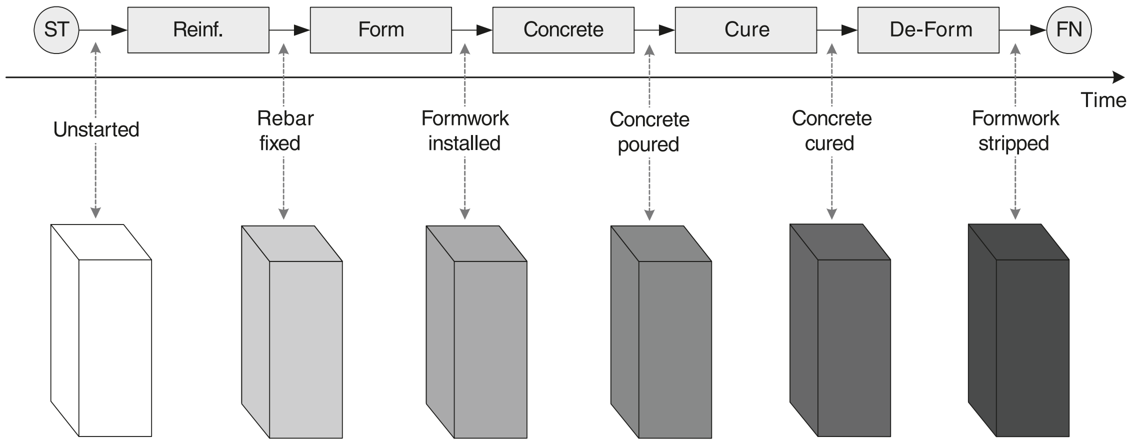
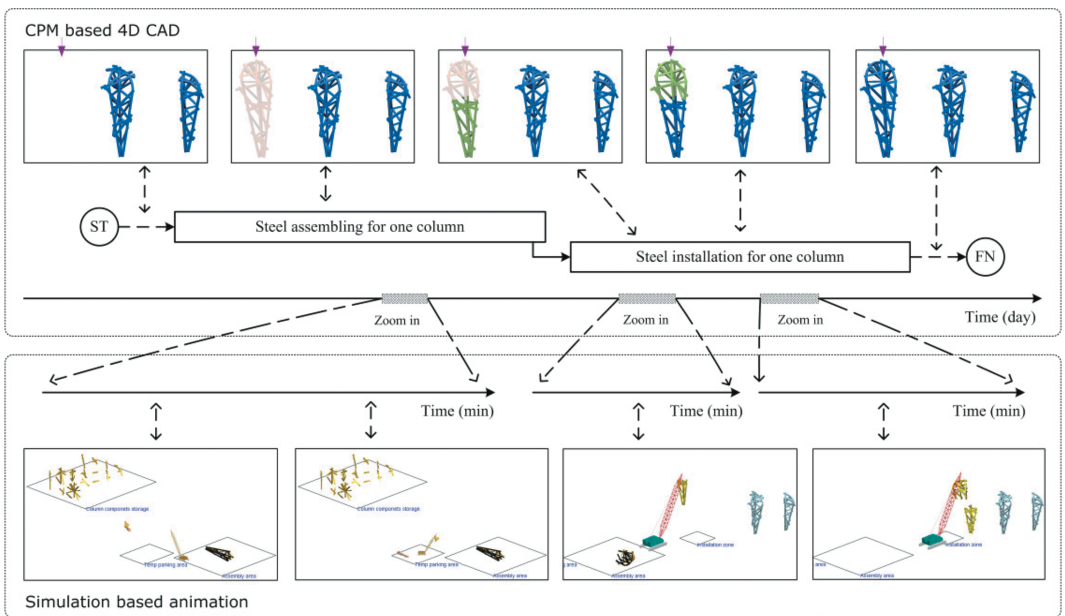


Fig. 2. "Zoom" interface illustrated with assembling and installing one steel column at the "Bird's Nest".



