Visualization in 4D Construction Management Software: A Review of Standards and Guidelines

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ABSTRACT

Visualization of construction schedules has much improved through the development of 4D modeling tools that offer an effective method for schedule planning and management. While increasingly used by the construction industry, existing 4D tools are being continually improved, and many new tools are being developed, especially with the increased adoption of building information modeling (BIM). The ability to observe the animated sequence of the construction process and track the construction status of each building component is just one of many possibilities offered by 4D modeling applications. However, as with the proliferation of any new technology, one of the inherent challenges with 4D modeling tools is a lack of agreed upon visualization standards for representing building elements and tasks. Specifically, each tool typically has its own standards for viewing and navigating the model and schedule. Interviews with AEC professionals and experts provide insights from the end-user perspective of the current visualization methods along with their recommendations. To start addressing some of these challenges, our team reviewed the current status and methods for visualizing construction schedules, building on the research efforts in the domains of information visualization and human-computer interaction. Based on the current experiences and feedback from AEC industry practitioners, a set of visualization guidelines for representing the construction process was developed, which supports future efforts in 4D model use and development.

INTRODUCTION

Project schedules are the method for the management team to communicate the thinking and planning process to other construction project stakeholders (Karshenas and Sharma 2010). One of a construction manager's principal tasks is to develop a project schedule, where different construction activities are linked based on the developed drawings (Chau et al. 2004). Traditionally, sequencing of construction activities is performed by reviewing 2D CAD drawings, compiling an extensive list of construction activities and mentally visualizing the sequencing logic. Chau et al. (2004) note, for example, that during the facility construction, site layout changes are rarely documented, as planners typically internalize these changes. This process can cause a cognitive overload of the scheduler's memory and it can reduce efficiency (Karshenas and Sharma 2010). Therefore, an important attribute recognized by industry professionals is the possibility to rapidly revise activities and their relationships, allowing fast schedule modifications and the analysis of the resulting outcomes (Karshenas and Sharma 2010).

Providing an ability to visualize the construction progress through visual imagery has been recognized by a number of researchers as an effective way to communicate progress monitoring metrics (Golparvar-Fard et al. 2009; Haque 2007; Kuljis et al. 2001). Visualization is also a critical step for understanding and solving a problems (Kuljis et al. 2001). According to Card et al. (1999) visualization is cognition that can be enhanced by the interaction with appropriate representation methods, for example with computer-generated visual data. In this sense, supporting the problem-solving process becomes a function of supporting the visualization process and thus can be greatly affected by the representation medium. Johnson (1997) explains that poor external representations can affect internal representations by forcing the user to extrapolate and filter information, resulting in inferior mental performance. Good visual representation, therefore, is one that enables users to easily understand and communicate information and data.

The science of information visualization is a relatively new field that explores principles of creating visual representations to enhance cognition (Mazza 2008). Card et al. (1999) examine information visualization through the use of computer-supported, interactive, visual representations of abstract data to amplify cognition. While construction engineering deals with information that is mostly spatial, research efforts in information psychophysics, cognitive research of information visualization, and human-computer interaction (HCI) provide helpful lessons for developing guidelines for model interaction and visualization, such as 4D models. A review of information visualization literature identified several relevant User Interface (UI) graphical elements and behaviors that can be integrated with 4D model interaction.

This paper reviews current visualization methods in construction planning tools through the lens of related research efforts in human-computer interaction and information visualization. This review process combined with industry interviews allowed for the identification of guidelines for future 4D model user interface (UI) behavior and elements.

VISUALIZATION IN 4D CONSTRUCTION: LATEST TRENDS

The growing trend of combining 3D models with construction schedules to create 4D models is beginning to address the problem of construction process visualization. 4D modeling technology has become widely implemented in construction fields for its ability to support project teams when visualizing construction projects, identifying conflicts, safety issues, and other potential challenges (Koo and Fischer 2000). While most 4D applications support reviewing of the schedules through an animated sequence of construction activities, some advanced uses include tasks such as analysis of construction equipment designs in simulation environments; trade and space coordination; assembly sequences; real-time virtual interactive modeling of construction equipment; development of different scenarios for interference analysis; accessing construction site model-based information over the internet using VRML; and dynamic 3D visualization of discrete-event operations simulations (Kamat and Martinez 2001). Visualization of the as-planned progress in 4D environment enables project participants and clients to understand spatial constraints and explore design and construction alternatives before construction starts (Song et al. 2005).

