

# A VIRTUAL PROTOTYPING SYSTEM FOR SIMULATING CONSTRUCTION PROCESSES

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**Abstract:** Virtual prototyping (VP) technology has been regarded as a cost-effective way of envisaging real circumstances that enhance effective communication of designs and ideas, without manufacturing physical samples. In the construction field, although a large number of digital technologies have been developed to visualize the innovative architectural design, few VP systems have been developed to facilitate integrated planning and visualization of construction plans of the building projects. This paper describes a virtual prototyping system, called the Construction Virtual Prototyping (CVP) system, which is developed for modeling, simulation, analysis and VP of construction processes from digital design. The CVP system allows project teams to check constructability, safety and to visualize 3D models of a facility before the commencement of construction works. The real-life case study presented in the study shows that the CVP system is effective in assessing the executability of a construction planning including site layout, temporary work design, as well as resource planning.

**Keywords:** Construction process planning, 3D model, simulation, virtual prototyping.

## 1. INTRODUCTION

Construction project planning has been considered as a critical process in the early project phases that determines the successful implementation and delivery of project. During this stage, project planners need to develop main construction strategies, to establish construction path and assembly sequences, and to arrange construction methods and resources required for the execution of work packages (Waly and Thabet, 2002; Jaafari et al., 2001; Koo et al., 2000). The critical path method (CPM) and bar charts have

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still been widely employed by project teams as a main tool to express the project schedules and coordinate the activities of members of project team (Koo and Fischer, 2000). Many project planners have continually relied on these traditional ways in selecting construction equipment, reviewing constructability, and arranging construction methods and site layout. These approaches impose a heavy burden on project teams due to the large amount of information and the interdependence between different elements (Waly and Thabet, 2002).

Such shortcomings of traditional communication tools together with the advances in digital technologies have stimulated various research and development efforts to develop new innovative construction process planning techniques in order to enhance the visualization of the construction sequence and finished product. The latest research development relates to the development of graphical presentation of construction plan via the four-dimensional (4D) geometric models (i.e. 4D-Planner) (Waly and Thabet, 2002). A 4D CAD model is generated from the combination of 3D graphic images and the time. The 4D visualization technique provides an effective means for communicating temporal and spatial information to project participants (Koo and Fischer 2000). Finished projects are visualized and spatial configurations directly shown. Visualization of construction plans allows the project team to be more creative in providing and testing solutions by means of viewing the simulated time-lapse representation of corresponding construction sequences (McKinney and Fischer, 1997), and prompting users to think about all missing details (e.g. site access) (Jaafari et al., 2001).

Despite such advancements, the current 4D models do not convey all the information required to evaluate the schedule. For example, building components and construction equipment are usually modeled in the 3D images and linked with schedule. These 4D CAD systems lack construction-specific components such as scaffolding and other temporary works integrated in the 3D model. Such 4D models do not show the space needs and corresponding potential congestion of temporary works (Koo and Fischer, 2000; Chau et al 2005). However, temporary works are a critical element of the overall construction plan. Failure in planning appropriate temporary structures affects safety, quality, and productivity adversely (Chini and Genauer 1997). In view of these practical deficiencies, the current paper purports to report on the development of a Construction

Virtual Prototyping (CVP) system. The CVP is a construction process simulator developed based on the Dassault Systemes (DS). The system can easily generate, reuse and modify 3D models of building components, construction equipment, temporary works as well as labour force. The proposed system will make 4D models more complete by adding temporary works and their activities to set them and dismantle them. It will aid planners to review the construction process planning and analyze the work space layout more efficiently. In this paper, the second section presents the current IT tools developed for improving construction process planning and implementation, and features of the system developed by us. The third section describes the overall approach of CVP. In the fourth section, a case study is presented to reveal the advantages of using CVP. The last section concludes and discusses the further development of CVP.

## **2. VIRTUAL PROTOTYPING (VP)**

Virtual prototyping (VP) is a computer-aided design process concerned with the construction of digital product models ('virtual prototypes') and realistic graphical simulations that address the broad issues of physical layout, operational concept, functional specifications, and dynamics analysis under various operating environments (Shen et al, 2005; Xiang et al., 2004; and Pratt, 1995). Dedicated VP technology has been extensively and successfully applied to the automobile and aerospace fields (Choi and Chan, 2004). For instance, an automobile can be fabricated virtually via the VP technology and allows various team members to view the 3D image of the finished products, evaluate the design, and identify the production problems prior to the actual start of mass production. However, the development and application of VP technology in the construction industry (i.e. construction process simulation) has been limited. This is probably because that each construction project is unique in term of their conditions, requirements, and constraints. Sarshar et al. (2004) identified three major industrial barriers to uptake VP technology, including cultural and risk issues related to information sharing, fragmentation of business interests and the lack of piloting on real construction projects.

