Optimizing construction planning schedules by virtual prototyping enabled resource analysis

Li, Heng; Chan, Neo; Huang, Ting; Guo, H. L.; Lu, Weisheng; Skitmore, Martin

Published in:
Automation in Construction

DOI:
10.1016/j.autcon.2009.04.002

Optimizing construction planning schedules by virtual prototyping enabled resource analysis

Abstract

The inherent uncertainty and complexity of construction work makes construction planning a particularly difficult task for project managers due to the need to anticipate and visualize likely future events. Conventional computer-assisted technology can help but is often limited to the constructability issues involved. Virtual prototyping, however, offers an improved method through the visualisation of construction activities by computer simulation – enabling a range of 'what-if' questions to be asked and their implications on the total project to be investigated.

This paper describes the use of virtual prototyping to optimize construction planning schedules by analyzing resource allocation and planning with integrated construction models, resource models, construction planning schedules and site-layout plans. A real-life case study is presented that demonstrates the use of a virtual prototyping enabled resource analysis to reallocate space, logistic on access road and arrange tower cranes to achieve a 6-day floor construction cycle.

Keywords: Construction Planning Schedule; Virtual Prototyping, Space, Resource Analysis.

1. Introduction

It is well known that successfully completed construction projects are a result of careful planning and execution and established techniques, such as the critical path method (CPM) and bar charts, are commonly used to enable this to be done in a systematic way. This involves the project team allocating the different resources needed associated with the major method selected and decides on the appropriate sequence of assemblies. However, contractors' project planners face many uncertain and complex tasks during construction period due to e.g., design errors and mismatch of what is planned and actually needed [1]. In addition, errors and mistakes in the construction planning schedule occur frequently as its compilation depends to a large extent on the project team's limited knowledge and experience [2]. As a result, a successfully tendered building project can be very much a gamble due to the main contractor inability to predict whether the project will result in a profit or a loss in advance of construction.

For many projects, a major limitation is the lack of an effective computer-assisted technology for resource allocation and planning. Due to the complexity and the large number of factors involved, computers can be an efficient tool to help project planners. Such basic computer aids as bar charts and the critical path method are quite limited as they are unable to provide spatial construction features or resource and working space requirements [3,4]. More sophisticated methods combine the three traditional techniques of resource allocation, resource levelling and Time-cost trade-off analysis. For example, Chan et al. [5], Hegazy [6], Leu and Yang [7] combine resource allocation and levelling using genetic algorithms (GAs); Li and Love [8] propose GAs for time-cost optimization problems; Hegazy and Kassab [9] combine a flowchart based simulation tool with the GA technique; and Wang et. al. [10] have developed a 4D Management for Construction Planning and Resource Utilization (4D-MCPRU) system which links a 3D geometrical model with resources to compute the resource requirement.

None of these previous resource planning and allocation methods take the real productivity rate into account in analyzing the resources. The application of virtual prototyping (VP) technology helps solve this problem by allowing planners to consider objective productivity data to predict potential constructability problems and analyze resource allocation including equipment, space and labour to modify construction sequences to provide a comprehensive construction planning schedule [11].

The paper first describes the framework of integrated planning using the VP technology. Next, a case study is presented to demonstrate how the construction planning schedule is optimized. Future improvements to the VP technology are discussed and concluded in the final section.

2. The framework for integrated planning on VP technology

2.1. Definition of the Construction Model

The Construction Model consists of two types of digital model. The first type is similar to the Building Information Management (BIM) model, which is a 3D model with information for the performance evaluation of the model. The key function of the BIM in the construction field is to allow planners to view their static realistic images and check for design errors and collisions. Temporary works are a critical element in construction planning [3] and this type of model is used to develop temporary work models generated by the parametric models. Details of the temporary work model are available in Huang et al. [12].

The second type of model is a detailed building component model, which is related directly to construction activities. The purpose of this model is as a design check and is also closely associated with the construction planning schedule. This type of model decomposes serial assembly models to develop a detailed construction activity. The decomposition of a product is a precondition of simulation and the assembly of parts is closely related to the simulation process. For example, assume the purpose of the simulation is to display the sequence of pouring concrete. One floor of the 3D concrete model will be decomposed into different assembly models (i.e. inner slab, half of outer slabs, outer wall, inner wall, each column) which are related to the sequence of the simulation (Fig. 1).

