

How 4D Visualization and Simulation Enhances Work Zone Safety and Traffic Mobility

Manish Mani and Rodolfo Valdes-Vasquez, Ph.D.
Colorado State University
Fort Collins, CO

Kelly Strong, Ph.D.
University of Northern Iowa
Cedar Falls, IA

There are multiple impacts on road users and construction workers due to highway construction activities that vary with time and location. A Four Dimensional (4D) visualization of construction work zones has the potential to identify the most significant impacts on the users and construction workers. In addition, it also aides the project planners with a better understanding of work zone impacts and effectiveness. This research demonstrates an application of work zone visualization to support intermittent, dynamic work zone deployment on a state highway project in the United States. Initial reviews of the 4D visualization demonstrate essential analytics and spatial transformations of the project with respect to time and location which would help in analyzing the diverse situations and possible impacts of work zone configurations with relative simplicity.

Key Words: 4D Visualization, Simulation, Work Zone Safety, Traffic Mobility

Introduction

One of the most viable ways of sharing project related information between stakeholders and the public is by the visualization of transportation projects (Keister & Moreno, 2002). Ready availability of three-dimensional (3D) models have facilitated many areas of architectural, engineering and construction industries as well as many new technological advancements. Simulation based modelling also known as 4D scheduling can be considered one of these technological advancements. The fourth dimension of the model originates by integration of "time" in the existing 3D model (Dang & Bargstädt, 2016). The fourth dimension brings the capacity to visualize a series of events occurring during the life of the project (Dawood & Sikka, 2008). With a 4D model, project participants can generate an animated sequence, which simulate each project component being built in synchronization with the activities of the project schedule (Russell, Staub-French, Tran, & Wong, 2009).

A major difference between the work schedule of road construction projects and standard building projects, is that the development staging of the former is associated with traffic management plans. Integrating the traffic management steps and the construction schedule into a work zone simulation allows the project team to consider and assess different traffic control options during the project development phase, such as detours, road closures, and exits (Liapi, 2003).

Researchers have identified many theoretical benefits of 4D scheduling. Clear visualization of the construction in a scheduled sequence provides better understanding of the project between different stakeholders. Visualization promotes effective decision making in the preconstruction phase which can reduce issues in the construction phase (Mahalingam, Kashyap, & Mahajan, 2010). Visualization also identifies sequential conflicts in the construction schedule and helps in reduction of rework by building a robust schedule. Several commercial software programs are available for application of 4D scheduling in construction projects which can be implemented on site and by which the user can maximize the benefits of 4D scheduling (Dang & Bargstädt, 2016).

The application examined in the research described below extends earlier approaches by incorporating various traffic measure options that can be integrated in the construction schedule in the form of "dummy activities". The resulting simulation would help to visually analyze the work schedule data and traffic planning and help in minimizing the work zone hazards and mobility reductions, reducing construction schedule delays, increasing worker safety, and improving the overall construction process.

Literature Review

4D visualization has been used increasingly in the architecture, engineering, and construction (AEC) sector. 4D visualization is developed in a virtual computer environment by combining the project schedule and the 3D model (Koo & Fischer, 2000). The visualization techniques have been used over the years as a tool to visually analyze the various stages of a project which influences the cost related planning and resource optimization (McKinney & Fischer, 1998). 4D visualization helps in the generation of interactive virtual models that result in improved communication throughout the preconstruction and construction phase of the project (Otto, Messner, & Kalisperis, 2005). The increased complexity in the projects gave rise to the 4D technology, which in turn helped in reducing project delivery duration and aided in efficient planning. The information provided through a traditional 2D model do not suffice the proper understanding of various components involved in the design as per the schedule and hence can be difficult to comprehend by person responsible (Kunz & Fischer, 2009). Because of the troubles in comprehension and visualization the diverse stages of the development plan, unforeseen clashes occur that undermine the accomplishment of the construction project (Liapi, 2003).

Liapi (2003) also points out that transportation projects often involve challenging geometries which make communication of project information between stakeholders very difficult and prone to errors". It is difficult to plan and coordinate any roadway construction project due to the complexity of the highway elements, constantly varying climatic conditions and traffic patterns. In order to avoid these complexities related to highway construction it is beneficial to use 4D visualization of the construction schedule.

