Simulating construction planning in a bridge project by using virtual prototyping, integrated design and resource allocation

Heng Li and Neo Chan
Department of Building and Real Estate
The Hong Kong Polytechnic University

November 2009
Hong Kong

Please do not quote or circulate this paper without prior consent from the authors
Simulating construction planning in a bridge project by using virtual prototyping, integrated design and resource allocation

Abstract

4D simulation, building information modeling, virtual construction and virtual prototyping are emerging topics within building construction. These techniques relate not only to buildings themselves, but also apply to other forms of construction, including bridges. Since bridge construction is a complex process involving multiple types of machinery, applying such virtual methods benefits understanding of all parties in construction practice. This paper describes the use of virtual prototyping integrated parametric 3D modeling and construction machinery with embedded mechanisms to simulate different construction planning processes. A case study is presented to demonstrate the use of virtual prototyping integrated with 3D model design and resource allocation to find optimal construction planning processes.

Keywords: virtual prototyping, parametric 3D model, construction machinery

1. Introduction

A review of literature from the building construction industry indicates that many researchers are already applying emerging technologies such as 4D simulation [1-5], building information modeling [6-10], virtual construction [11] and virtual prototyping
[12-16] to optimize the construction planning of building construction projects. However, there is limited knowledge on how these techniques are used in bridge or highway projects. Liapi [17] applied 4D CAD to an actual project to provide a better understanding of the aspects and spatial constraints of the project compared with the traditional 2D format. Zhou and Wang [18] applied 4D simulation to bridge construction to provide the user with a forecast of construction schedule and resource consumption over time.

Compared with building construction projects, bridge and highway construction involves fewer activities and crew. However, the degree of complexity in constructing a bridge or highway is similar to that of building construction projects. Also, the construction of bridge and highway projects of any magnitude has become increasingly difficult due to the highly competitive environment and complexity of the management process [19]. Bridge construction involves complex geometric configurations that render communication of project information among interested parties very difficult and prone to errors [17]. Applying these innovative techniques to bridge construction projects for construction planning and scheduling would assist project planners in making more appropriate planning decisions.

In bridge and highway construction, there already exist approaches that attempt to optimize construction planning. For example, Askew et al [20] have developed a computer-based system to generate earthwork activity through a knowledge-base and by simulating the earthwork processes; El-Rayes [21] and Hassanein and Moselhi [22] have
developed an object-oriented model for planning and scheduling highway construction; El-Rayes and Kandil [23] created a multi-objective genetic algorithm using a three-dimensional time-cost-quality trade-off analysis to identify optimal resource utilization plans and Said et al. [24] have applied computer simulation to optimize the planning of bridge construction and associated resources involved.

However, even when 4D CAD is applied [17, no existing model can optimize construction planning by allowing for potential collisions between construction machinery and space conflict among activities. Virtual construction [11] and virtual prototyping (VP) [15], on the other hand, are effective tools to avoid such collisions while the value of virtual simulation [11, 25] and VP [15] is in helping to simulate various construction methodologies. Furthermore, VP technology can assist project planners in optimal construction planning through parametric 3D models and construction machinery in addition to appropriately allocating resources.

The aim of the research described in this paper was to apply VP technology integrated parametric 3D modeling and resource allocation to bridge projects to enable optimal construction planning. The paper first describes the theory of parametric 3D modeling and modeling construction machinery and resource allocation in bridge construction. Next, a case study is presented to demonstrate how optimal construction planning is possible. Future improvements to VP technology are discussed and concluded in the final section.
2. The characteristics of bridge projects

Bridge construction involves multiple recurring activities, such as building foundations, piers and decks [21], processes which are comparatively straightforward in comparison with building projects. While constructing bridges involves less working activities than building construction, it does not necessarily follow that bridge construction is an easy task. Problems and uncertainties are always likely to occur during the working process. Some factors are especially critical, including the relationship between the terrain and proposed bridge and the various designs of working platforms, determining the number of resources and duration of the project.

A bridge project is a continuous linear project [22, 27], characterized by a geometrically linear layout and no clearly identifiable units. Highway and bridge projects involve an intensive period of earthwork and the topography often changes with the filling and cutting work involved. While building construction projects contain discrete time-linked objects such as columns and slabs [27], bridge project activities cannot be clearly identified and linked with discrete schedule activities.

