VISUALIZATION AND AUTOMATIC VERIFICATION OF A SCHEDULE-DRIVEN 4D MODEL

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ABSTRACT: *By integrating physical 3D elements with time, 4D technology provides a comprehensive tool to visualize construction sequences as part of an interactive experience. With years of development, 4D technologies were adopted in more and more projects, to improve crew coordination, shorten the construction period, and to reduce request for information. Though research that improves the productivity of 4D tools exists, most studies so far failed to keep synchronization between work schedules and animations and are not capable to verify the 4D model automatically. By evaluating commonly used 4D visualization tools, the pros and cons are concluded in this article. Then, a schedule-driven 4D model is proposed, which consists of physical element model, geometry model, schedule model and visualization model. With this model, different construction operations can be represented by colors, textures, and transformations. What's more, processes for model verification and frame rendering were proposed in this research. Finally, demonstration of this model was implemented in the construction of a cable-stayed truss bridge over the Yangtze River. It is illustrated that with automatic model verification and a better visualization, the proposed model can reduce rework and mistakes. Future improvements of the model are also discussed in this article.*

KEYWORDS: *Four dimensional, Visualization, Model verification, Schedule-driven model.*

1. INTRODUCTION

Due to the complexity and the dynamic nature of construction processes, it is hard to get a better understanding of the construction processes with traditional Gantt charts or CPM schedules, visualization tool based on 4D technology has been proven to be an effective tool (Staub et al., 1999, Koo and Fischer, 2000) for improving construction process planning and management. Since 1990s, owing to the significant potentials of 4D CAD, several studies have been made on this field. Overview on generating, evaluating and visualization construction schedules with CAD tools (McKinney and Fischer, 1998) or geographic information systems (Bansal and Pal, 2008) was also presented. Consequently, various construction visualization and management prototypes emerged, such as GCPSU (Hu and Zhang, 2011) and PECASO (Dawood and Mallasi, 2006). Besides, cost, as a "fifth dimension" of project information, was also incorporated in some systems to enable virtual construction. Moreover, 4D visualization was also applied for safety management in metro construction (Zhou et al., 2013), and merits of web-based 4D visualization for collaborative construction planning and management were also studied (Castronovo et al., 2014). With years of developments, 4D CAD concept (McKinney et al., 1996) has been implemented in dedicated construction visualization and management software, such as Synchro Pro (Synchro, 2015) and Vico Office (VicoOffice, 2015) and has also been incorporated in full-fledged BIM tools.

However, difficulties in 4D modeling, especially the tediousness and error-proneness, have been widely experienced by all levels of users of 4D visualization tools. First, lots of physical elements and schedule tasks are involved in the creation of the 4D model, which may increase the complexity of the work, and result in spending more time in linking different elements to their corresponding tasks (Heesom and Mahdjoubi, 2004). What's more, colors and animations, which can improve the understanding of the construction processes, are always incorporated in 4D modeling. Setting different colors and animations for different construction activities will take users more time to learn and be acquainted with 4D visualization tools. Besides, most of the 4D tools failed to use textures in the visualization of construction processes, and a new model is needed to incorporated textures as an enhancement of the visualization of construction processes. Moreover, there is no proper mechanics between the schedule and the animation. Changes in schedule cannot reflect in the animation without any manual work. Finally, verification of a 4D model is crucial and require lots of time and experiences, the only approach now is to play the 4D visualization for many times and find possible mistakes by eyes. Though automatically generation of the 4D model based on spatial reasoning (Weldu and Knapp, 2012) or attributes of physical elements (Montaser and Moselhi, 2015) have been discussed respectively, most systems still lack an easy-to-use method to accomplish 4D modeling and verification, especially for common users who lack adequate knowledge and experience.

In this paper, by comparing different 4D visualization and construction management tools, their pros and cons are concluded, which motivates the development of the new model. Then, a schedule-driven model that incorporates colors, textures, and animations for 4D visualization is proposed, and workflow for model verification and visualization based on this model is also presented. After that, with application in the construction of a cable-stayed steel bridge, the feasibility of the model is carefully validated. Finally, the application results and future improvements are discussed.