Relevance of 4D Visualization in Pre-Construction

Highway construction activity could be significantly affected by the unexpected risks which might occur. These risks can cause delay in the schedule, increase in the scope changes and increase the risks related to work zone safety. These increased risks can result in increased costs for the contractor, the transportation agency, and the public. These risks can be identified, quantified, and mitigated by using a 4D visualization model which also helps as a response to the risk events that might occur. The traditional techniques of communicating the design intent through two-dimensional (2D) drawings, construction schedule, and written description of work is a difficult task. 3D models help communicate the overall design intent but fall short of effectively communicating details such as staging, traffic switches, and constraints on the contractor’s means and methods, which 3D models and 2D drawings leave to interpretation.

4D models help with the identification and mitigation of risk by providing detailed planning and analysis techniques that helps identify the potential issues and allow them to be resolved preemptively (Chau, Anson, & Zhang, 2004). The 4D visualization provides clarity and consistency in better understanding the design intent, which in turn, aids in improved collaboration and communication (Bolpagni, 2013).

Many State Transport Authorities (STAs) have established practices for developing 3D designs and critical path method (CPM) schedules as a part of the contract documentation process, leading to an opportunity to incorporate 4D visualization into the processes of permit acquisition, development of the bid documents, and the engagement of the public and stakeholder (Liapi, 2003). Based on their risk perception, the contractors prepare bid responses, including construction schedules and cost estimates. There can be a significant reduction in the contingencies and the delays in the schedule with the reduced events of uncertainty. In a highway construction project, the 4D analysis can be done in two ways. The first one uses 4D animations that link construction schedule and traffic planning with the physical geometry of the roadway. In the second technique, the 4D visualization simulates the perception of the traveling public as they drive through the construction work zone.

Advantages of 4D Scheduling Implementation

One of the major advantages of 4D scheduling is visualization (Fox & Hietanen, 2007; Russell et al., 2009; Eastman, Eastman, Teicholz, Sacks, & Liston, 2011; Jacobi, 2011). After the animated simulation is generated and completed, it can be exported to a video file and played back to visualize the construction process in chronological sequence. This ability to visualize construction sequence provides better understanding of all the events that occur during the construction phase to all the project participants such as owners, design firm, municipal authorities, and regulatory agencies by providing a bird's eye view of the process. By this everyone can get a clear impression of how the project will appear rather than having to imagine the end-product from plans or Gantt charts. Hence, with the help of 4D modeling, information can be understood clearly, construction can progress faster and thereby reduce the amount of rework (Dawood & Sikka, 2008). These visual representations can assist greatly in identification of effective construction strategies for reducing project durations, achieving higher productivity, and judging overall schedule quality.

A 4D model is a powerful communicating tool and promotes effective coordination between project participants. They facilitate brainstorming among project staff and can provide rapid feedback on design or methodology changes to the project team. Powerful and rapid decision making promotes effective communication. This approach helps in eliminating last minute changes and rework (Dang & Bargstädt, 2016). Ability to visualize aids efficient communication of construction plans between contractors and client. It helps in review of project progress and control project execution by study of "what if" scenarios (Mahalingam et al., 2010). Detection of space-time clashes, installation conflicts, and workflow management can be performed before the work begins by use of 4D visualization. Proper evaluation of 4D model can detect potential on-site clashes between different trades (Akinci, Fischer, Kunz, & Levitt, 2002; Turkan, Bosche, Haas, & Haas, 2012). Use of 4D visualization facilitates comparison of a virtual model to the real-time product in the field. It enables project participants to locate differences in the planned project and the as-built project. The reasons for these deviations can then be analyzed.

In addition, the user can create different construction schedules, run simulations, compare the methods with each other and choose the best method for execution of activities (Han & Golparvar-Fard, 2015). It is one of the very strong advantages of 4D model. If the 3D model is generated with precision and accuracy, a 4D model can facilitate extraction of precise information related to quantities of different building components. Quantity of resources required for each component can be generated automatically which can ease the process of cost estimation and generating procurement plans (Dang & Bargstädt, 2016). Visualization facilitates resource planning and resource levelling to optimize resource utilization to ensure that all projects are completed on time, within budget and to acceptable standards of quality (Edwards, 2011). Improvement and accuracy in documentation is an essential aspect brought to the table by 4D implementation. Proper documentation results in less site errors which improves quality and results in less litigation (Roundtable, 2010). The availability of 4D-model aids in asset management and improves operation and maintenance efficiency (Azhar, 2011; Roundtable, 2010). It is evident that benefits associated with 4D visualization can be used to improve operational efficiencies of the construction project. However, many researchers point out that that it is still not widely adopted in the construction industry (Dawood & Sikka, 2008; Mahalingam et al., 2010).