3. Applying the concept of virtual prototyping to bridge projects

Virtual prototyping, which originated in the manufacturing industry, has considerable potential for the design of 3D models [30], helping to build a parametric 3D model and construction machinery. Also, virtual prototyping can help assign the construction equipment in planning for resource analysis [15].
3.1. Parametric 3D modeling

Parametric 3D modeling is applied to building construction projects worldwide [12, 28-29]. Huang, for instance, has applied this form of modeling to temporary work elements [17] and Sacks et al. have used a parametric 3D model to design precast concrete [28]. The model is based on operations and constraints, with constraints maintained as an integral part of the model geometry during editing. The design of our parametric 3D model is based on fundamental constraints, user requirements and safety issues. This model provides a user-friendly platform for sketching and modifying the basic 2D design. The parametric 3D model will automatically generate various levels of detail. Fig. 1 shows the model of a steel platform created through the application of this technology, with the user designing the shape and inputting external dimensions. Such application assists users in realistically illustrating their ideas.

![Generated parametric 3D model from horizontal design](image)

Fig. 1. Generated parametric 3D model from horizontal design

3.2. The model of construction machinery

The model of construction machinery is an enhanced equipment-based model [15] which is applied to construction planning. The specifications of the construction machinery are
embedded in the model. This includes the turning and working radius, lifting capacity, etc. The construction machinery model simulates real-life working processes. If the plan is not constructible in reality (e.g., there is not enough space for driving or not enough distance from the target), these problems will be highlighted by the VP technology based on the specification data. Furthermore, the VP technology can detect a potential collision course between the machinery involved.

3.3. Resource allocation

In VP technology, the resource amount can be adjusted by the user. The user can apply different working platform designs to allocate different machinery when simulating the construction process. Such variables, including different machinery types and resource amounts generate varying results and durations relating to the construction planning process.

4. Case Study

4.1. Introduction

The case study involves the widening of a section of Ting Kau Viaduct, which is a part of the Tuen Mun Road, a road link between Tuen Mun and Kowloon, Hong Kong. The total length of the road is 15 km and it has been in service for more than 30 years, having a long history of traffic congestion and accidents. The road was designed and constructed in the mid-1970s and there was a need to raise the road to current standards as far as
practicable. In addition, reconstructing the road was planned to minimize repair works, traffic congestion and accidents, and therefore create less disturbance for road users.

The main contract scope of work included widening sections of the existing carriageways and vehicular bridges and highway structures, including Tsing Lung Tau Bridge, Telford Bridge, Ting Kau Viaduct and Yau Kom Tau Bridge. The work also included widening the eastern end of Sham Tseng Viaduct eastbound carriageway to meet current expressway standards, with the associated provision of hard-shoulders and verges.

The work of widening the section of Ting Kau Viaduct included the construction of viaduct foundations, piers, deck and finishes. Ting Kau Viaduct is supported by numerous piers that are placed on a hillside, and twenty-eight new piers required for the widening of the Tuen Mun road. The work concerned involved a complex site topography, localized site formation work, foundation, superstructure and stitching work to existing road works.

The project planners encountered several types of problems relating to construction planning and constructability, including potential risks to road users in the construction area, and a number of key concerns were incorporated at this stage, including site safety, site access, temporary work design, cranes and machinery deployment. A central issue for the project planners concerned the working platform to be used in the construction process. This involved choosing one of three different platform designs. However, the choice is not easy, due to:
1. Difficulties in imagining the site environment.

2. Difficulties in determining the best platform for foundation and pier construction.

3. Difficulties in estimating the maximum resources involved in different platform designs.

4.2. Building the virtual terrain contours, existing viaduct and proposed widening of viaduct structures

To increase the precision of results, the research team obtained topographical survey data of the project site from the land surveyors involved. This included terrain contours and details of the existing Tin Kau Viaduct and was built into 3D model. The 3D virtual terrain contours provided a clear and detailed view for the project planners, allowing them to imagine the relationship between the terrain contours and existing viaduct and to predict safety issues and potential accidents during construction. The proposed widening of the viaduct structure was modeled to include geometric configurations after construction, based on the 2D drawings (Fig. 2).
4.3. Parametric 3D modeling for temporary work

The choice of platform design was influenced by two main considerations:

1. The haul road - an access road from Castle Peak Road to the construction site for construction machinery to be transported.