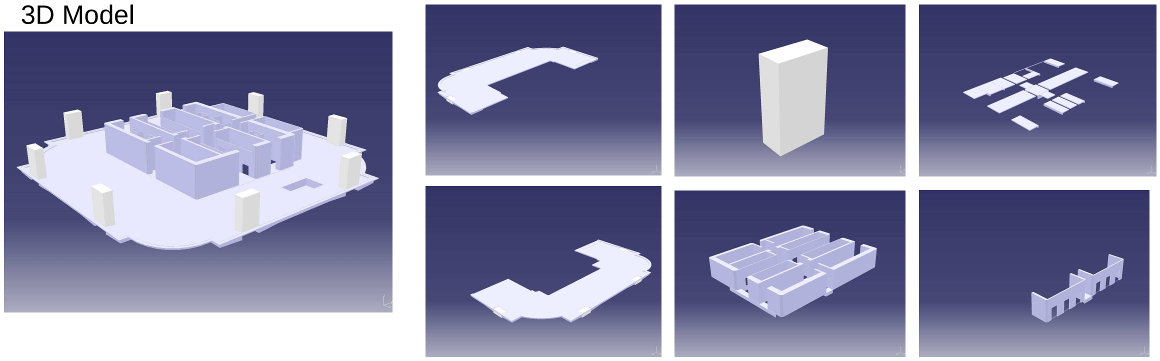


Fig. 1. Decomposition of 3D building model

2.2. Definition of the Resources Model

Two resources models can be identified: an equipment-based model and an activity-based model.

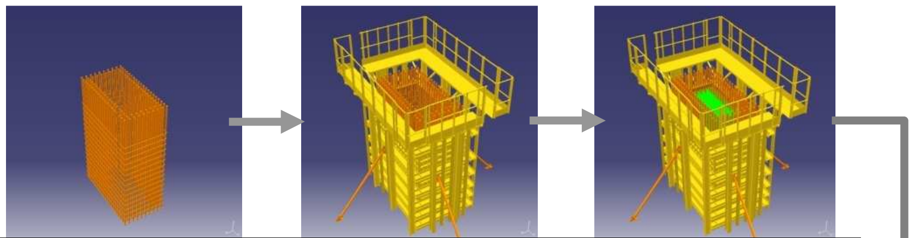
Equipment-based Model - The equipment-based Model is a 3D-geometry model linked with the productivity rate of equipment in an Excel library database and physical capacity data. For example, the tower crane model contains graphical information that is the exact geometry, shape and dimension for space analysis and capacity (i.e. maximum capacity, maximum lifting height and maximum radius) for testing the operating capacity.

Activity-based Model - The activity-based Model is a non-physical model linked with the productivity rate in an Excel library database. The fixing reinforcement activity is an example. The activity-base model is linked with the construction model by users when generating the VP simulation to develop one process activity in the system.

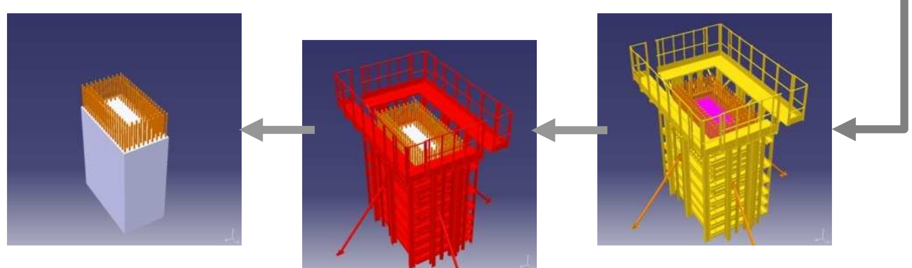
2.3 The importance of detailed simulation

It is important for the construction planning schedule to have detailed activities. A master program does not show all the detailed activities that occur in a project. The planning activities should be elaborated as more details are required. In the construction planning schedule, it is very difficult for the project planners to consider the detailed activities, resource allocation and space requirement. Project planners pay a lot attention to the master program but tend to neglect detailed activities. They understand that resource allocation is a key factor in the construction planning schedule but they lack mathematical method to analyze resource allocation. The space required by construction activities is the most difficult element for them to analyze as space is static stage *and* dynamic. Since spaces required by activities change in all three dimensions through time [13-16], the time-space may conflict between activities.

A detailed 4D planning schedule is required to compute the duration of each activity and associated space required. The activity "concreting wall" provides a good example (Fig. 2). It includes many types of activity related to time-space. Fixing reinforcement, erecting formwork and falsework, pouring, casting and dismantling formwork and falsework also require process time, space for crews to work and to temporarily store and manage the materials and equipment items needed. There are many factors to be considered in this simple activity. All of them are directly related to the construction planning schedule.