Given the successful implementation in manufacturing industries, various research efforts have attempted to apply the VP concept in forming an effective dynamic construction project planning and scheduling tools. The Virtual Design and Construction (VDC) method was designed as a model for integrating the product (typically a building or plant) so that the contractor can design, construct and operate based on the model (Kunz and Fisher 2005). Virtual Facility Prototyping (VFP) was another interesting work developed for visualizing the building facilities during the construction planning phase by Penn State and Immersive Virtual Environment (IVE) was designed to improve the project planning process by generating and reviewing construction plans in a virtual environment (Yerrapathruni et al, 2005). 4D site management model incorporates the 4D concept into fields of construction resource management and dynamic site planning (Chau et al 2005). Waly and Thabet (2002) developed an integrated virtual planning tool called the Virtual Construction Environment (VCE) which allows the project team to undertake inexperience rehearsals of major construction processes and examine various execution strategies in a near reality sense before the real construction work. In a research project named as DIVERCITY, virtual workspaces has been developed to conduct client briefing, design reviews, simulation of lighting and acoustic design and energy consumption, site planning for time and safety enhancement, and 4-D visualization of building sequence (Sarshar et al. 2004).

The IT tools developed for improving construction process planning and implementation so far can be summarized as Table 1. Currently there is no integrated application to include all functions listed in the table. However, virtual prototyping application in manufacturing is far more advanced than construction. Integrated virtual prototyping application has been used for years in manufacturing and is proved to be effective in reducing cost and time, and improving safety and quality.

**Table 1: Summary of current construction process planning IT tools**

<b>IT Tool</b>	<b>Application</b>	<b>Information Presentation</b>
Scheduling software	Planning of construction activity sequence and the associated resources.	Gantt chart, bar chart, network diagram
Resource leveling	Optimization of resources usage.	Text, bar chart
Layout planning	Plan layout of plant and materials for safe and smooth construction operations.	3D visualization
4D	Visualization of construction plan by linking activity sequence with 3D building models to reveal status of construction works in different period of the project.	3D visualization
Process simulation	Calculation of construction process duration based on sequence of works and productivity information.	Text, diagram
Virtual reality	Mimicking real world physical property in computer and provide intuitive interactive interface to examine construction process.	3D visualization

One of the most powerful virtual prototyping applications in manufacturing is *DELMIA* from Dassault Systemes. *DELMIA* is part of the product lifecycle management applications for addressing requirements from design to production and maintenance. The core of *DELMIA* is a product, process and resources model that link up with various application like 3D model design, process planning, resources planning, discrete and continuous event simulation, 3D visualization, layout planning and virtual reality, all in the same platform. The *DELMIA* application has been customized by the authors to suit construction use and this customized version is called Construction Virtual Prototyping (CVP). CVP contains library of parametric 3D models of construction plants, temporary work facilities and building components, virtual agent technology for simulating spontaneous collaborations among construction workers, stochastic discrete event simulation engine for simulating construction activities. This CVP is a tool which allows the project team to visually assemble 3D models of a building project before the actual construction. This approach also allows the project team to check on the design constructability, anticipate shortages and pitfalls before the execution of the construction

works. The proposed CVP model assists the planners to modify the design or to make corrective action in order to overcome the potential constructability problems.

### 3. CONSTRUCTION VIRTUAL PROTOTYPING – OVERALL APPROACH

One of the main concerns of planners for the construction project planning is the issue of which construction approaches and methodologies to be adopted during the real construction execution. This is particularly important to the building contractors during the project tender bidding stage. The Construction Virtual Prototyping (CVP) system developed helps to provide a rapid prototyping of projects and present the feasibility of construction method statements. The CVP system can also assist in developing a detailed or improved construction programme during the construction phase. Both constructability and safety can be evaluated in the virtual experiment.