2. The platform itself.

The haul road

Most of the critical construction work was situated under the existing viaduct and on the hillside. However, the hillside was not a suitable situation for workers and construction machinery and the construction machinery had to be driven from Castle Peak Road to the
proposed construction site through a haul road (Fig. 3). The essential requirements of the haul road was that the slope was not larger than 1/10 and had a minimum width of 5m and these two requirements were built into the haul road model.

![Image of haul road](image)

**Fig. 3. The haul road from castle peak road to construction site**

**The platform**

The function of the steel platform was to provide a working space from which the construction machinery could drive pilings. This would have proved difficult for the project planner to confirm a platform design because of its importance to the success of the project. Using the parametric 3D model however, the design of steel platform could be drawn or modified easily and quickly. The platform safety designs remained fixed
throughout the modeling process, and the railings of the platform were generated automatically in each of the three model designs produced by the research team.

4.4. *Construction machinery models*

All the construction machinery (Fig. 4) were modeled in detail, including the external dimensions, working radii, moving and working space requirements and lifting capacity. For example, a 3D model of crawler crane CCH50T was built which included its external dimensions based on the specifications, degrees of low and high limit of turning radius, rear-end swing and working radius (Fig. 5). The various lifting capacities were based on the length of working radius.
4.5. Construction planning

The construction planning involved temporary work design and resource allocation. Through the parametric 3D modeling, the precision and reliability of the temporary work design can be increased. The project planner allocated varying amounts of construction machinery into the three different working platform designs. Using the model of construction machinery, any potential collision between construction machinery can be
detected in the simulation. The different feasible construction planning processes can be simulated according to the fundamental construction sequence, as shown in Table 1.

<table>
<thead>
<tr>
<th>Order*</th>
<th>Activity</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Haul Road Construction</td>
<td>13 days</td>
</tr>
<tr>
<td>2</td>
<td>Timber Platform Erection</td>
<td>14 days</td>
</tr>
<tr>
<td>3</td>
<td>Minipile for Steel Platform Driving</td>
<td>27 days</td>
</tr>
<tr>
<td>4</td>
<td>Footing for Steel Platform Construction</td>
<td>10 days</td>
</tr>
<tr>
<td>5</td>
<td>Timber Platform Removal</td>
<td>7 days</td>
</tr>
<tr>
<td>6</td>
<td>Steel Platform Removal</td>
<td>21 days</td>
</tr>
<tr>
<td>7</td>
<td>Pre-bored H-Pile Works</td>
<td>12 days</td>
</tr>
<tr>
<td>8</td>
<td>Pipepile Wall Driving</td>
<td>20 days</td>
</tr>
<tr>
<td>9</td>
<td>Pile Cap Excavation</td>
<td>7 days</td>
</tr>
<tr>
<td>10</td>
<td>Pile Cap Concreting</td>
<td>7 days</td>
</tr>
<tr>
<td>11</td>
<td>Pier Construction</td>
<td>24 days</td>
</tr>
<tr>
<td>12</td>
<td>Pier Head Construction</td>
<td>12 days</td>
</tr>
<tr>
<td>13</td>
<td>Launching of Precast Beam**</td>
<td>2 days</td>
</tr>
<tr>
<td>14</td>
<td>Deck Construction</td>
<td>7 days</td>
</tr>
</tbody>
</table>

* Fundamental construction sequence is set in an order from 1 to 14.

**Precast beam should be launched after two piles of head construction.

Table 1. The duration of each activity for one pair of piers

The three different designs of steel platform as shown in Fig. 6. These comprised:
**Design A** - Each platform overlapped two piers, with the entrance was connected to the haul road.

**Design B** - Each platform fully overlapped all piers but with only one entrance connected to the haul road.

**Design C** - Each platform is similar to that of design B but each pair of piers provided one entrance connected to the haul road.

Fig 6. Three different designs of steel platform

Construction machinery was assigned to different activities in the construction sequence (Table 2). Eight types of construction machinery and two types of platforms were
involved. The user can assign varying amounts of construction machinery to the three platform designs. Based on different designs and different resource allocations, the VP technology was used to simulate the construction planning.