According to the most recent available statistics, an average of seven road users and one highway construction worker are killed every week nationwide. In 2014 alone, around 1,607 crashes occurred in Colorado construction zones that accounted for 130 injuries and 9 deaths (CDOT, 2015). There has been a significant increase in pressure from the public on transportation agencies to be transparent in terms of how the agency uses their resources, since the agencies have to advocate for increases in funding at both the federal and state level. In addition, the agencies also face the challenges of limited funding to construct and operate their aging transport infrastructure. Thus, transportation agencies need to find new ways to manage risk, optimize resources, communicate with the public, and account transparently for construction expenditures. Four-dimensional (4D) models can help address each of these concerns. To summarize, there are four primary ways in which 4D models can aid STAs in delivering projects.

- Public Information Management.
- Risk Mitigation and Management.
- Tracking progress and payments.
- Resource optimization.

In addition, the 4D visualization technique can also be used to provide various construction related information for the construction instructors to use in their classrooms. There are a few free computer applications that students can use to develop and analyze any model such as Infraworks. Infraworks application was used in our case study and it can be put to use to any other construction related scenario if needed. These applications use can be introduced in construction safety classroom sessions to help the students better understand the construction process and help minimize the safety issues.

Methodology

The methodology involved an exploratory case study research method followed by expert validation, intended to gather information for future studies. For this research project, a case study was selected for developing and analyzing the potential benefits of 4D visualization of a transportation construction project. We selected this area we because the lead researchers had established good working relationships with the director of safety research in the State Department of Transport and with the contractor performing the work. Although, the same technique for visualization can be used for any highway at any other place. The case study project is a 2-lane state highway in mountainous terrain in the western United States. The State Transportation Authority began repairs on the highway caused by damage from severe flooding three years ago. The repair work was done in two phases. The first phase included reconstruction to the shoulders, rock scaling, slope stabilization and asphalt paving, and the installation of culverts to carry water under the road. Phase II repairs involved finalization of culvert work and roadway paving to the junction with a major federal highway.

4D Modeling Framework for Visualization

The aim of this research is to disseminate real time traffic related information to the travelling public and construction workers as an advance warning for the activities going on in the construction zone. The most suitable approach to this objective was to develop photo-realistic visualizations through the driver's perspective and analyzing the output video file through observations. The 4D visualizations include the 3D digital models that consist of all the traffic control signage and devices that are indicated on the construction and traffic planning documents. This includes the terrain, the existing and proposed road network along with the other natural objects such as the tree line and water bodies, in the visualized area. Views of the surrounding environment including distant buildings, hills, etc. have also been incorporated in the model. Figure 1 shows a sequential flow of the research process that has been adopted for achieving the objective.

1. Collection of 2D data for the proposed road design and the construction schedule from STA and contractor.
2. Developing 3D terrain model including the built environment using the 2D plans.
3. Linking construction schedule and the 3D model.
4. Creating rendered 4D visualization for analysis.
5. Distribution of the generated video file to a focus group for analysis