The proposed CVP model has chosen the ‘*Product*’, ‘*Process*’ and ‘*Resources*’ (*PPR*) models of Dassault Systemes for program development. The first model is the ‘*Product*’ which represents the building which is intended to be constructed. The ‘*Resources*’ is another model in the proposed CVP which relates to the construction equipment and temporary work to be used for moving or supporting building components. The ‘*Process*’ model represents the procedure of how ‘*Product*’ is built by using the ‘*Resources*’. The *CATIA V5*<sup>iii</sup> and *DELMIA V5*<sup>iv</sup> are two core software in the *PPR* framework. The *CATIA* module allows the users to create 3D models of building, temporary work as well as construction equipment, while the *DELMIA* module helps define and simulate construction processes. Both *CATIA* and *DELMIA* are built on the same platform called *V5*. The *DELMIA* shares the single, unified interface with *CATIA*. The following section will describe and summarize the main features of the CVP system.

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<sup>iii</sup> *CATIA V5* is one of the PLM technologies developed from IBM. Dassault Systemes has been used this system for digital design in the construction industry, such as the Guggenheim Museum in Bilbao, Spain, the Experience Music Project in Seattle and the Walt Disney Concert Hall in Los Angeles (M2 Presswire 2003). Digit Project provided by Gehry Technologies is built on the advanced *CATIA V5* geometry and information management engine, and a suite of applications designed to support the digital design of construction projects (M2 Presswire 2005). Swire Properties has pioneered the application of those technologies in Hong Kong.

<sup>iv</sup> *DELMIA V5* is another PLM technology from IBM

### 3.1 Digital Models of Building and Temporary Works

The CVP application is commenced from the 3D CAD models which are provided by architects or planners. The resources plan (i.e., construction equipment and temporary work) however are usually not generated in the digital design. In the proposed CVP, the digital model of temporary work can be constructed as the components of building (i.e. columns, walls and slabs) from scratch in *CATIA V5* and linked to a digital design. To enable rapid prototyping, parametric models are developed to generate temporary works elements (i.e., wall form, slab form, beam form and working platform) (Figure 1). Parameters in these models are defined according to their specific design criteria. Categories are used to contain resource databases which allow storing and retrieving required information, and provide the project team with support information necessary for project planning.

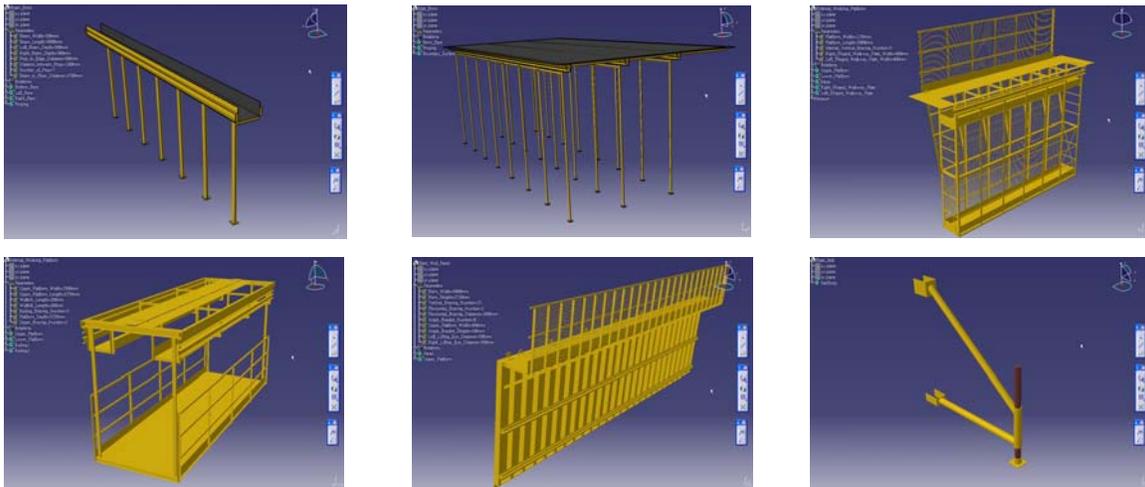


Figure 1: Parametric models of temporary work elements

### 3.2 Definition of Construction Equipment

One important step of the development of the project-specific CVP relates to the definition of the construction equipment. The construction equipment in CVP is established by using the *Device Building* workbench. The 3D CAD models of equipment

parts are first generated through the *CATIA V5*. To accomplish the equipment motion, every movable part has to be distinct. If the construction equipment required  $n$  degree of freedom, the distinct parts of  $n+1$  are needed for the  $n$  movable part with one fixed base. Using the tower crane as an example, the tower crane has three degrees of freedom. The jib circumvolves with the base and the roller moves along with the jib. The hook is put down and raised by the roller. Finally, the 3D model of tower crane consists of four parts including base, jib, roller and hook.