2. COMPARISON OF 4D VISUALIZATION TOOLS

There are many commercial systems for 4D visualization, construction planning and management these days. Among all these systems or tools, 4 widely used 4D tools were selected to implement the comparison; they are Navisworks, Navigator, Vico Office, and Synchro Pro. In order to evaluate these above-mentioned 4D tools and find their pros and cons, the following three aspects were considered and analyzed (Table 1):

(1) Visualization: as a basic feature, all the selected tools can utilize different colors and visibilities to represent different statuses of construction activities. For instance, light green and blue can be used to represent elements before installation and after installation respectively, while for elements of a temporal structure, their visibility should be set to false after dismantling. Meanwhile, key-frame animation was supported by all the selected tools too. Moreover, Synchro Pro stands out among the 4D tools by supporting path-based animation and growth animation; the latter animation can also be linked to a specific task of the schedule and be controlled by that task. However, it is found that neither of them persists a mechanics between the schedule and key-frame animation for synchronization. That is, if you set your animation to take 5 seconds, it won't change no matter how fast your schedule is moving in the simulation.

(2) Scheduling: interoperability between schedule modeling tools and the mentioned 4D tools is improved continuously. Each of the tools supports integrating schedule data from Microsoft Project, P3, and P6. However, since Navisworks and Navigator mainly focus on coordination and visualization, task sequences are kept but could not be edited in these tools. On the contrary, not only the time but also the task sequences can be edited in Vico and Synchro because they mainly focus on construction planning and management.

(3) 4D modeling: obviously, basic operation that links 3D objects to tasks of the schedule is supported by all the 4D tools. Despite of this, users can also link 3D objects to tasks by a drag and drop tool, while Navisworks provides a filter based the property of 3D objects to create a search set, which can then be linked to specific tasks.

Except for the above-mentioned features of these 4D visualization tools, other functions like clash detection and resource management, are also provided, due to their low relevance to this research, these functions were omitted when comparing the 4D visualization tools.

It is obvious that these tools are appropriate for coordination, planning, resource and cost management, but still with inadequate ability for 4D visualization. Neither system explicitly supports for synchronization between work plans and animations. It is a boring task to find mistakes made in creating a 4D model.

Table 1: Comparison of different systems for 4D visualization and construction planning and management.

	Visualization				Scheduling	4D modeling	Model verification	Schedule animation Sync
	Color	Texture	Visibility	Animation				
Navisworks 2015	√	×	√	√ Key frame	√ Time & Duration × Task sequences	√ Manually √ Search Set based	×	×
Navigator V8i	√	×	√	√ Key frame	√ Time & Duration × Task sequences	√ Manually	×	×

Vico Office R4	√	×	√	√ Key frame	√ Time & Duration √ Task sequences	√ Manually	×	×
Synchro Pro	√	×	√	√ Key frame √ Path √ Growth	√ Time & Duration √ Task sequences	√ Manually √ Drag & Drop	×	×
Proposed model	√	√	√	√ Key frame	√ Time & Duration √ Task sequences	√ Manually	√	√

3. THE SCHEDULE-DRIVEN 4D MODEL

Generally, the model for construction process visualization consists of four parts of information: (1) *physical elements*, such as building elements and equipment, (2) *3D representations* of physical elements, (3) *time and duration of tasks*, which can be obtained from scheduling applications, (4) *visualization* used to depict the construction operations. Considering the above-mentioned requirements, a schedule-driven 4D model composed of physical element model, geometry model, schedule model, and visualization model was proposed for construction visualization and verification (Fig. 1). In this 4D model, relationship between the element model and the visualization model is established by the schedule model, which is also used to keep synchronized between the animation for construction visualization and the schedule when time of the tasks changes. Thus, the schedule model performs as the core part of the proposed model, that is why the model was named as *schedule-driven 4D model*. What highlighted this model is, it provides a strong relationship between schedule/time and visual states (including transformation, colors, textures, and visibility). Since animation is just the change of visual states when the time changes, it can be generated based the schedule and its related visual states easily. It is obvious that any change of the schedule can be simultaneously reflected in the animation.