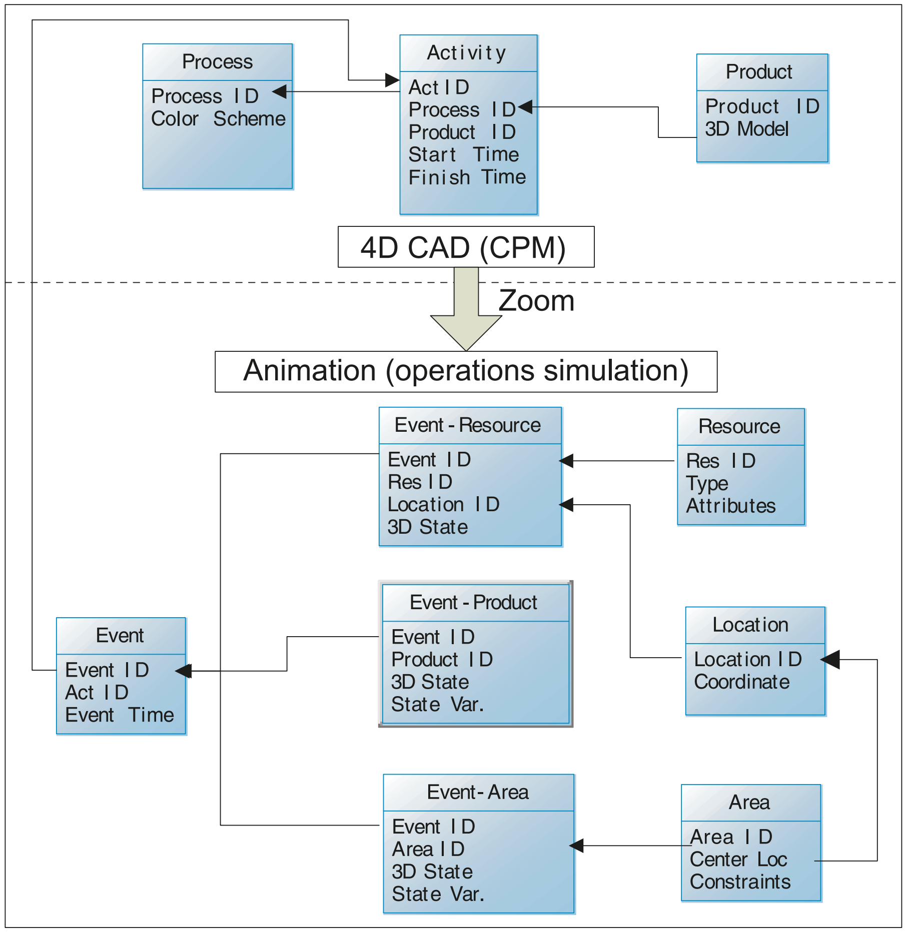
idan 2008). 3D CAD can enable architects and engineers to explain structural design and construction operation more effectively than traditional methods (Kang et al. 2007). With the 3D CAD technology, many complicated construction problems can be identified and addressed before they would actually materialize on site, thus avoiding potential design errors, operation delays, and added costs of revisions in construction (Danso-Amoako et al. 2003).

The established construction planning methodology of critical path method (CPM) builds on the definition of a work breakdown structure of a project that subdivides the project into component activities; each activity is a well-defined scope of work that usually terminates in a deliverable product (Halpin and Woodhead 1998). It is noteworthy that CPM relies on bar charts and project network diagrams for visualizing activity status and sequence. Recent developments have attempted to turn drab visual aids of CPM into vivid 3D computer graphics by linking CPM with the building design data defined in 3D CAD models, resulting in a four-dimensional (4D) view of a CPM plan (Koo and Fischer 2000).

With the objective of reducing resource idling time and boosting site productivity, operations simulation provides an effective methodology for modeling construction processes and addressing time conflicts in allocating the utilization of resources. Over the past three decades of research, construction simulation tools have evolved from the original activity cycle diagram based CYCLONE (short for "CYCLic Operation NEtwork") (Halpin 1977) to the full-fledged STROBOSCOPE (short for "STate and ResOurce Based Simulation Of COnstruction ProcessEs") boasting flexible programmability and extensibility (Martinez 1996). In addition, visualization of simulated operations in 3D significantly adds to the credibility of simulation models and provides valuable insight into the subtleties of construction operations that are otherwise difficult to quantify or present (Kamat and Martinez 2001).