Constraint-driven assembly is suitable for the definition of construction equipment. By carefully defining assembly constraints, fixed parts can be constrained and unmoved. *Parts* that are not fully constrained are able to move in accordance with the remaining 'degrees of freedom'. Using the illustrative example of tower crane, the crane base is assumed to be a fixed part. One revolute joint is created for the jib's rotation, and two prismatic joints are created for the motions of roller and hook of tower crane. Once all the joints are defined, the 'command' is then defined for each remaining degree of freedom in order to drive the mechanism. The command defines the travel limit of joints such as the jib's length or the jib's rotation limitation.

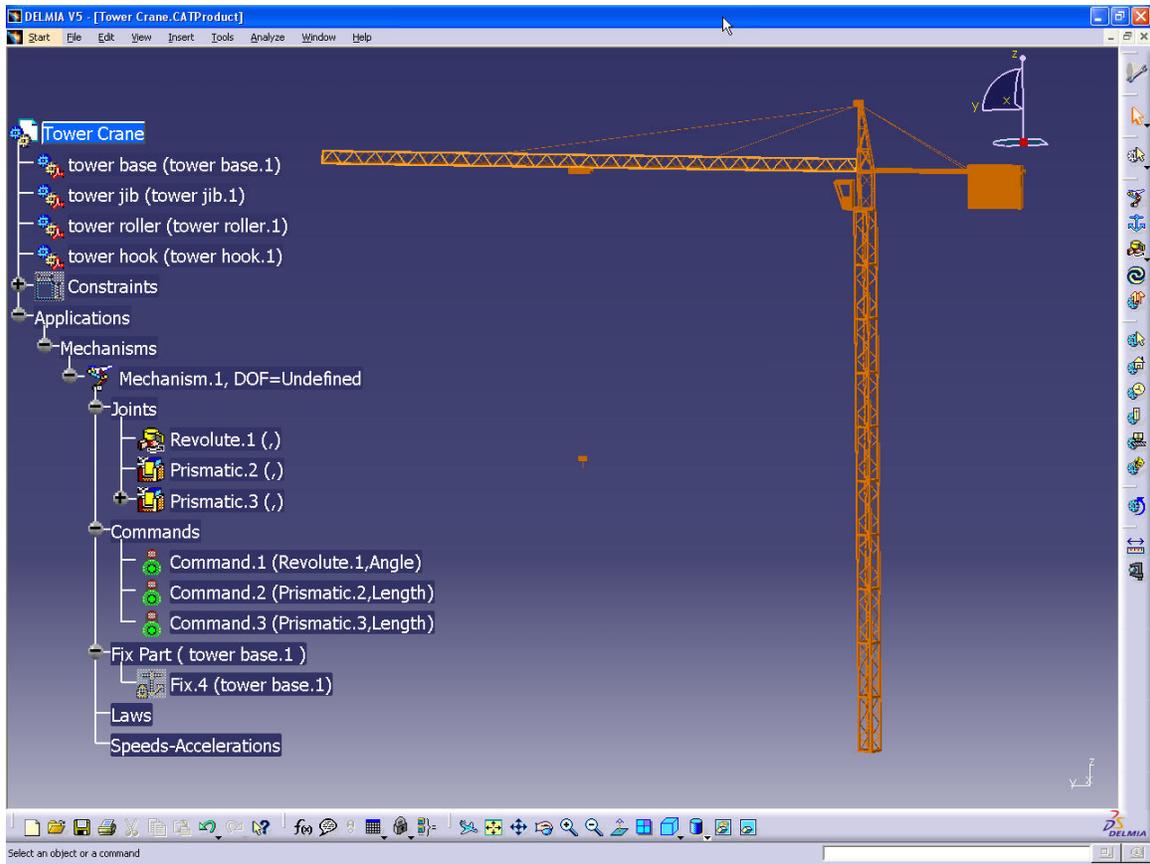


Figure 2: Mechanism model of tower crane

### 3.3 Process Simulation

*DELMIA* Digital Process for Manufacturing (DPM) is an assembly process planning and verification solution for developing manufacturing and maintenance processes. This provides the capability to link and view product data from any major CAD system, examine construction sequences and processes, and connect each process step to the construction resources. Planners usually break down construction process into small activities. *DELMIA* DPM helps to define process as a series of