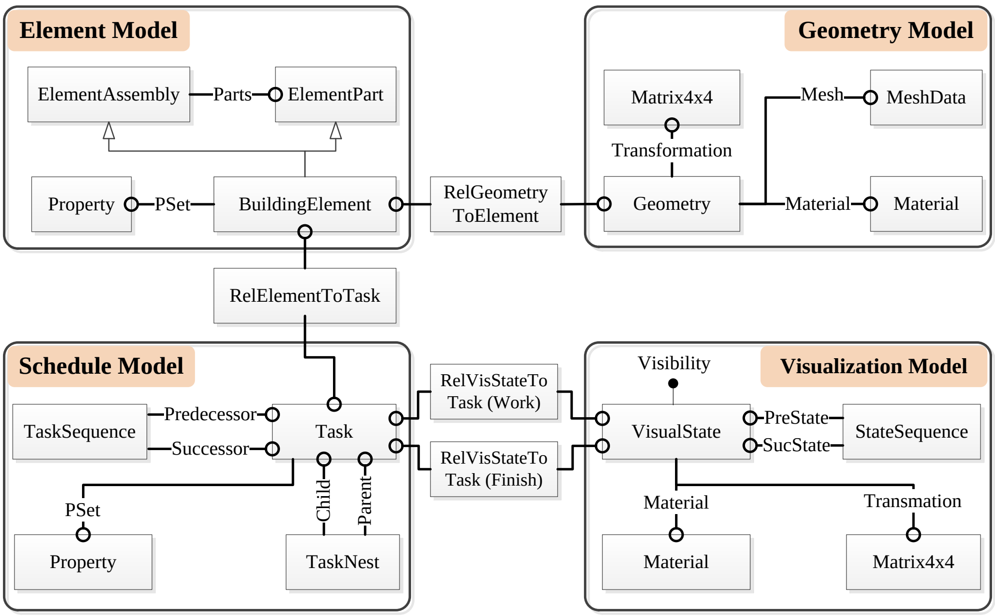

Fig. 1: The schedule-driven 4D model

3.1 Element Model

Element model defines physical objects in the Architectural, Engineering, and Construction (AEC) domain, including building elements (such as wall, beams, columns, slabs, and windows, etc.) and construction resources (like formworks, cranes, and trucks). Each physical object can be composed of different parts, or can be a part of another physical object, for example, a door may be decomposed into door panel and door lining. With object assembly and object parts, it is possible to model the same object with different level of details in different phases of the AEC project.

Basic property is provided for each physical object, and property set is also provided for extension of the objects. Since this is not important for construction visualization, details on property set are omitted. Generally, information in property set can be used as the mechanics to link physical elements and schedule tasks.

3.2 Geometry Model

Geometry model is 2D or 3D representation of physical objects, and is connected to element model by *RelGeometryToElement*. Since few model editing operations is done in most simulation platforms, tessellated surface model is adopted in geometry model. All tessellated surfaces are encapsulated in *MeshData*, in which vertices, face indices and types of primitives (such as triangles, quads, points, lines) are kept in *VertexData*, *IndexData*, and *PrimitiveType* respectively. Material is adopted to represent the shading style of the geometry. In this article, textures, ambient color, diffuse color, specular color, and transparency are taken into account when modeling material. A 4x4 matrix is utilized to represent the transformation (including translation, rotation, and scale) of the geometry. Generally, translation ($T(\mathrm{d})$), scale of three axes ($S(\mathrm{s}_x, \mathrm{s}_y, \mathrm{s}_z)$), and rotation around three axes ($\mathrm{R}_z(\alpha), \mathrm{R}_y(\beta), \mathrm{R}_x(\gamma)$) can be represented by 4x4 matrices. Thus, the final transformation of a geometry model can be represented by a 4x4 matrix (M_f):

$$M_f = T(\mathrm{d}) \cdot \mathrm{R}_z(\alpha) \cdot \mathrm{R}_y(\beta) \cdot \mathrm{R}_x(\gamma) \cdot S(\mathrm{s}_x, \mathrm{s}_y, \mathrm{s}_z)$$

Where

$$T(\mathrm{d}) = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, S(\mathrm{s}_x, \mathrm{s}_y, \mathrm{s}_z) = \begin{bmatrix} \mathrm{s}_x & 0 & 0 & 0 \\ 0 & \mathrm{s}_y & 0 & 0 \\ 0 & 0 & \mathrm{s}_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{R}_z(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 & 0 \\ \sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathrm{R}_y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathrm{R}_x(\gamma) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma & 0 \\ 0 & \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

3.3 Schedule Model

As the core entity of schedule model, *Task*, is typically used to describe an activity for the construction or installation of products. *TaskSequence* is a sequential relationship between tasks where one task (*Predecessor*) must occur before the other (*Successor*) in time and where the timing of the relationship may be described as a type of sequence, including *Finish_Start*, *Finish_Finish, Start_Finish, and Start_Start*. A *Task* may be contained within another *Task* using *TaskNest* relationship, which indicates decomposed level of detail. Similar to the *BuildingElement*, *Task* can also have property set as its extension. In order to visualization schedule delay or work ahead of time, both the plan schedule and the actual schedule should be contained in the *Task*. Finally, relationship between physical elements and tasks can be established by *RelElementToTask*.