Construction planning is a collaborative and iterative process, and as projects shift toward integrated delivery, establishing a common understanding of how information is represented becomes critical. Yet, while 4D modeling has demonstrated benefits in reducing construction costs through better communication and trade coordination (Messner et al. 2002), as more 4D simulation tools become available, one of the inherent challenges is a lack of agreed upon visualization standards in representing building elements and tasks. The lack of standards becomes particularly challenging as building projects grow more complex, along with the number of objects in the 3D model, resources, and activities. Information visualization research identifies four-dimensional data representation as one of the most challenging tasks (Mazza 2008). Developing a good visual representation concern the process of mapping graphical elements and properties such as color, texture, size, or shape to the data (ibid). Color, which can be further defined by its hue, lightness or transparency, is central to 4D models in representing different information such as activity types (e.g., construction, removal, temporary), progress (e.g. percent complete), or their statuses (e.g., on time or delayed). Chang et al. (2007) identified a lack of agreement in color representation of activity statuses (e.g., *non-started, under construction*, and *finished*). To easily identify construction processes, two types of color schemes are proposed – cooler colors for activities progressing by the schedule and warmer colors for delayed activities (Chang et al. 2009).

Interacting with the information to control the level of detail is also identified as an important aspect for developing useful visual representations, particularly when dealing with large data sets. In recent research Boton et al. (2013) explore the development of a collaborative platform for 4D simulations. Applying theories of information visualization, human computer interaction (HCI), and computer-supported cooperative work (CSCW) the authors propose 4D visualizations as systems of coordinated multiple views (CMV). Individually adapted views linked to a 3D model provide each actor in the construction process with the appropriate planning view (e.g., Gantt chart, PERT network, or Linear planning).

Research indicates both the lack of, and the importance of shared visual representation standards to support the users to quickly and easily understand and communicate information.

USER INTERVIEWS AND PRACTICE: DEFINING THE PROBLEM

To understand how existing lack of 4D visualization standards affect the current practice and identify future development needs, five interviews with AEC industry professionals were conducted. The semi-structured interviews were composed of two sets of questions. The first set of questions asked the users to evaluate their level of knowledge and experience in scheduling applications and 4D simulations. The second set of questions sought to identify perceived challenges in the current use of 4D simulations, as well as recommendations for their future development. Following is a compiled list of challenges and recommendations revealing two main areas for improvement (Table 1). Aligned with Chang et al. (2009) hypothesis, there is a need for either agreed upon color representations of schedule activities or a color-coding legend as a reference to objects or tasks being simulated. Interactive features such as controlling, filtering, and viewing activities by the task or trade area were also identified as helpful in supporting the simulation of trade specific construction. Some of the specific task representations such as trade sequence or spatial coordination are currently done manually.

Table 1. Interview results – current challenges

PROFESSIONAL'S ROLE	IDENTIFIED CHALLENGES
Integrated Construction Manager	"The possibility of defining and viewing area based tasks, so then detailed elements present in that area can be dynamically embedded and viewed, could facilitate knowledge sharing."
Assistant Process Manager	"Having a color-coded legend that illustrates what objects are being simulated, would bring value to the simulation."
Virtual Design and Construction Director	"The highlighting of zones in the 4D simulation, to show higher level of detail and specific color coding, is definitely a helpful feature."
BIM Project Engineer	"The main help that 4D scheduling has given us is in coordinating trade construction, and the possibility to illustrate how detailed sequences influence each other is a valuable feature."
Virtual Construction Manager	"There isn't an interface that supports the viewing of the general 4D model of the building together with the viewing of trade specific 4D mock up models."

Interviews reveal a common practice of developing an entire facility 4D simulation tailored for major stakeholders, such as owners. Meanwhile, detailed trade-specific simulations of assemblies are developed separately from the main model. One participant expressed the need for the overall simulations to be able to directly embed trade-specific simulations with a high level of detail, within the same 3D space. Shneiderman's (1996) addresses some of these user-interaction issues and argues that features such as overview, zoom, filter, and details-on-demand are critical in supporting the user's behavior when visualizing a large amount of data. Similarly, Card et al. (1999) point out the importance of filtering, selective aggregation, micro and macro reading, highlighting, and distortion. Therefore, a 4D simulation should allow a general overview of an entire facility construction. While this feature is useful for some users and owners, one widely recognized potential of 4D simulation is the capability of showing the trade sequencing and coordination with abilities to zoom into a facility section, highlight details and filter information. However, to promote a higher level of coordination and integration between disciplines, a UI should not remove the context of the detailed information during the focused simulation. Mackinlay et al. (1991), Furnas (1986), and Card et al. (1999) have illustrated how the context availability during the viewing of detailed information can support a visually guided task and allow for the discovery of further information. Hence, the possibility of maintaining the context during its 4D simulation can provide additional value for the stakeholder and key construction players.

An important UI element in 4D simulations is the visualization method of scheduled activities. Tufte (1998) identifies a timeline as a common and valuable graphical technique. In production and construction management, timeline as the visualization of construction activities is typically conducted through the use of Gantt charts. Plaisant et al. (1996) developed a UI strategy for viewing and interacting with timelines, which reduces the chance of missing information, streamlines the access to details, and can be utilized for other applications. The tool developed by Plaisant et al. (1996) demonstrates that several UI behaviors, such as the ability to zoom into a timeline, to reveal and filter details that are related to it are essential in supporting the dynamic visualization of details within a large schedule of activities. This technique conforms to Shneiderman's (1996) recommendations and is recognized as an important inclusion in future developments of the 4D visualization.