The motivation of the present research is to develop innovative, cost-effective planning methods to facilitate visualization of the construction plan for the main stadium for the Beijing 2008 Olympic Games (the "Bird's Nest"). The stadium occupies an area of 258 000 m^2 in Beijing's Olympic

Fig. 3. Data structure linking four-dimensional computer-aided design and animation of operations simulation.



Park and is a new landmark structure in the capital city of China. A giant steel latticework makes the saddle-shaped frame of the stadium (333 m long, 294 m wide, with the height varying from 40 to 69 m) that bears a resemblance to a bird's nest. Its grandstand is a huge bowl-shaped concrete structure and the roof framework is supported by twenty four steel columns circumventing the grandstand. The "Bird's Nest" can accommodate 91 000 spectators and served as the venue for the opening and closing ceremonies of the 29th Summer Olympic Games, as well as the track and field events and the final soccer game. In this research, we propose a "zoom" interface to logically and seamlessly blend the use of 4D CAD and 3D animation of construction operations into visualization solutions. First, we review research developments related to (*i*) 4D CAD and (*ii*) 3D animation of construction operations.

Literature review

Visualization by four-dimensional computer-aided design

Zhang et al. (2002*a*) proposed the "4D site management model+" by extending the functions of a 4D model beyond a tool for visualizing CPM; those functions include generation of site layouts, estimation of resource requirements, and estimation of direct cost. To ameliorate 4D modeling, Chau et al. (2005) annotated activities in CPM with resource requirement information and displayed temporary storage facilities with their statuses updated in the 3D site layout view. An empirical study to contrast 4D models against the two-dimensional (2D) drawings and bar charts by Kang et al. (2007) demonstrated that the use of 4D models facilitates detection of logical errors more frequently, faster, with fewer mistakes, and minimizes the need for team communication.

Visualization by operations simulation

Zhang et al. (2005) described the integration of a cell space model with a CYCLONE simulation model of bridge redecking operations. The cell space model divides space into cells; the change of each cell's state over time reflects space occupancy by a resource or an activity. A tight coupling of CYCLONE with a space model was considered difficult due to the absence of a site layout representation in the CYCLONE's schematic model (Zhang et al. 2005). An interface between a simulation model with a CAD package (such as AutoCAD® or MicroStation) describing the building product as well as site layout characteristics was found instrumental for the exchange of soil and travel route data in earthmoving simulation applications (AbouRizk and Mather 2000; Xu et al. 2003). Kamat and Martinez (2001) developed a generic visualization tool called VITASCOPE (acronym of "VIsualizaTion of Simulated Construction OPErations") to enable spatially and chronologically accurate visualization of specific construction operations in 3D. In

Fig. 4. Four cases for handling interpolation of resource location and three-dimensional states between two consecutive events in simulation.