Activity	Fixing rebar	Erecting formwork and falsework	Pouring concrete
Productivity Rate Need	Workers’ productivity rate	Workers’ productivity rate	Pouring speed and volume



Completed	Dismantling formwork and falsework	Casting concrete
	Workers’ productivity rate	Casting time

Fig. 2. The detailed sequence for concreting wall

2.4. Implementation

The database of the productivity rate and the construction planning schedule is stored in Microsoft Excel format. The virtual prototyping system is implemented using Visual Basic for Applications (VBA) in the DELMIA V5 environment, and Microsoft Excel to develop the productivity database and planning schedule linking with the 3D Model. VBA is an object-oriented programming language to develop specific functions. VBA provides a seamless link between the components of the model, supported by a powerful graphical user interface (GUI). The equipment-based model and the activity-based model link with the productivity rate of equipment and the activity’s productivity rate respectively.

2.5. Integrated Construction Planning Schedule, Site Layout Planning and all construction process activities

The 3D site layout model is developed based on the 2D site layout planning on the VP system. Through the VP technology, a process activity is generated by linking a construction model and an activity-based model or by putting a construction model and an equipment-base model together. Combining each process activity with the construction planning schedule, along with the 3D site layout planning, a process simulation is developed (Fig. 3).

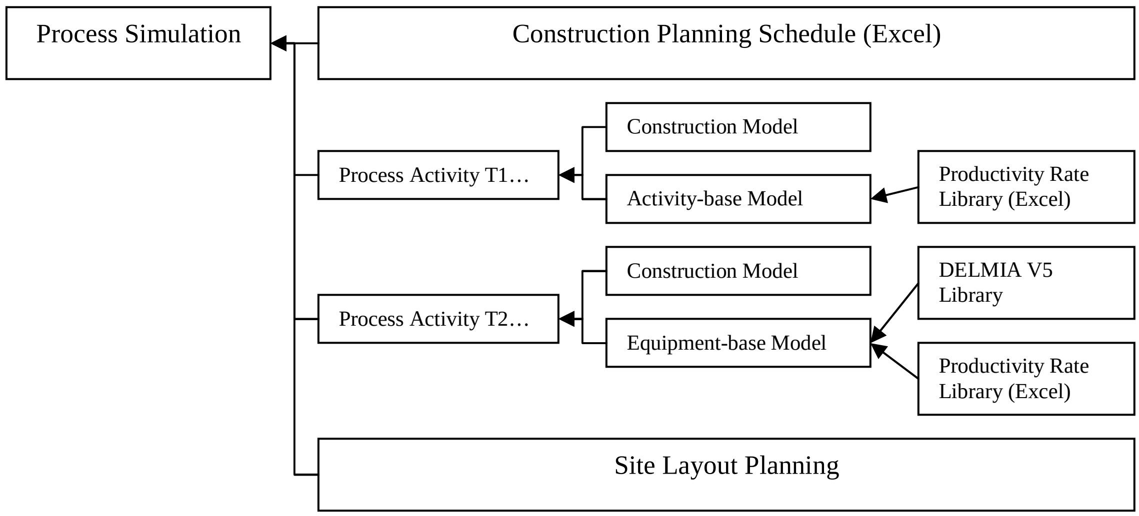


Fig. 3. VP Structure

2.6. Resource Analysis

In the construction field, all activity duration estimates are based on the experience of the project managers. The duration of activities is therefore often uncertain. One major function of the VP system utilizes real productivity data from the system database to verify and then adjust the resource allocation. Through the process simulation, resources, such as space, equipment and crew, can be analyzed. Most building construction projects rely on tower cranes to perform lifting and hoisting activities [17]. The tower crane is the most critical component of the construction planning schedule. Through 3D visualization and simulation of the tower cranes, the planner understands the planning in detail and is able to predict planning mistakes [18]. The following sections provides a case study to demonstrate how resource allocation is analyzed.

3. Case Study

3.1. Introduction

The case study involves two residential building projects in Hong Kong. At the time of the research, the foundations of the two buildings were already completed. The site layout planning had also taken place. During construction, the project managers encountered different types of critical problems while planning the typical construction cycle. They would like to have visualization, digital and mathematical method to measure the constructability of the construction planning schedule. They provided the researchers with a preliminary construction planning schedule of a typical floor construction, comprising a 6-day cycle time slot - planning schedule (Fig. 4).