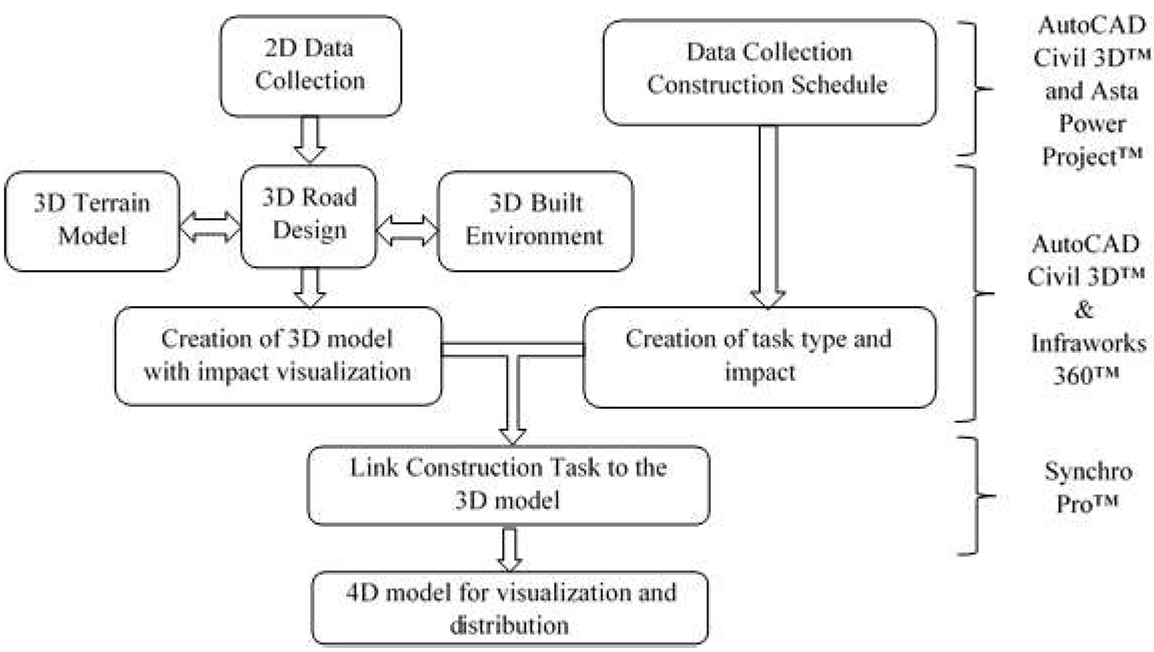

Figure 1: Sequential Flow of Process.

List of computer applications used to achieve the required visualization:

- AutoCAD civil 3D™ & Autodesk Infraworks 360™ – For 3D model generation from 2D plans.
- Autodesk Revit™ – For developing custom models which were not available in the default library of materials.
- Asta Power Project™ and Synchro Pro™ – For integrating scheduling data into the 3D model.
- Google Earth – For identifying the location of buildings and tree line as a reference for the visualization.

Visualization Process Development

In order to make the visualization, the first step was to do the site modeling, which involved using the Infraworks 360™ and AutoCAD civil 3D™ computer applications. The Infraworks computer application helps its users to download the GIS data from its web based cloud storage. This GIS data is synchronized with Google Earth™ and helps in the generation of the 3D terrain of the focused area to be analyzed.

Figure 2: Google Earth™ Image.

Figure 3: Infraworks 360™ Driver's View.

The terrain obtained does not include the proposed design roads as specified in the construction documents. The AutoCAD Civil 3D™ application was used to modify the existing roads to the proposed design roads. In order to make the visualization realistic, the 3D model went through a series of modifications with reference to the Google Earth™ to identify the location of the buildings, tree line and the surrounding environment. Infraworks also helped in setting the traffic demand that had to be incorporated in the visualization. The traffic volume was selected from annual average daily traffic record (AADT) from the web-based Online Transportation Information System (OTIS) data bank provided by State Transportation Authority. For the visualization the combined traffic counts from both the primary and secondary directions were considered. The visualizations were made to analyze the process based on different times of a day and with varying sky conditions.

Figure 4: Infraworks 360™ View at 10:35am.

Figure 5: Infraworks 360™ View at 07:35pm.

Next step was to create the video file that would include the 3D model with the design specifications, the traffic flow and the surrounding environment. Using all of these features a fly-through from the driver's view was created in the storyboard mode using the Infraworks application. An example video can be watch using the following link https://youtu.be/2Usi3s7npeU

Discussion and Conclusion

The findings were shared in the form of a video file with a panel of six experts from the transportation industry to gather their feedback. Five out of the six experts agreed that 4D visualization is a valuable tool for work-zone planning and highway safety. Four out of six agreed that 4D visualization can be an important tool for an effective coordination of equipment movement. Four out of six strongly agreed that 4D visualization is an effective training tool. Five out of six strongly agreed that 4D visualization is a fundamental tool to communicate effectively with all the trades. Per the experts, the visualization illustrated the site conditions well and has the potential of improving work-zone planning and safety, however, a few experts also identified a few limitations to the visualization which have been addressed later in this paper.

The results of the study suggest that 4D work zone visualization can assist greatly in identification of effective construction strategies for mitigating construction work zone risks and provide better traffic mobility. The visualization can help in developing better traffic management plans and contribute to more effective traffic flow. In addition, this ability to visualize construction sequence can provide better understanding of all the events that occur during the construction phase to all the project participants such as owners, design firm, municipal authorities, and regulatory agencies by providing a 4D view of the project. Making the visualization available to the travelling public can potentially help in the reduction of work-zone hazards and improve the overall construction process.

One of the limitations of this study is that the visualization could have been made interactive and more realistic by using more advanced software. This is one of the limitations of the Infraworks 360™ application that was used to render the video output. The visualization can be made interactive if it is used with a more advanced computer application, but, for such active interaction session, the user needs to have more knowledge and more powerful processing systems. The tradeoff between interactivity and resource demands is an open question to be addressed by each transportation agency. The intention of this study was to distribute traffic related information to the travelling public which was easier in the form of a drive-through video which could be used by anyone without requiring the knowledge of any software.