3.4 Visualization Model

VisualState is used to describe the visual style of an activity and the transformation of the physical elements related to the activity. Each visual state is attached to construction tasks by *RelVisStateToTask*, multiply visual states are supported to represent different visual styles under and after construction. *Visibility* of a visual state is used to control whether the 3D representation of an element should be visible or not when the corresponding activity happens, while the changes of visual style (like color, and texture) and transformation (including movement, scale, and rotation) are represented by *Material* and *Transformation* respectively. In addition, smooth effects for switching one visual state to another, like fade in/out, were also considered in the model. Visual states can have a predecessor and a successor to describe the order that they should apply to the 3D representations. Thus, key-frame animation can be represented by a combination of visual states, and every visual state is attached to a task in a schedule. Since the duration of each key-frame is extracted from the task, and every time a schedule changes it causes a refresh of the animation. Synchronization between schedule and key-frame animation is easily kept.

4. MODEL VERIFICATION AND VISUALIZATION

4.1 Model Verification

In this paper, the main objective of model verification is to find mistakes made in 4D modeling, two types of mistakes are handled in model verification: 1) space error: location relationship of elements is incompatible with the schedule; 2) visualization error: sequence of visual states conflicts with the schedule.

For space errors, basic rules should be defined based on spatial relationships, for example, assembly of a steel truss should be compliant to a bottom-up manner. This type of mistake is detected in four steps:
(1) Filter tasks related to the same segment or region of the whole structure, then sort the filtered tasks by their start/finish time;
(2) For every pair of the tasks, Take one geometry from the task starts/finishes earlier, and take another geometry from the later task;
(3) By comparing their axis-aligned bounding boxes (AABBs) and locations of the two geometries, their spatial relationship can be automatically categorized into:
   a) Horizontal adjacent: elevations of the two geometries have a small difference, and their AABBs are near to each other (overlay with each other or distance between them no more than a predefined threshold).
   b) Vertical adjacent: AABBs of the two geometries are near, and elevation of one geometry is higher;
   c) Others.
(4) Find whether the spatial relationship conflicts with the predefined rules or not, if conflicts, warn the user.

For example, for geometries in a vertical adjacent relationship, assembly of the lower one should be earlier than the other, if the schedule conflicts with this (Fig. 2 (a)), the users should be informed.

Visualization errors occur when visual state of an earlier task has a predecessor related to a later task. This type of problem can be addressed by the following steps:
(1) Sort the all the tasks by their start/finish time;
(2) For every pair of the tasks, get visual state *S1* of the task starts/finishes earlier, and get visual state *S2* of the later task too;
(3) Find whether *S1* is the successor of *S2* or not, if the answer is true, warn the user.

For instance, assembly visual state (*S1*) for elements of the segment *n+1* is the successor of jacking visual state (*S2*) of segment *n*, if a mistake of the element assembly time of segment *n+1* was made in scheduling (Fig. 2 (b)), it can be automatically detected.