SHATIN PASS ESTATE 6 Day Cyle Date : 28-11-2007

	1	2	3	4	5	6
B1 (A)	7:00 - 8:00 上間牆鐵 7:00 - 14:00 扎間牆鐵完成 8:00 - 10:30 上佛沙 10:30 - 18:00 裝嵌間牆鐵模	7:00 - 15:00 裝嵌及驗收鐵模	80:00 - 14:00 落間牆石矢	7:00 - 18:00 擰螺絲拆鐵模板 13:00 - 18:00 釘樓面板 15:00 - 18:00 升工作台 / 拆模落地	7:00 - 12:00 拆模落地 / 升工作台 8:00 - 14:00 釘樓面板 14:00 - 18:00 上樓面鐵扎樓面	8:00 - 15:00 扎樓面鐵 15:00 - 18:00 落樓面石矢
B1 (B)	7:00 - 12:00 裝嵌及驗收鐵模	10:30 - 14:00 落間牆石矢 (泵)	7:00 - 18:00 擰螺絲拆鐵模板 13:00 - 18:00 釘樓面板 15:00 - 18:00 升工作台 / 拆模落地	7:00 - 12:00 拆模落地 / 升工作台 8:00 - 12:00 釘樓面板 14:00 - 18:00 上樓面鐵扎樓面	8:00 - 15:00 扎樓面鐵 16:00 - 18:00 落樓面石矢 (泵)	7:00 - 8:00 上間牆鐵 7:00 - 14:00 扎間牆鐵完成 8:00 - 10:30 上佛沙 10:30 - 18:00 裝嵌間牆鐵模
B2 (A)	7:00 - 18:00 擰螺絲拆鐵模板 13:00 - 18:00 釘樓面板 15:00 - 18:00 升工作台 / 拆模落地	7:00 - 12:00 拆模落地 / 升工作台 8:00 - 14:00 釘樓面板 14:00 - 18:00 上樓面鐵扎樓面	8:00 - 15:00 扎樓面鐵 15:00 - 18:00 落樓面石矢	7:00 - 8:00 上間牆鐵 7:00 - 14:00 扎間牆鐵完成 8:00 - 10:30 上佛沙 10:30 - 18:00 裝嵌間牆鐵模	7:00 - 15:00 裝嵌及驗收鐵模	80:00 - 14:00 落間牆石矢
B2 (B)	7:00 - 12:00 拆模落地 / 升工作台 8:00 - 14:00 釘樓面板 14:00 - 18:00 上樓面鐵扎樓面	8:00 - 15:00 扎樓面鐵 15:00 - 18:00 落樓面石矢	7:00 - 8:00 上間牆鐵 7:00 - 14:00 扎間牆鐵完成 8:00 - 10:30 上佛沙 10:30 - 18:00 裝嵌間牆鐵模	7:00 - 15:00 裝嵌及驗收鐵模	11:00 - 15:00 落間牆石矢	7:00 - 18:00 擰螺絲拆鐵模板 13:00 - 18:00 釘樓面板 15:00 - 18:00 升工作台 / 拆模落地

Fig. 4. Time slot- construction planning schedule

The building had prefabricated concrete facades supported by in-situ concrete walls, a lift core and half an in-situ slab. The two buildings were named No.1 and No.2 respectively. The project managers divided the buildings into two working bays in the middle. The bays of building No.1 were named 1A and 1B. The bays of building No.2 were named 2A and 2B. The construction cycles of each bay were contiguous to fully utilize the tower crane.

A set of steel formwork panels was applied for all the concrete walls and concrete slab. The project managers planned to construct the two buildings at the same time but only one set of steel formwork was used. Two tower cranes were installed on the construction site for lifting the formwork panels, prefabricated concrete façade, reinforcement bars and concrete buckets. One tower crane (T1) was installed between Bay 1A and Bay 1B while the other (T2) was installed in the middle of Bay 2A and Bay 2B (Fig. 5). The two tower cranes were of different capacities. The maximum radius of T1 was long enough to reach Bay 2B whereas the maximum radius of T2 could only reach the temporary storage space. There were two ways of lifting the steel formwork. One was directly lifting the formwork from bay 1A to bay 2A by using T1. The second was lifting the formwork from Bay 1A to the temporary storage space between the two buildings by T1 and then the formwork was lifted by T2 to Bay 2B. For pouring concrete, both Bay 1A and Bay 1B used the tower crane while a placing boom was used in Bay 2A and Bay 2B.