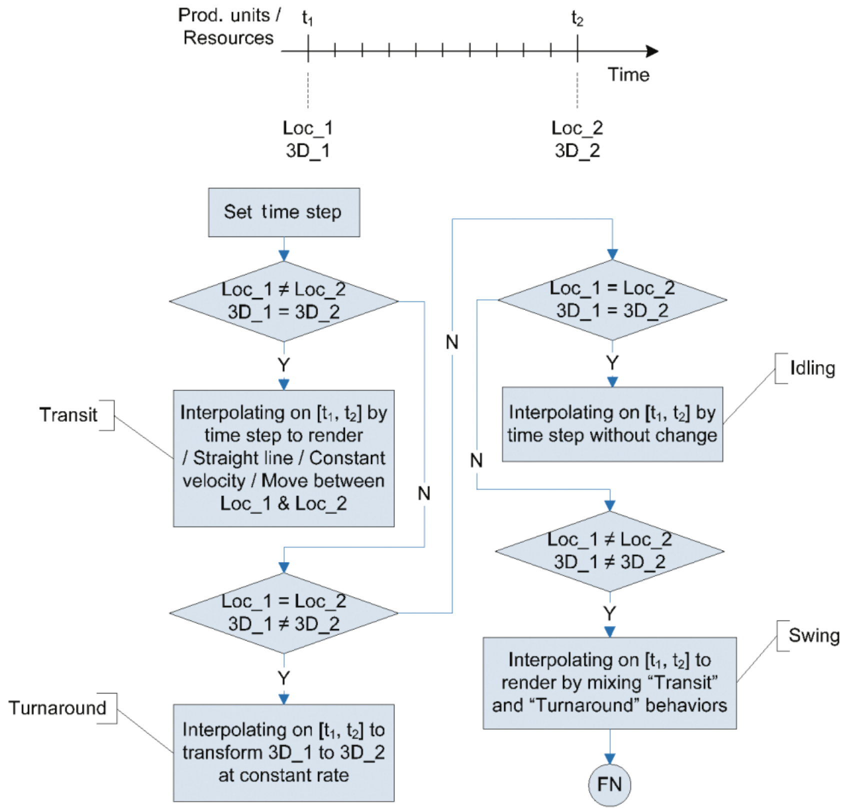


Fig. 5. Four-dimensional computer-aided design model for visualizing the critical path method plan of steel structure installation.

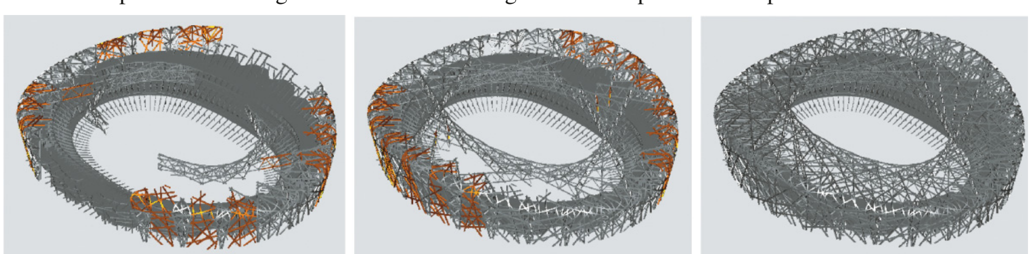
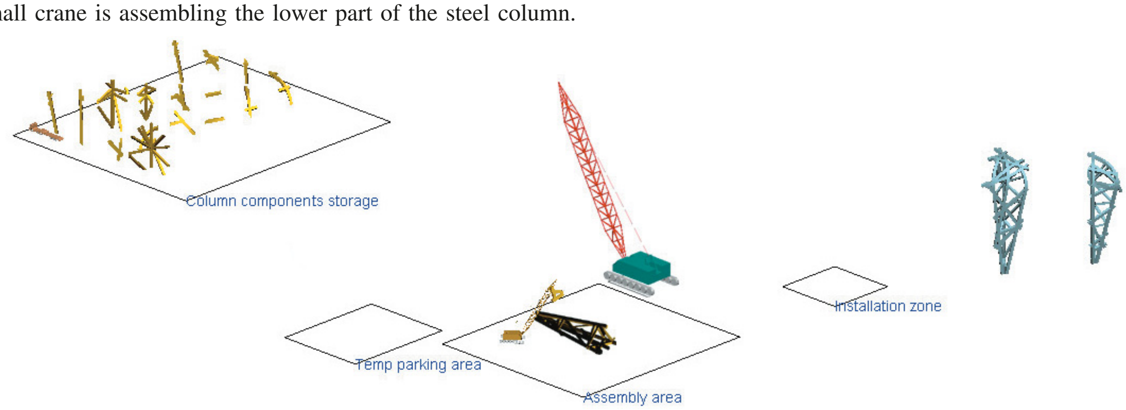


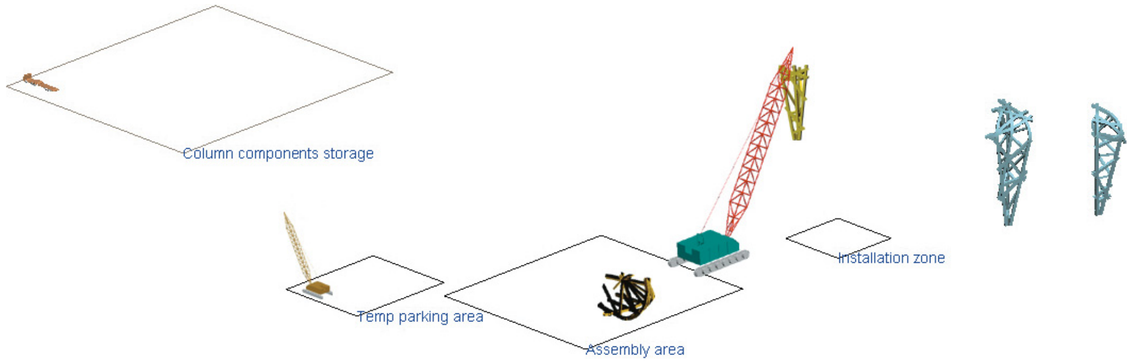
Fig. 6. A small crane is assembling the lower part of the steel column.



