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# COMPARISON OF SIMULATION-DRIVEN CONSTRUCTION OPERATIONS VISUALIZATION AND 4D CAD

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## ABSTRACT

Several recent research efforts in visualizing construction are rooted in scheduling. They involve linking activity-based construction schedules and 3D CAD models of facilities to describe discretely-evolving construction "product" visualizations called 4D CAD. The focus is on communicating what component(s) are built where and when. The construction processes or operations actually involved in building them are usually implied. Ongoing research at Virginia Tech focuses on designing automated, simulation-driven methods to visualize, in addition to evolving construction products, the operations and processes that are performed in building them. In addition to what is built where and when, the effort is concerned with visualizing who builds it and how by depicting the interaction between involved machines, resources, and materials. This paper expounds the differences in concept, form, and content between 4D CAD and dynamic 3D visualization of operations simulations. An example of a structural steel framing operation is presented to elucidate the comparison.

## 1 INTRODUCTION

Although the planning and control techniques used in planning construction at the project and operation levels are different, both can benefit substantially from dynamic 3D visualization. Different people in construction thus understand different things by the term visualization. As a result, the term has been used in the literature to refer to any kind of series of sequential computer frames without taking into account their origin or their contents (Op den Bosch 1994). In effect, numerous computer-based visual activities that can be directly or indirectly used for construction planning may be appropriately termed visualization. These activities include, but are not limited to, the animation of construction schedules (i.e., 4D CAD), design analysis of construction equipment in physical simulation environments (e.g. Working Model), visualization of assembly sequences and real-time virtual interactive modeling of construction equipment (e.g. IV++), scenario creation and animation for interference analysis (e.g. Bentley Dynamic Animator), construction site model-based information access over the internet using VRML (Campbell 2000) , and dynamic 3D visualization of discrete-event operations simulations (Kamat and Martinez 2001).

This paper elucidates the differences in concept, form, and content between two notions of visualizing construction i.e. 4D CAD and dynamic 3D visualization of discrete-event operations simulations. The article is motivated by our frequent encounters with persons who often confuse our work in enabling visualizations of the latter type with 4D CAD. In the following sections, we will thus attempt to place both these construction visualization research initiatives into proper perspective.

## 2 4D CAD VERSUS CONSTRUCTION OPERATIONS VISUALIZATION

Visualization research efforts at the project level are motivated by the shortcomings of traditional scheduling and control techniques such as bar charts and CPM in being able to represent all aspects of construction necessary for project level planning (Skolnick 1993, Koo and Fischer 2000). Visualization is achieved by linking a 3D CAD model representing the design of the facility and a construction schedule (Cleveland 1989). This form of visualization has popularly become known as 4D CAD.

4D CAD focuses on the visualization of the construction product over the period of its construction. As time advances, individual components (CAD elements) of the facility are added to the visual model in their final position and form as dictated by the schedule. 4D CAD models thus convey what physical components are built where and in which time frame. Numerous research studies have explored and exploited such dynamic project level 3D visualization since the involved technology is straightforward and available.

In contrast, visualizing construction at the operations level is a much more complex proposition that, in addition to visualizing the evolving product, involves being able to view the interaction of the various resources as they build the product or perform a support service. These resources include, but are not limited to, temporary structures, materials, equipment, and labor as they create the product. At this level-of-detail, visualization of the evolving construction product can be naturally achieved as a byproduct.

In order to visualize an operation it is necessary to see, in addition to the physical components of the facility, the equipment, personnel, materials and temporary structures required to build it. Moreover, it is necessary to depict the movements, transformations and interactions between these visualization elements. The movements and transformations must be spatially and temporally accurate. In order to depict smooth motion, visual elements must be shown at the right position and orientation several times per second. Issues such as trajectories in 3D space, speed and acceleration need to be considered.

Visualizing construction operations also encompasses construction procedures that do not necessarily involve the assembly of a tangible product such as a building or a bridge. For instance, construction operations such as paving, tunneling, quarrying, and earthmoving can obviously be simulated and visualized at the operations level. However, at the project level, construction of this nature can only be planned in terms of the desired production rate and has no corresponding visualization (i.e. 4D CAD) context due to the absence of a tangible product that requires assembly.

Construction operations of any duration and complexity can be visualized dynamically in 3D by linking together discrete-event simulation models and CAD models of the infrastructure, construction equipment (i.e. machines), temporary structures, and other resources (Kamat and Martinez 2001). The results are smooth, continuous 3D animations of simulated construction operations that not only describe what is built where and when, but also convey who builds what and how they build it. Visualization of construction at the operations level thus allows us to “see” graphically on the computer, the operations being carried out in the same way as they would be in the real world. Such 3D animations of simulated construction operations facilitate rapid verification and validation of the underlying discrete-event simulation models. In addition, the practical and educational benefits of being able to visualize construction at this level of detail are phenomenal.