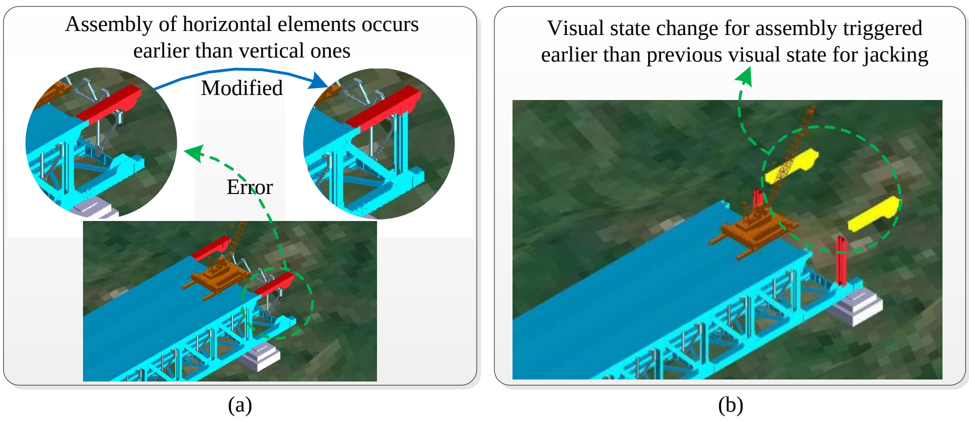

Fig. 2: The typical mistakes made in 4D modeling

4.2 Frame Generation for 4D Visualization and Animation

Based on the model proposed, 4D visualization as well as animation of different 3D geometries can be automatically generated. Generally, 4D visualization and animations can be taken as a series of frames (or pictures) with specific sequence. Thus, it is easy to obtain 4D visualization and animations of a project as long as a frame at any time can be generated based on the schedule-driven 4D model, which is also not hard to achieve. As shown in Fig. 3, a frame *n* can be generated as following:

(1) Calculate the current time of the schedule based on *n*; and iterate all the tasks of the schedule.
(2) Get visual states of current frame (*Sn*) and previous frame (*Sn-1*) through the relationship between tasks and visual states, if they are the same, which means no change need to make to the related geometries, just return to step (1); otherwise, do the following.
(3) Update the corresponding geometries with visual state *Sn*. Interpolation of transformations, colors, or textures may be needed in order to get a smooth switching effect of visual states.
(4) Put all changed geometries into the collection *Geometry2Render*.
(5) After completing iterating all the tasks of the schedule, render all geometries in collection *Geometry2Render*, then go to the next frame.

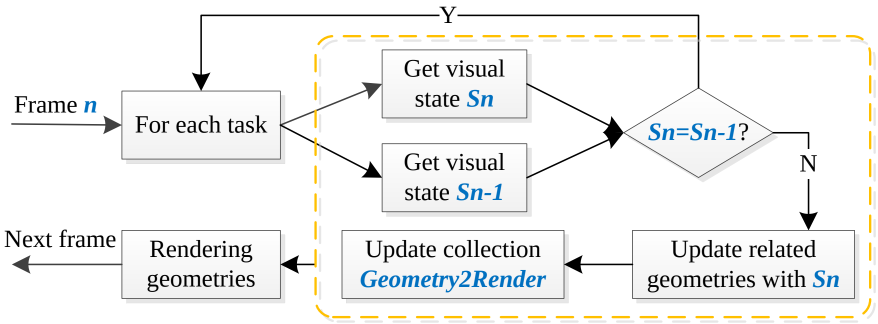

Fig. 3: Frame generation based on schedule-driven 4D model

5. DEMONSTRATION

With a total length of 920m and a longest span of 432m, the new Baishatuo Yangtze River Bridge (NBYRB) is the major project milestone of Chongqing-Guiyang high speed railway. It is the first double-deck cable-stayed truss bridge with six tracks (Fig. 4), and with the greatest load per meter in the world. The upper deck with 4 tracks is for passenger rail transportation and the lower deck with 2 tracks is for rail freight transportation. There are two main towers with cables in a modified fan arrangement in both sides; the taller tower is 192m, while the other one is 175m. Construction of the bridge starts on December 31, 2012, and will finish on August 31, 2016. By extending previous developed 4D construction management system 4D-BIM (Hu and Zhang, 2011), the schedule-driven 4D model was tested in the construction of NBYRB and utilized in the visualization of bridge truss assembling and jacking.

Fig. 4: The new Baishatuo Yangzte River Bridge

Design model of the bridge was created by Catia V5, and imported into 4D-BIM by 3dxml. There are 4,512 elements, 71,118 element parts, and 1573 work tasks in total, and elements of the steel truss of the bridge were grouped into 68 segments (once a segment is assembled, the bridge can be jacked forward). It will be a crucial task to check all the mistakes made in 4D modeling manually. Relationship between physical elements and work tasks are established by semi-automatically matching element names to work tasks. Since the main type of animation in this project is for the jacking process, every time a segment is assembled, an activity that jacking the truss forward should be made. Colors, textures and visibility (visual state) for different elements are modeled in 4D-BIM. By default, the transformation of the visual state is an identity matrix, when a jacking operation is necessary, a translation matrix representing the jacking direction and distance should be set. Considering every jacking operation is a movement relative to the previous state (location of elements), its predecessor (previous visual state) should be selected when editing the current visual state, therefore forming a state chain of all the physical elements. When 4D modeling is finished, model verification can be achieved by one click, then the elements with possible errors will be highlighted in the 3D view (Fig. 2). Users can then check the related work tasks or the visual states to resolve the problems. After the above-mentioned work, 4D visualization and animation are generated from the model (Fig. 5), and provide a better way to represent the construction processes of the bridge. Any change of the schedule will trigger the updating of the 4D visualization and the regeneration of animation, keeping their synchronization.