an earthmoving case, output data from a STROBOSCOPE simulation model were translated into the proprietary code of VITASCOPE for visualizing the motion of resources and states of completion on a constructed facility. Al-Hussein et al. (2006) experimented with 3D visualization for operations of a group of tower cranes and identified potential lift collisions between two adjacent cranes through integrating a commercial animation software package (3D Studio Max) with a crane operations simulation system.

It should be pointed out that the focus of the operations simulation in the research efforts previously mentioned is on providing data to visually represent resource interaction,

Fig. 7. A big crane is installing the lower part of the steel column.



operations sequence, and site layout given a construction process. This differs from operations simulation based on Monte Carlo sampling techniques, which is more concerned with applying statistical methods to assess uncertainties at both component and system levels.

Integration of four-dimensional computer-aided design and operations simulation

Compared with a bar chart representation, 4D CAD considerably enhances the visualization of a CPM plan by tracking time events associated with product state changes occurring as the result of completing a particular construction process. For example, Fig. 1 shows five activities relevant to concreting a column, which are distinguished with varied gray scales on the 3D column model to reflect product state changes over time in 4D CAD modeling.

Nevertheless, 4D CAD in general does not realize visualization of construction operations featuring dynamic interaction of various resources as they build the product (Kamat and Martinez 2001). We herein propose a "zoom" interface between CPM-based 4D CAD and operations simulation. First, 4D CAD displays major activities along with structural elements and the site layout model rendered in a 3D environment; then, when engineers spot an activity of interest, they zoom into it for detailed operations simulation and 3D animation of simulation results.

In Fig. 2, the "zoom" interface is illustrated with the assembling and installing of a one steel column on the "Bird's Nest". In the 4D CAD visualization, one steel column is handled in two parts (lower column and upper column). Installation of the two adjacent columns has been completed before the "steel assembling" activity starts on the current column (the leftmost of the three columns). In our 4D CAD model, different color schemes apply to denote product state changes (e.g., green for "assembling done" and blue for "installation done"). It is observed from the 4D CAD model (top of Fig. 2) that once the lower part of column is installed (lower column turns blue), assembling on the upper part of column is also done (upper column turns green). At the end of "steel installation for one column" activity, the whole column product turns blue.

Also shown in Fig. 2, when we zoom into a CPM activity in the 4D CAD model for detailed operations simulation modeling, the time unit of modeling switches from days to minutes and the product of the column breaks down into production units, which are smaller column components placed at site storage at the beginning. In the course of column assembling, a truck moves column components from the storage to the assembling yard in accordance with the proper column-assembling sequence. A small crawler crane is deployed at the assembling yard to handle the column components during assembling. Once the lower part of column is assembled, a big crawler crane lifts it up and transits it to the installation spot for final placement. Afterwards, the crane returns to the assembling yard and the upper column installation ensues.

The data structure linking 4D CAD and animation of operations simulation is given in Fig. 3. Note in the "Activity" table of the 4D CAD model, an activity definition combines a product and a process and its start and end times are derived from CPM analysis. Zooming into an activity for operations simulation, the product breaks down into material resource units (assembling components or production units) while the process is represented with events describing interactions of equipment or labor resources at a particular location and time. The site location and 3D state of a *resource* involved in a simulation event are tracked in the "Event-Resource" table in Fig. 3 to enable the visualization of operations simulation. In addition, the state change of the product involved is also tracked at particular simulation events in the "Event-Product" table (e.g., at an event time, the complete percent of the column being assembled along with its 3D state). In addition, the state change of a particular site area involved in the activity is also traced at particular event times in the "Event-Area" table (e.g., the storage holding column components becomes empty at the end of the steel assembling.)