Although, the use of computer aided applications proved to be very useful in simplifying the construction process and improving safety, it is also accompanied by a few limitations related to tasks that can be performed using the applications. For instance, the Infraworks™ application has limited digital models in its default library which resulted in relying on other applications like Revit™ and AutoCAD™ for developing custom 3D traffic elements like the traffic signs. Another limitation was the application's inability to show the solar glare in the visualization as would be encountered in early and late day conditions as the highway used in the case study had an east-west orientation. Future research can be made in this direction to explore the possibilities of incorporating the visualizations in an open-access web-based applications that can be used by anyone with basic knowledge of computer skills.

References

Akinci, B., Fischer, M., Kunz, J., & Levitt, R. (2002). Representing work spaces generically in construction method models. *Journal of Construction Engineering and Management, 128*(4), 296-305.

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering, 11*(3), 241-252.

Bolpagni, M. (2013). The implementation of BIM within the public procurement: A model-based approach for the construction industry. *VTT Technology, Finland, 130*.

State Transportation Authority (2014). Historical Construction Zone – Related Crash Data. Retrieved from https://www.codot.gov/library/statistics/Historical%20Construction%20Related%20Crashes%201986_2006.pdf/view

State Transportation Authority. (2017). Flood-Related Projects. Retrieved from https://www.codot.gov/projects/floodrelatedprojects/sh-7-estes-park-raymond

Chau, K., Anson, M., & Zhang, J. (2004). Four-dimensional visualization of construction scheduling and site utilization. *Journal of Construction Engineering and Management, 130*(4), 598-606.

Dang, T., & Bargstädt, H.-J. (2016). 4D Relationships: The Missing Link in 4D Scheduling. *Journal of Construction Engineering and Management, 142*(2), 04015072. doi:doi:10.1061/(ASCE)CO.1943-7862.0001007

Dawood, N., & Sikka, S. (2008). Measuring the effectiveness of 4D planning as a valuable communication tool. *International Journal of Information Technology in Construction*.

Eastman, C., Eastman, C. M., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*: John Wiley & Sons.

Edwards, M. (2011). Synchro 4D/5D BIM Software.

Fox, S., & Hietanen, J. (2007). Interorganizational use of building information models: potential for automational, informational and transformational effects. *Construction Management and Economics, 25*(3), 289-296.

Han, K. K., & Golparvar-Fard, M. BIM-Assisted Structure-from-Motion for Analyzing and Visualizing Construction Progress Deviations through Daily Site Images and BIM *Computing in Civil Engineering 2015* (pp. 596-603).

Jacobi, J. (2011). 4D BIM or Simulation-Based Modeling. Structure Magazine (April, 2011).

Keister, M. S., & Moreno, D. (2002). Cutting-edge visualization tools: Graphic simulations that stimulate project understanding and decision making. *TR News*(220).

Koo, B., & Fischer, M. (2000). Feasibility study of 4D CAD in commercial construction. *Journal of Construction Engineering and Management, 126*(4), 251-260.

Kunz, J., & Fischer, M. (2009). Virtual design and construction: themes, case studies and implementation suggestions. *Center for Integrated Facility Engineering (CIFE), Stanford University*.

Liapi, K. A. (2003). *4D visualization of highway construction projects.* Paper presented at the Information Visualization, 2003. IV 2003. Proceedings. Seventh International Conference on.

Mahalingam, A., Kashyap, R., & Mahajan, C. (2010). An evaluation of the applicability of 4D CAD on construction projects. *Automation in Construction, 19*(2), 148-159.

McKinney, K., & Fischer, M. (1998). Generating, evaluating and visualizing construction schedules with CAD tools. *Automation in Construction, 7*(6), 433-447. doi:http://doi.org/10.1016/S0926-5805(98)00053-3

Otto, G. H., Messner, J. I., & Kalisperis, L. Expanding the Boundaries of Virtual Reality for Building Design and Construction *Computing in Civil Engineering (2005)*.

Project:BIM, A. P. (2015). Retrieved from http://astapowerproject.net/wp-content/uploads/2015/07/Asta-Powerproject-BIM-US.pdf

Roundtable, C. U. (2010). BIM implementation: An owner's guide to getting started. *Æhttp://www. aia. org/aiaucmp/groups/aia/documents/pdf/aiab085571. pdfæ (Apr. 25, 2013)*.

Russell, A., Staub-French, S., Tran, N., & Wong, W. (2009). Visualizing high-rise building construction strategies using linear scheduling and 4D CAD. *Automation in Construction, 18*(2), 219-236.

Turkan, Y., Bosche, F., Haas, C. T., & Haas, R. (2012). Automated progress tracking using 4D schedule and 3D sensing technologies. *Automation in Construction, 22*, 414-421.