While being focused on project level planning and visualization, researchers and industrial proponents of 4D CAD have always been aware of the importance of operations level planning in general and operations level visualization in particular. This is evident from recent 4D CAD research works that aim to convey operations planning information about construction space requirements through 4D visualizations (Akinci and Fischer 2000, Riley 1998). The planning information that 4D visualization synthesizes is however derived from project level planning tools (i.e. CPM schedule and CAD model of the infrastructure). It is therefore not possible to visualize the actual construction operations that lead to the construction of the end product using the sources of 4D CAD (Adjei-Kumi and Retik 1997, Fukai 2000).

In other words, 4D CAD can depict the evolution of the construction product but not the interaction of the resources that build it. As described above, the latter is the essence of dynamic operations level visualization and can only be considered by tools for planning construction at that level (e.g. discrete-event process simulation models). Operations visualization therefore differs significantly in concept, content, and usage when compared to 4D CAD. In the following sections, we will clarify and further elucidate these differences with the help of an example of a structural steel frame erection operation.

## 3 STRUCTURAL STEEL ERECTION

Figure 1 presents a typical framing plan for a multistory steel-framed building. The small rectangular formations in the middle of the building frame are typically provided for accommodating openings for elevators, stairways, and mechanical shafts. Erection of a multistory steel building frame starts with the first tier of framing. Each tier typically spans two building stories. Erection of the steel components begins with a crane that starts erecting the columns for the first tier. The columns are usually furnished in sections that are slightly taller than two stories to facilitate the splicing of column sections for subsequent tiers. The columns are picked up from organized piles on the site and lowered carefully over the anchor bolts and onto the foundation.

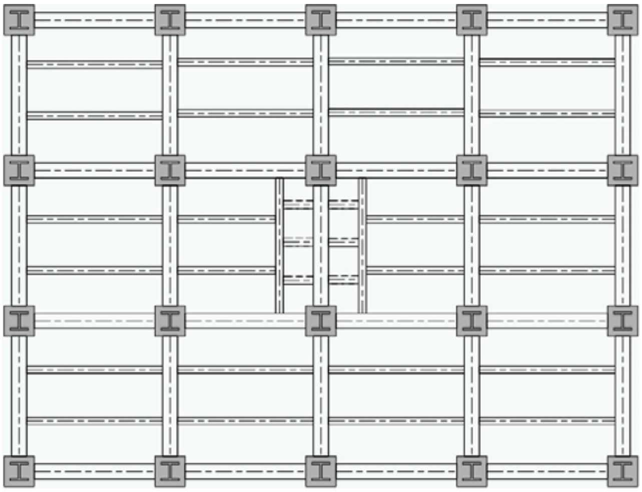

Figure 1: Typical Framing Plan for a Multistory Steel Framed Building

After the first tier of columns has been erected, the beams and girders for the first two stories are similarly picked up, lowered, and bolted in place. The two-story tier of framing is then plumbed up using diagonal cables and turnbuckles. Erection of the subsequent tiers then proceeds much like that of the first.

## 4 SCHEDULING STEEL ERECTION ACTIVITIES

A scheduler may choose to represent the erection of the entire steel frame as a single activity in the planned construction schedule. Depending on the size of the building (and the frame), such an activity could span multiple days. In addition, erection of the frame may also be planned by dividing it into zones based on how wide the structure spans horizontally (Sawhney et. al. 1999). A more elaborate schedule may also break up the erection operations into multiple sub-activities such as 1) Erect first tier columns, 2) Erect first floor girders and beams, 3) Erect second floor girders and beams etc. Figure 2 presents such a possible schedule for erecting the frame shown in Figure 1. For simplicity, the sub-activities of conveying and installing bundles of decking and/or installing and maintaining a safety net are omitted.

Based on the level of detail incorporated into the schedule, a 4D CAD visualization involves depicting the state of the completed facility at the end of each unique activity (or sub-activity). In the present example, a 4D CAD visualization would represent the status of the completed steel frame at the end of each of the sub-activities, however detailed the level of sub-activities is. For example, the highest level of detail in erecting a steel frame is a single steel shape. However, a separate activity for erecting each of them is a ridiculous and unnecessary option from the scheduling point of view. Figure 3 presents snapshots of a 4D CAD visualization corresponding to the schedule in Figure 2.