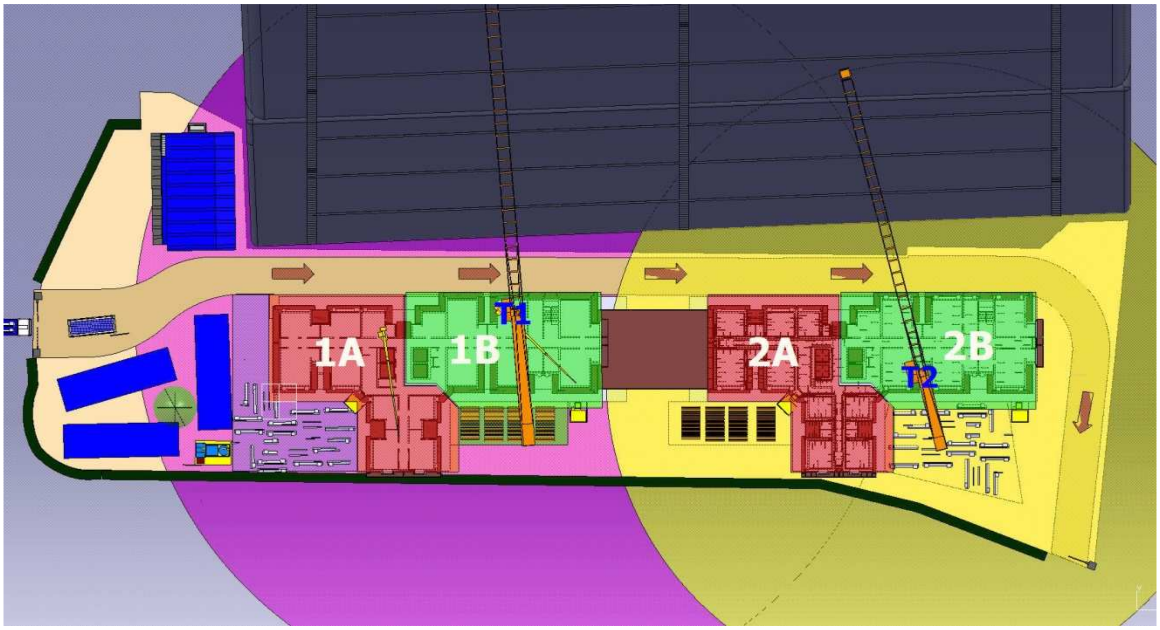


Fig. 5. The location of the two tower crane and the four bays

The project planners encountered the following critical problems in the planning schedule

1. There was a limited storage area for storing facade elements, steel formworks, reinforcements and temporary supports as they needed to plan what materials would arrive, and when and where they would be stored.
2. There was a limited working area for workers and access road for material transportation such as transit mixers, transportation material truck for reinforcement and façade elements.
3. The preliminary planning durations of the activities were not computed mathematically. The project planners wanted to use the real productivity rate data to verify the construction planning schedule especially for the cranes as they were the critical elements of the whole construction planning schedule.

3.2. Preparation of the Construction Model and Resource Model

A construction model for temporary work was developed based on the design drawings prepared by nominated subcontractor and the building component was built based on the process activities to decompose the suitable assembly models. The two tower cranes and the placing boom were built into the equipment-based Model. Their capacities were based on their capacity catalogues. The activity-based Model was prepared from previous projects.

3.3. Start from Preliminary Construction Planning Schedule

The main construction method was to use one set of steel formwork for two buildings to reduce the cost of steel formwork However, there was not enough space for storing the steel formwork. The schedule of the project was represented by a simple time slot document. The researchers generated a template of a construction planning schedule in VP-Excel format for inputting the time slot planning data (Fig. 6). The planning schedule was imported into the VP system. This allowed the users to link the process activities with their related Construction Models and Resource Models (Fig. 7).