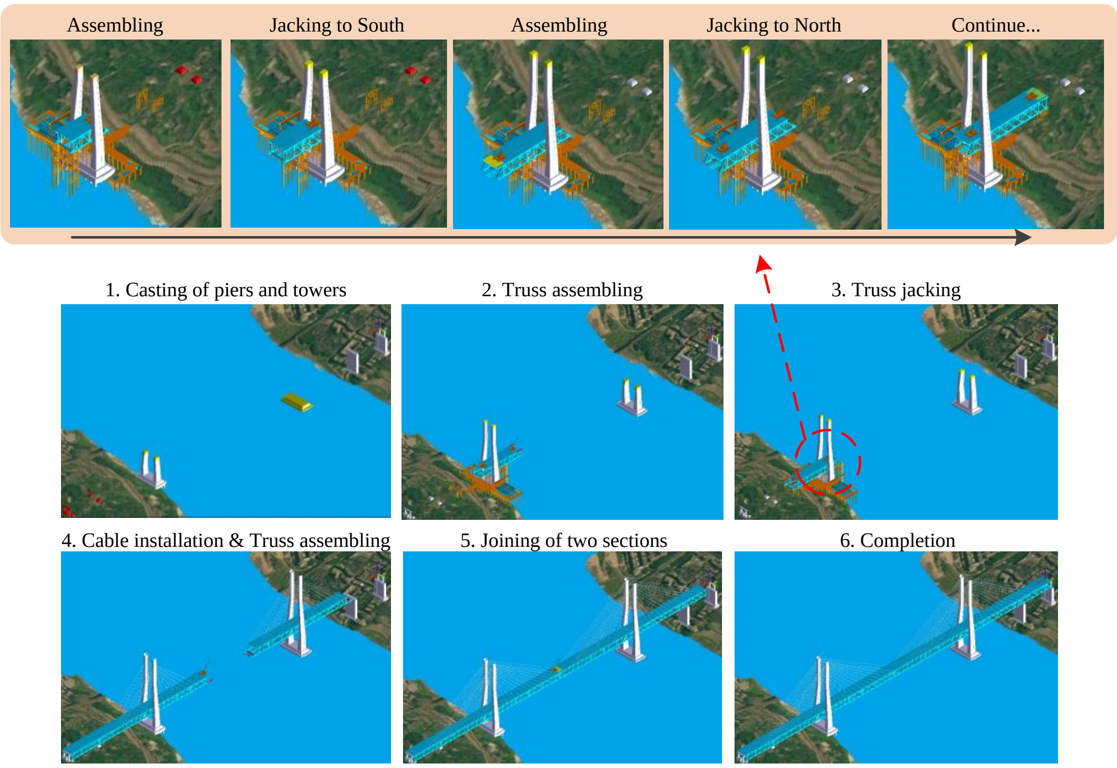

Fig. 5: 4D visualization of the construction process of NBYRB

6. CONCLUSION AND DISCUSSION

Review of related researches and comparison of 4D visualization tools showed that a new 4D model which facilitates schedule-animation synchronization and model verification is needed. Therefore, a schedule-driven 4D model is proposed, to address these problems. Based on this model, mistakes made in linking 3D geometries to tasks of a schedule can be detected, thus helping to reduce rework in 4D modeling. Meanwhile, through a strong relationship between visual states (including transformation, and shading styles) and schedule/time, changes made to a schedule can be easily reflected in the animation. Evaluation of the model is made in the construction process visualization of the new Baishatuo Yangtze River Bridge. Results show that the model can reduce rework when linking 3D objects and the schedule, while keep a better synchronization between animation and the schedule, thus eliminating work for the adjustment of animations. In addition, verification of the model can also be used to detect mistakes made when collecting actual schedule of a project. However, improvements of the proposed model are still needed: 1) rendering and animation of large model is slow, that’s the common problem for all kinds of 4D tools; 2) model verification can be improved by providing more rules to avoid more mistakes or errors made in 4D modeling.

7. ACKNOWLEDGEMENT

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