The snapshots depict the state of the completed construction facility at the end of each uniquely identifiable activity in the construction schedule. Static CAD models of cranes, temporary equipment, and materials may be included in such snapshots to help identify space and layout constraints and to increase the visual impact. The interaction of these resources and the processes involved in erecting the steel shapes themselves are however not depicted in such visualizations.

## 5 DESIGNING STEEL ERECTION PROCESSES

Designing construction processes involves comparing and choosing among alternative construction methods, pieces of equipment, labor levels, and operating strategies for accomplishing the planned activities. The focus is on planning construction at the field (i.e. production) level.

Figure 4 presents a Stroboscope (Martinez 1996) process model that simulates the processes involved in erecting the steel frame depicted in Figure 1. A tower crane is used to erect the steel shapes. The schematic model presented in Figure 4 is simple and self-explanatory. The model however exploits Stroboscope's notion of characterized resources and its programmability to simulate the operation in great detail.

Stroboscope characterized resources allow each steel shape to be uniquely identified. This fact is exploited in determining the durations of each involved erection task. For each steel shape (column, beam, or girder), the amount by which the loaded crane cable must be raised, the amount by which the boom must swing, the amount by which the tower crane trolley must slide etc. are all functions of the final in-place configuration of the erected steel shape. For example, the amount by which the crane operator must swing the boom is different when erecting a near column on tier 1 than the amount of swing necessary for erecting a far girder on tier 2. When sampling the durations of each erection task, Stroboscope accesses and considers the in-place configuration of the shape that is currently being

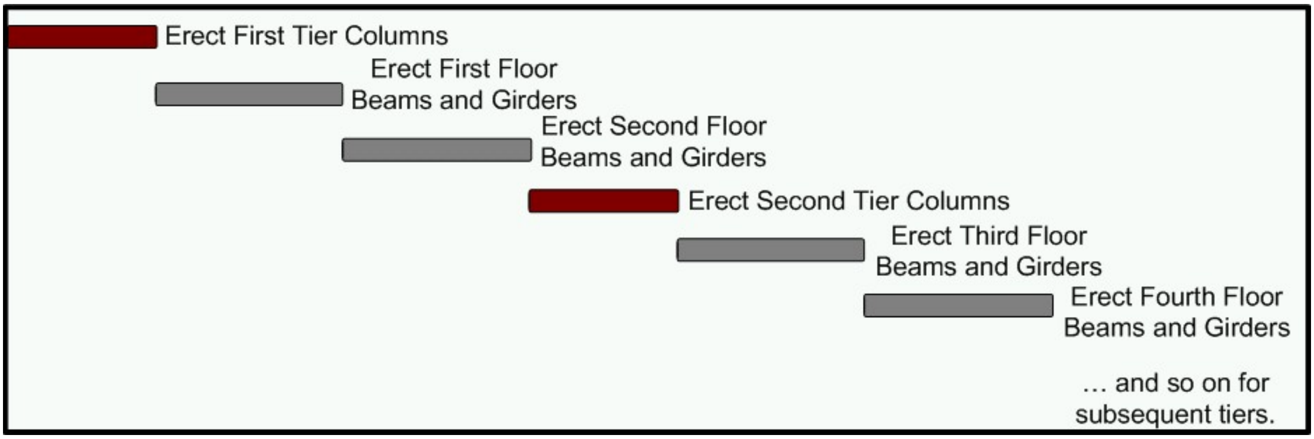

Figure 2: Possible Steel Frame Erection Schedule

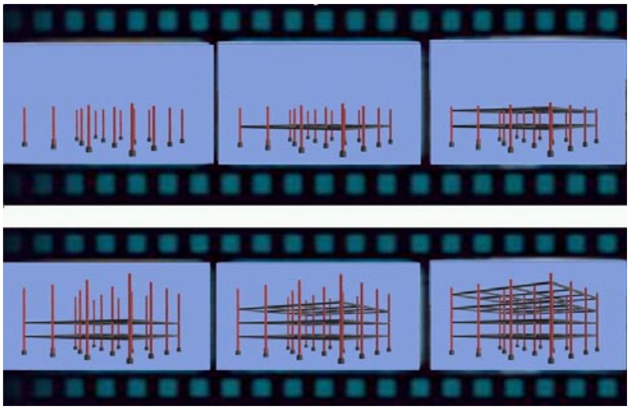

Figure 3: Snapshots of 4D CAD Visualization

processed. The duration of each erection task is thus a function of the particular shape that is being erected, as it would be in a real erection operation.