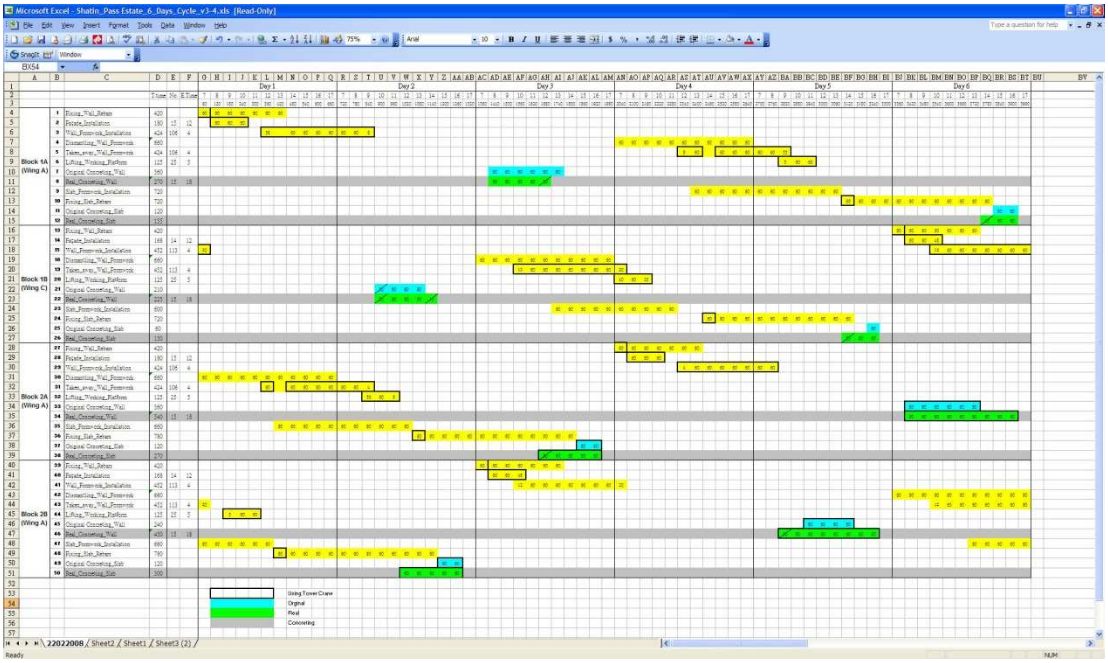


Fig. 6. Construction planning schedule in VP-Excel Format

Fig. 7. Assignment of the tower crane to lift the façade in one process activity

3.4. Build site layout environment

The project planners had finished the site layout planning before the researchers joined. The 2D site layout planning was used to build the 3D site layout environment, including the location of the two different types of tower crane, site office, storage area, passenger and material hoists and access road. The 3D site layout could provide a virtual construction site for the VP system to analyze the access road, space requirement and the assignment of tower cranes.

3.5. Analysis the resource allocation

By integrating the preliminary construction planning schedule, site layout planning, construction models and resource models, the simulation of the construction process was developed to analyze resource allocation. All productivity data of the activities were obtained from numerous previous projects. The data was thus objective. Most major activities were related to the tower cranes, access road and space. These three factors were applied to these activities. The data included the duration of delivery material, as the material must be delivered to the site before the installation to prevent delays to other work. There were different types of productivity rate related to these three factors (Table 1). The users then defined activities linked with tower cranes, access road and space in order to analyze the accuracy of the construction planning schedule.

	Tower Crane	Access Road	Space
The capacity of transit mixers	Yes	Yes	Yes
The speed of pouring by using tower crane	Yes	Yes	Yes
The speed of pouring by using placing boom		Yes	Yes
The time of fixing rebar per area			Yes
The lifting time of rebar	Yes		
The lifting time of steel formwork from the building to temporary storage platform	Yes		Yes
The lifting time of steel formwork from 1B to 2B	Yes		
The rising time of the working platform	Yes		
The lifting time of rising and installation of facades	Yes		
Size of steel formwork			Yes
Size of facade			Yes
Area of temporary storage			Yes
Area of storing reinforcement			Yes
Area of storing façade			Yes
Required quantity of reinforcement for 6 day cycle			Yes
Required quantity of facade for 6 day cycle			Yes

Table 1. Different types of productivity rates related to three factors

Allocation on Access Road

It was important that there was no overlapping of transportation routes in the planning of the access road logistic as there was only one access road for transportation on the site. The trucks carrying reinforcement / facade and transit mixer would stay on the access road. In particular, the transit mixer would stay on the access road approximately 10 hours for pouring concrete into a bay and so would obstruct the road. All types of trucks needed be arranged correctly to avoid any overlapping of transportation routes in the planning schedule. The VP system determined the number of transit mixers to be used based upon the required quantity of concrete for different working bays. Also, it computed the exact duration for pouring each bay by using the tower crane or placing boom since the speed of pouring by placing boom was double to that of pouring by tower crane. The VP system simulated the construction planning schedule and allocation of access road to find any conflicts of access road use.