In summary, the visualization of 3D elements in 4D simulations can be influenced by both their graphical properties such as color, lighting, or transparency and the level of interaction. Color and its attributes (hue, lightness and transparency) is the key parameter in representing 4D schedules. The overview of current typical 4D modeling tools reveals different color palettes used to represent the activity type – usually construction, demolition, or temporary. Transparency typically indicates the percentage of task completion. Lighting and shadowing allows for the highlighting of focused building elements.

PROPOSED VISUALIZATION GUIDELINES

Based on the review and interview results, current trends and efforts in 4D simulation research were identified, together with the most prominent information visualization techniques. Following is a set of guidelines that have been found to be critical to inform future development efforts in the field of 4D simulation and visualization. The first sets of guidelines suggest design principles for user interface interaction in the planning and 3D views (Table 2). The user interface should aim to provide adapted views for each trade and stakeholder with appropriate interactive properties. These views must contain a 3D view of the model, and a planning view of the model, illustrating the related schedule activities. The interaction with the 3D model should be based on an overview, zoom and filter, and details-on-demand framework. The filtering and the provision of details will provide each trade with possibility to view 4D simulations of specific building assemblies. The adapted views should maintain the detail’s context during its 4D simulation, to provide additional value for the stakeholder and key construction players. Lastly, in the planning view, one should utilize the timeline zoom, reveal, and filter details, visualization technique.

The second set of guidelines that were selected suggests design principles for the graphical representation of building elements within the 3D view. These design guidelines address the visualization of the building element’s color, lighting, transparency, and graphical quality (Table 3), during the 4D simulation process. From the user interviews, the choice of color has been found to be a key design focus. The choice of color allows tying the 3D elements to the type of activity being performed on it, and the current status of the activity. The colors must make the building elements distinguishable from their background and from other elements. Hence, more saturated colors should be applied on selected objects in the 3D space. Additionally, color coded legends must serve as visual cues for the system that is currently being constructed. This has been found to be essential for the various stakeholders, to easily identify the appropriate system. Another design factor is the lighting of the elements, which should provide strong depth cues. Casting shadows allows the user to visually tie objects to a highlighted surface, which then defines depth. Additionally, applying a higher luminance onto the selected object distinguishes it from its context. The use of transparency is a key visualization technique to display and highlight building elements, while still maintaining the surrounding transparent context. Additionally, various levels of transparency can dictate the status of an activity. Lastly, in the displaying of higher levels of detail for trade specific views, anti-alias should be utilized for regular patterns, fine textures, or narrow lines.

Table 2. Visualization Guidelines for UI Views and Interaction

Adapted views for each actor. (Boton et al. 2013)
Overview and simulate construction model, zoom into the model, and filter the information, query details of the model. (Shneiderman 1996)
Maintain the detail's context during its 4D simulation. (Mackinlay et al. (1991), Furnas (1986), and Card et al. (1999))
Zoom into a timeline, reveal and filter details. (Plaisant et al. 1996)

Table 3. Visualization Guidelines for UI Elements

ELEMENT	GUIDELINE
Color	Use color schemes for 3D elements to dictate the activity type and progression. (Chang et al. 2009)
	Use color-coded legends as visual cues.
	Utilize color saturation to distinguish object selection. (Ware 2013)
Lighting	Use shadows and luminance difference to distinguish highlighted elements. (Ware 2013)
Transparency	Use transparency to distinguish importance. (Ware 2013)
	Use various levels of transparency to dictate the status of the activity. (Chang et al. 2009)
Graphical Quality	Use Anti-alias visualizations wherever possible. (Ware 2013)
	Avoid patterns that can lead to aliasing problems. (Ware 2013)

CONCLUSION

The possibility to conduct constructability and schedule reviews through the use of 4D simulations are an important process in the design and construction of facilities. The interviews conducted with AEC industry professionals, have provided a set of challenges that future developers of 4D software or modelers using existing tools need to address. These challenges highlight that with the spread of 4D software, there is a lack of agreed upon standards in visualizing building elements and tasks. Additionally, there is a need for UI visualization techniques, interactions, and elements to support the collaborative process of building construction and design. By reviewing previous research efforts in the field of 4D visualization, information visualization, and human-computer interaction the research team was able to develop as set of guidelines and standards for 4D application development. These guidelines address both UI interaction and behavior, together with perceptual elements within the UI. The research team believes that the possibility of detailed temporal zooming into an overview 4D simulation, while maintaining the facility's context will address some of the challenges presented earlier. With this contribution the research team hopes to provide future developers with the necessary design areas for the development of new 4D visualization techniques and standards.

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