## 6 3D VISUALIZATION OF STEEL ERECTION PROCESSES

In addition to simulating the operation and obtaining the statistical parameters of interest, the simulation model can generate a dynamic 3D visualization of the steel erection processes. This is accomplished using the Dynamic Construction Visualizer (DCV) (Kamat and Martinez 2001). Using CAD models of the site, the tower crane, and each unique steel cross-section (not individual shapes), the DCV can recreate the entire frame erection operation in a 3D virtual world. Such a visualization depicts the tower crane erecting each member of the frame using the same logic and constraints that are embedded in the underlying simulation model.

The DCV has a language that allows simulation models to communicate dynamic, time-stamped events and geometric transformations to an ASCII text animation trace file. The file can contain references to the CAD models of the involved resources. Using the information recorded in the trace files and the pre-existing CAD models, the DCV recreates a faithful representation of the simulated (and recorded) operation. The simulation models are instrumented to write (to the trace file) the relevant time-stamped animation instructions on each pertinent simulation action event (e.g. ONSTART of activities and/or ONFLOW of links). Figure 5 presents a short segment of an automatically generated trace file that when processed will depict the erection of a near column on tier 2.

Figure 6 presents a snapshot strip depicting a few frames that are visualized when the animation trace file segment presented in Figure 5 is processed. The continuity and the smoothness of the animated processes are not apparent by looking at the snapshot strip. Only the animation can convey that information.

## 7 CONCLUSION

In construction, both project and operations level planning can benefit substantially from dynamic 3D visualization. Research efforts in project level visualization (4D CAD) are rooted in scheduling interests and focus on communicating what component(s) are built where and when. Cur-