Allocation on Tower Crane

Planning the usage of the tower cranes was crucial to the timely and safe achievement of the 6 day floor planning schedule as the cranes were involved in various activities across the construction site and a large number of building components were installed by the cranes. Firstly, the VP system, based on the real productivity rate, was used to check the duration of the construction planning schedule used by the tower cranes and then adjust the activity duration. Secondly, the VP system based on the preliminary construction planning schedule was used to visualize and identify clashed activities by using tower cranes in the display and Gantt Chart respectively (Fig. 8). The user adjusted the construction planning schedule to eliminate the clashed activities.

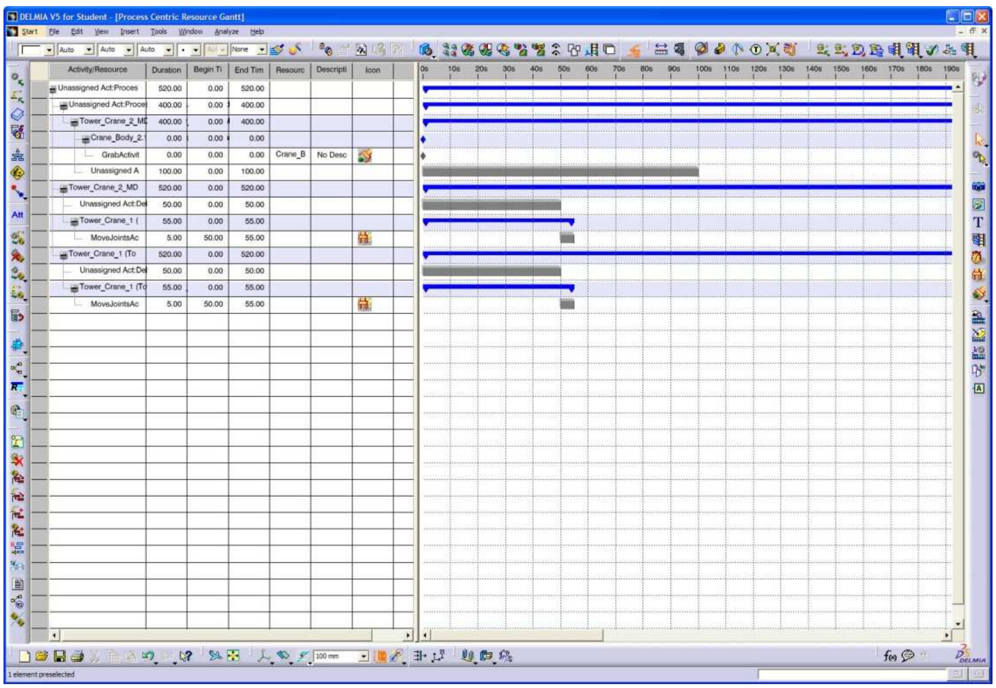


Fig. 8. Assignment of two tower cranes in Gantt Chart

Space

The space involved storage material, equipment, and working space in 3D through time. Because of the limited construction site area, the storage amount of reinforcement and façade needed to be considered. The VP system determined the number of trucks based upon the required quantity of reinforcement and facade for the 6 day cycle and then computed the capacity of storage area needed for the reinforcement and façade. Based on the availability of the access road, these data were then used to determine when the trucks come to site

The project planners had an innovative idea for solving the limited construction site area. This was to build a temporary platform for storing the steel formwork for a short period. Through VP technology, the space with time could be analyzed accurately.

4. Future improvements to construction virtual prototyping

Feedback from the project planners indicate that it would be better for the construction planning schedule to be developed together with the site layout planning in VP system. A good site layout planning can increase the productivity of construction activities, improve safety and avoid obstructing material and equipment movements on the construction site [19-21]. A comprehensive planning and efficient site layout are the main preliminary factors for successful construction management [22]. A computer-aided environment can support the site layout planning design. Ma et al.[23] developed an integrated site planning tool called the 4D Integrated Site Planning System (4D-ISPS) which integrates schedules, 3D models, resources and site spaces together with 4D CAD technology to provide 4D graphical visualization capability for construction site planning.

5. Conclusion

The purpose of using VP technology for construction simulation is to assist project planners to better understand the construction process and predict possible mistakes. This paper describes how a construction model and resource model can be prepared for VP in support of the construction planning process. A case study demonstrates an application in which the VP system enabled the user to validate a proposed construction planning schedule. This shows that the VP system can be used for this purpose and site layout planning is a key issue in preparing the construction planning schedule. We are currently looking for other real projects to integrate site layout planning in order to optimize the construction planning schedule before building.