<table>
<thead>
<tr>
<th>Order</th>
<th>Activity</th>
<th>Construction Machinery</th>
<th>Other Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Haul Road Construction</td>
<td>Lorry</td>
<td>a large number of crew</td>
</tr>
<tr>
<td>2</td>
<td>Timber Platform Erection</td>
<td>Lorry</td>
<td>a large number of crew</td>
</tr>
<tr>
<td>3</td>
<td>Minipile for Steel Platform Driving</td>
<td>Crawler Crane CCH50T</td>
<td>Hydraulic Crawler Drill HD90</td>
</tr>
<tr>
<td>4</td>
<td>Footing for Steel Platform</td>
<td>Crawler Crane CCH50T</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Timber Platform Removal</td>
<td>Lorry</td>
<td>a large number of crew</td>
</tr>
<tr>
<td>6</td>
<td>Steel Platform Erection</td>
<td>Crawler Crane CCH50T</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Pre-bored H-Pile Works</td>
<td>Pile driving machine 325L</td>
<td>Crawler Crane HS873HD</td>
</tr>
<tr>
<td>8</td>
<td>Pipepile Wall Driving</td>
<td>Crawler Crane HS873HD</td>
<td>Crawler Crane CCH50T</td>
</tr>
<tr>
<td>9</td>
<td>Pile Cap Excavation</td>
<td>Excavator</td>
<td>Lorry</td>
</tr>
<tr>
<td>10</td>
<td>Pile Cap Concreting</td>
<td>Crawler Crane CCH50T</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Pier Construction</td>
<td>Crawler Crane HS873HD</td>
<td>Steel formwork</td>
</tr>
<tr>
<td>12</td>
<td>Pier Head Construction</td>
<td>Crawler Crane HS873HD</td>
<td>Steel formwork</td>
</tr>
</tbody>
</table>
In design A, based on the existing viaduct and platform design, it was found that the crawler crane HS873HD could not be driven from one platform to the next due to the limited height available. Some parts of the crawler crane had to be dismantled and reassembled after the crawler crane was driven to the next platform, a process which would take 30 days. Other construction machinery did not have such problems.

In design B, there is one access road for transportation. Pier construction therefore would be undertaken one by one. One construction machine was the maximum allocation. The reassembly time of the crawler crane HS873HD from design A could be eliminated as the crawler crane did not need to pass the haul road from the one platform to another.

In design C, each platform is connected to the haul road and the next steel platform. The crawler crane can move across the connection between two steel platforms. Once again, dismantling and reassembly of the crawler crane HS873HD can be eliminated. Design 3 provides the best transportation model for the construction machinery.

Through the VP system, therefore, the project planners were able to investigate several practical and precise construction plans involving different resource allocations. This allowed the optimal construction plan to be selected based on project duration, cost of resources and cost of temporary work.
5. Future improvements to construction virtual prototyping

The critical issue of construction planning in bridge or highway construction is the nature of the working platform design. As the case study shows, the VP system can be useful in testing the feasibility of the platform in conjunction with the practical experience of project planners. Feedback from project planners indicated that it might be better to have a fully automated VP platform design process in future, which opens the way for further research in this application.

6. Conclusion

One use of VP technology in the construction process is to assist project planners to better understand the relation between designing working platforms and allocating resources. This paper describes how a parametric 3D model and a model of construction machinery can be utilized by VP in support of the construction planning process. The case study demonstrates an application in which the VP system enabled the user to validate the design of working platform by allocating different resources. This shows that the VP system can be used for such a purpose and can simulate construction planning to avoid any collisions between construction machinery and construction elements. It can help the project planner imagine construction planning in relation to varying working platform designs. According to the feedback received, the VP system is a useful tool to test the feasibility of working platform designs in the construction process. However, there is still room for improvements to the VP system, including the opportunity for
automatic working platform designs. The authors are currently investigating the application of other emerging technologies to bridge and highway projects in order to optimize construction planning and prevent planning mistakes during construction.
References


[7] A. Khanzode, M. Fischer and D. Reed, Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project, Special Issue Case studies of BIM use vol. 13, ITcon (2008), 324–34.