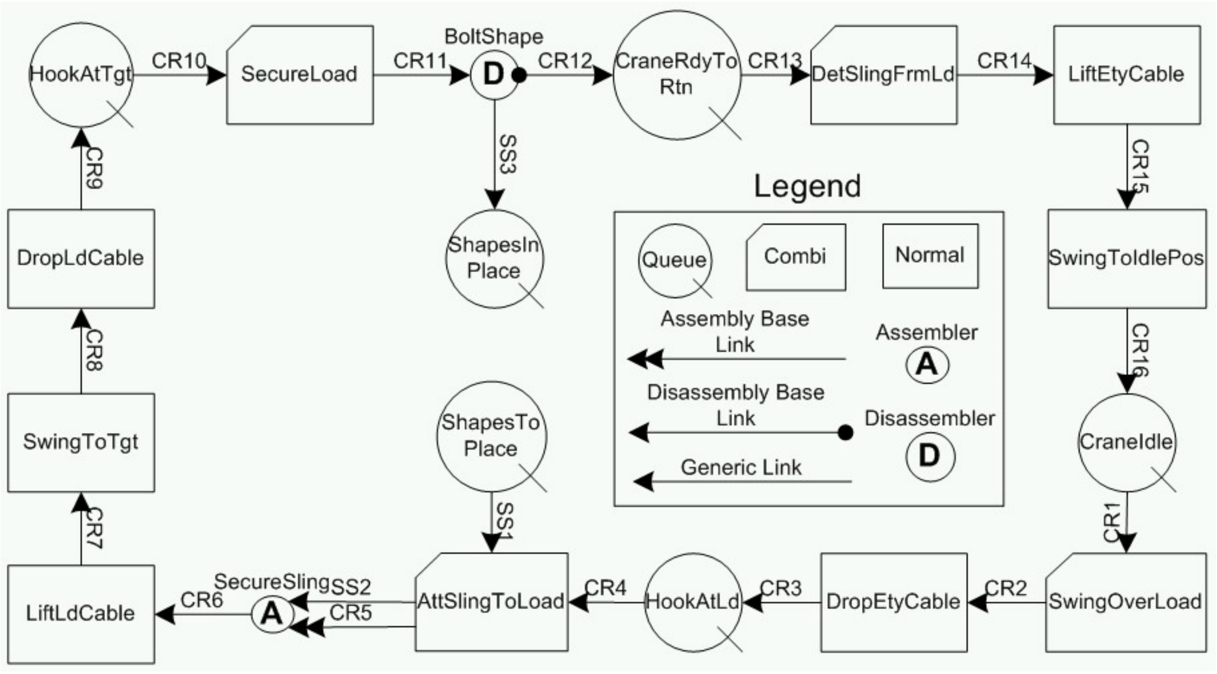

Figure 4: Simulation Model of Steel Erection Processes

```
TIME 6760.000000;
CREATE Shape65 Column;
TGTSCALE Shape65 (1,9.00,1) 0;
PLACE Shape65 AT (-14.00,0.00,8.00);
TIME 6770.000000;
ATTACH Shape65 TheHook (0,-0.5,0);
TIME 6770.000000;
SCALE TheCable (0,-30.00,0) 15.00;
SLIDE TheHook (0,30.00,0) 15.00;
TIME 6785.000000;
TGTROTATE TheBoom HOR 151.93 20.00;
TGTSLIDE TheTrolley (17.00,0,0) 20.00;
TIME 6805.000000;
TGTSCALE TheCable (1,16.30,1) 15.00;
TGTSLIDE TheHook (0,-16.30,0) 15.00;
TIME 6805.000000;
ROTATE Shape65 HOR 28.07 15.00;
TIME 6830.000000;
DETACH Shape65;
PLACE Shape65 AT (0.00,18.00,0.00);
HORIZORIENT Shape65 0.00;
```

Figure 5: Segment of Generated Animation Trace File

rent operations level visualization research efforts at Virginia Tech, on the other hand, are rooted in operations modeling interests. The work focuses on designing automated simulation-driven methods to visualize, in addition to evolving construction products, the operations and processes that are performed in building them. In addition to communicating what is built where and when, the effort is concerned with visualizing who builds it and how by depicting the interaction between the various involved machines, resources, and materials.

By utilizing an example of a multistory structural steel erection operation for comparison, this paper demonstrated that 4D CAD and simulation-driven dynamic 3D operations visualization differ significantly in concept, content, and form. 4D CAD visualizations only depict the discrete evolution of the construction product and are achieved by linking together project planning tools (i.e. CPM schedules) and CAD models of static facility components. Dynamic operations visualizations, on the other hand, depict not only the continuously evolving facility, but also the interactions of the various resources (machines, materials, temporary structures etc.) that are involved in building it. Enabling visualizations of the latter type is much more complex and is achieved by synthesizing operations planning tools (i.e. simulation models) and CAD models of both static and dynamic entities.

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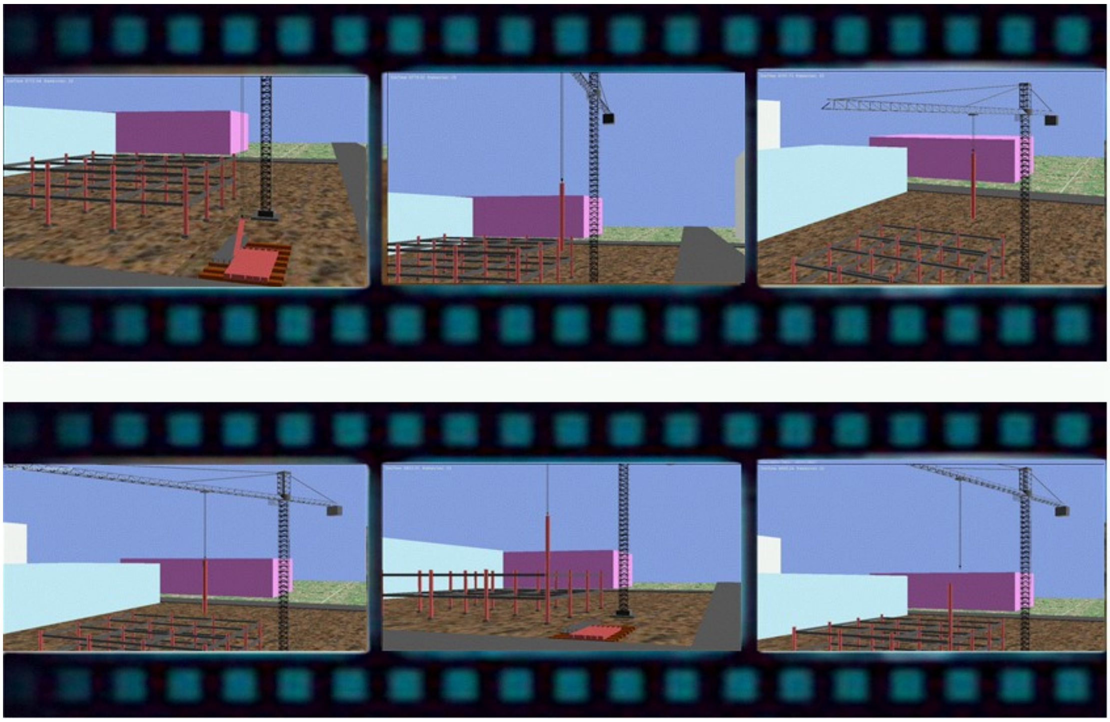

Figure 6: Snapshots of Steel Erection Processes

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