References

[1] H. Li, H.L. Guo, M. J. Skibniewski and M. Skitmore, Using the IKEA model and virtual prototyping technology to improve construction process management, Journal of Construction Engineering and Economics 26 (2008), 991-1000

[2] A.F. Waly and W.Y. Thabet, A virtual construction environment for preconstruction planning, Automation in Construction 12 (2002) 139–154

[3] B. Koo and M. Fischer, Feasibility study of 4D CAD in commercial construction, Journal of Construction Engineering and Management 126 (4) (2000) 251–260

[4] K.W. Chau, M. Anson and J.P. Zhang, Implementation of visualization as planning and scheduling tool in construction, Building and Environment 38 (2003) 713–719

[5] W. Chan, D. K. H. Chua, and G. Kannan, Construction Resource Scheduling with Genetic Algorithms, Journal of Construction Engineering and Management 122 (2) (1996) 125-132

[6] T. Hegazy, Optimization of Resource Allocation and Leveling Using Genetic Algorithms, Journal of Construction Engineering and Management 125(3) (1999) 167-175.

[7] S. S. Leu and C. H. Yang, GA-Based Multicriteria Optimal Model for Construction Scheduling, Journal of Construction Engineering and Management 125 (6) (1999) 420-427
[8] H. Li, and P. Love, Using improved genetic algorithms to facilitate time-cost optimization, Journal of Construction Engineering and Management 123(3) (1997) 233–237
[9] T. Hegazy and M. Kassab, Resource Optimization Using Combined Simulation and Genetic Algorithms, Journal of Construction Engineering and Management 129(6) (2003) 698-705
[10] H. J. Wang, J.P. Zhang, K.W. Chau and M. Anson, 4D dynamic management for construction planning and resource utilization, Automation in Construction 13 (2004) 575-589
[11] H. Li, T. Huang, C.W. Kong, H.L. Guo, A. Baldwin and N. Chan, J. Wong, Integrating design and construction through virtual prototyping, Automation in Construction 17 (2008) 915–922
[12] H. Li, H.L. Guo, M. J. Skibniewski and M. Skitmore, Using the IKEA model and virtual prototyping technology to improve construction process management, Journal of Construction Engineering and Economics 26 (2008), 991-1000
[12] T. Huang, C.W. Kong, H.L. Guo, A. Baldwin and H. Li, A virtual prototyping system for simulating construction processes, Automation in Construction 16 (2007) 576–585
[13] B. Akinci, M. Fischer, R. Levitt and R. Carlson, Formalization and automation of time-space conflict analysis, Journal of Computing in Civil Engineering 16(2) (2000a) 124-134
[14] B. Akinci, M. Fischer, R. Levitt and R. Carlson, Automated generation of work spaces required by construction activities, Journal of Construction Engineering and Management 128 (4) (2000b) 306-315
[15] W. Thabet and Y. Beliveau, Modeling work space to schedule repetitive floors in multistory buildings, Journal of Construction Engineering and Management 120 (1) (1994) 96-116
[16] P. Zouein and I. Tommelein, Time-space tradeoff strategies for space-schedule construction, Journal of Computing in Civil Engineering ASCE, New York, (1994) 1180–1187
[17] M. Al-Hussein, M. A. Niaz, H. Yu and H. Kim, Integrating 3D Visualization and Simulation for Tower Crane Operations on Construction Sites. Automation in Construction 15 (2006) 554-562
[18] K. Tantisevi, and B. Akinci, Simulation-Based Identification of Possible Locations for Mobile Cranes on Construction Sites. Journal of computing in civil engineering 22 (2008) 21-30
[19] F. Sadeghpour, O. Moselhi and S. Alkass, Computer-Aided Site Layout Planning, Journal of Construction Engineering and Management 132(2) (2006) 143-151
[20] T. M. Hegazy and E. Elbeltagi, EvoSite: Evolution-based model for site layout planning, Journal of Computing in Civil Engineering 13(3) (1999) 198–206
[21] I. D. Tommelein, R. E. Levitt and B. Hayes-Roth, SightPlan model for site layout, Journal of Construction Engineering and Management 118(4) (1992) 749–766

[22] K.W. Chau, M. Anson and J.P. Zhang, Four-Dimensional Visualization of Construction Scheduling and Site Utilization, Journal of Construction Engineering and Management 130 (4) (2004) 598–606

[23] Z.Y. Ma, Q.P. Shen and J.P. Zhang, Application of 4D for dynamic site layout and management of construction projects, Automation in Construction 14 (2005) 369-381