Given the states of a production unit or a resource are known at two events (namely, *location 1* at t_1 with *3D graphic 1* and *location 2* at t_2 with *3D graphic 2*), the algorithmic framework for interpolating 3D frames at each time step between t_1 and t_2 is given in Fig. 4. Note the time step setting is related to the frequency of refreshing the screen in rendering animation of operations simulation. Depending on changes on location and 3D state (i.e., shape, dimensions, configuration, and orientation) of the production unit or resource concerned, four cases are categorized in interpolating frames between t_1 and t_2 (Fig. 4), namely, case "Transit", case "Turnaround", case "Idling", and case "Swing":

- For case "Transit", only the site location of the production unit or the resource changes between events t_1 and t_2, with the 3D state remaining steady. Thus, 3D frames of the production unit or the resource are interpolated between t_1 and t_2 by assuming a straight-line move between two locations at a constant velocity.

- For case "Turnaround", the site location of the production unit or the resource stays relatively unchanged, while its 3D state transforms from "*3D_1*" at t_1 to "*3D_2*" at t_2. To render animation, the algorithm simply inserts frames on [t_1, t_2] to gradually transform the initial 3D state of the resource into its final 3D state.
- For case "Idling", both site location and 3D state of the production unit or the resource remain stable between t_1 and t_2, implying waiting or idling states at the site. As such, the 3D frames are inserted at each time step between t_1 and t_2 without change.
- The case "Swing" is to aggregate the effects of case "Transit" and case "Turnaround" as changes occur to both site location and 3D state of the production unit or the resource.

For concept proving and application demonstration, we seamlessly integrated two computer systems resulting from previous in-house research, namely, a 4D CAD platform called 4D-GCPSU (four-dimension graphics for construction planning and resource utilization) (Zhang 1996; Zhang et al. 2000, 2002*a*, 2002*b*; Wang et al. 2004) and an operations simulation platform called SDESA (simplified discrete event simulation approach) (Lu 2003; Lu and Wong 2007; Lu et al. 2007). By implementing the "zoom" interface between 4D-GCPSU and SDESA, data exchange is automated between the two systems. With regard to the "Bird's Nest" application, a 4D model is first developed with the aid of a 4D-GCPSU for visualizing a CPM construction plan in a 3D environment, thus enabling a construction planner to inspect 3D building product models and site layout models which are dynamically linked with the time schedule. Figure 5 shows three 4D CAD frames for steel column installation on the "Bird's Nest".

It is reemphasized that the objective of zooming into the processes of a CPM activity for operations simulation modeling is to assess the impact of activity constraints (such as resource utilization, site layout, and alternative installation sequence) upon activity time. Once a zoom activity is identified, a SDESA simulation model is established to simulate detailed construction processes under practical site constraints. The follow up animation of operations simulation would take advantage of the 3D graphic engine of the 4D-GCPSU. Visualizing simulation outputs in 3D enables engineers to validate simulation models, identify potential glitches in construction operations, and further refine the simulation model. When the simulation model is tuned to its best state, the simulation output of activity time can be obtained to update the CPM plan, resulting in a more accurate 4D CAD model. Two screenshots were taken to show operations simulation for assembling and installation of the lower part of a steel column in Fig. 6 and Fig. 7, respectively.

Conclusions

Following a state review of modeling methodologies for 4D CAD and 3D animation of operations simulation, we have presented our efforts of integrating the two separate, but organically linked research streams in planning construction of the main stadium for the Beijing 2008 Olympic Games (nicknamed the "Bird's Nest"). Our research has contributed to proposing a fusion methodology built on in-house computer platforms through years of continuous research. The resulting "zoom" interface between 4D CAD and 3D animation of operations simulation, including data structure and algorithmic framework provides a flexible and effective method to visualize the master project plan and the detailed operations plan in construction of complex structures like the "Bird's Nest." 4D CAD displays major activities along with structural elements and the site layout model rendered in a 3D computer environment; when engineers spot an activity of interest, they zoom into it for detailed operations simulation and 3D simulation animation. For concept proving and application demonstration, we have succeeded in seamlessly integrating two computer systems resulting from previous in-house research to plan and visualize the construction of the "Bird's Nest" in close collaboration with the main contractor.

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