linked activities, each of which has a defined duration. Activities can be independent (parallel), dependent (serial) or a combination of parallel and serial, as shown in PERT chart (Figure 3). Furthermore, *DELMIA* DPM provides three ways to view a process. Prior to defining the construction processes, the default *Process, Product and Resource (PPR)* model defines digital building as ‘Product’, and both temporary works and construction equipment as

'Resource'. The PERT chart in Figure 3 showed the relationships among activities. The start time, duration and end time of activities are displayed in a Gantt chart. When an activity is created, it is linked to a resource and the duration is defined. The start time is calculated based on the accumulated time of all preceding activities, while the end time becomes the sum of the start time and the duration, which in turn becomes the start time of the next activity. After these details are all set, the simulation can be processed. The planners can evaluate and optimize the construction process by running the process simulation provided. The clash between construction activities within the proposed construction process can be automatically detected while running the simulation.

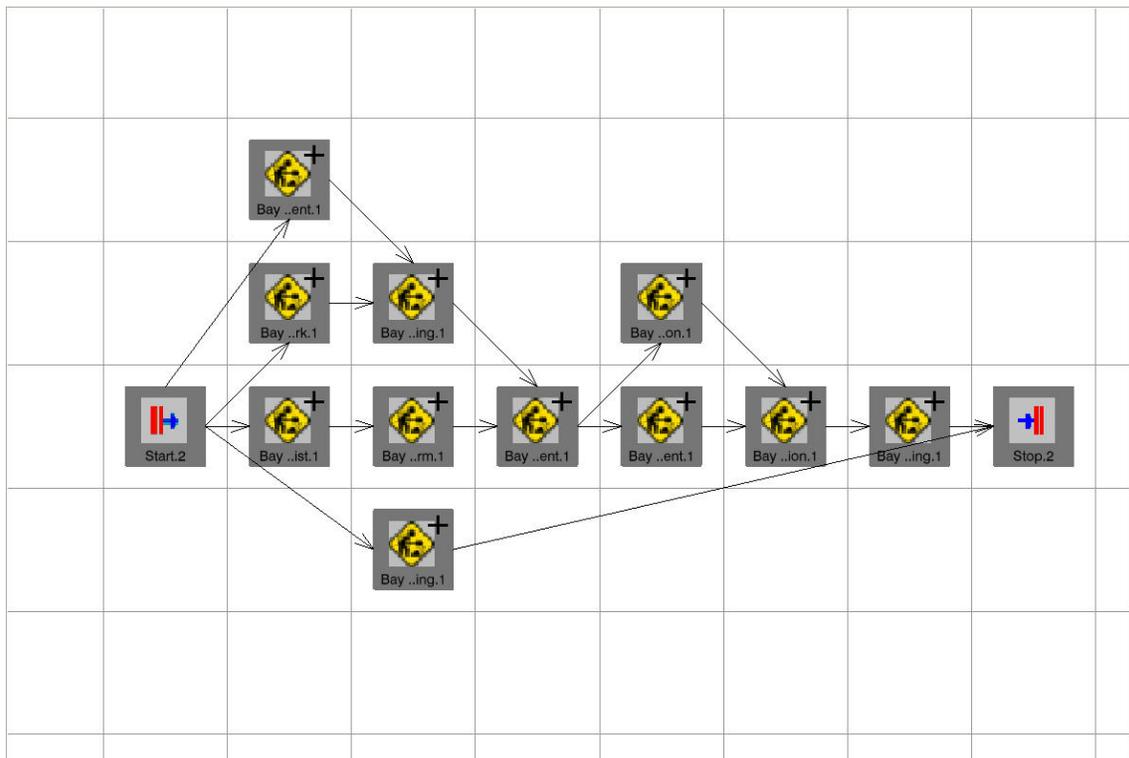


Figure 3: Linking serial and parallel activities using PERT chart view

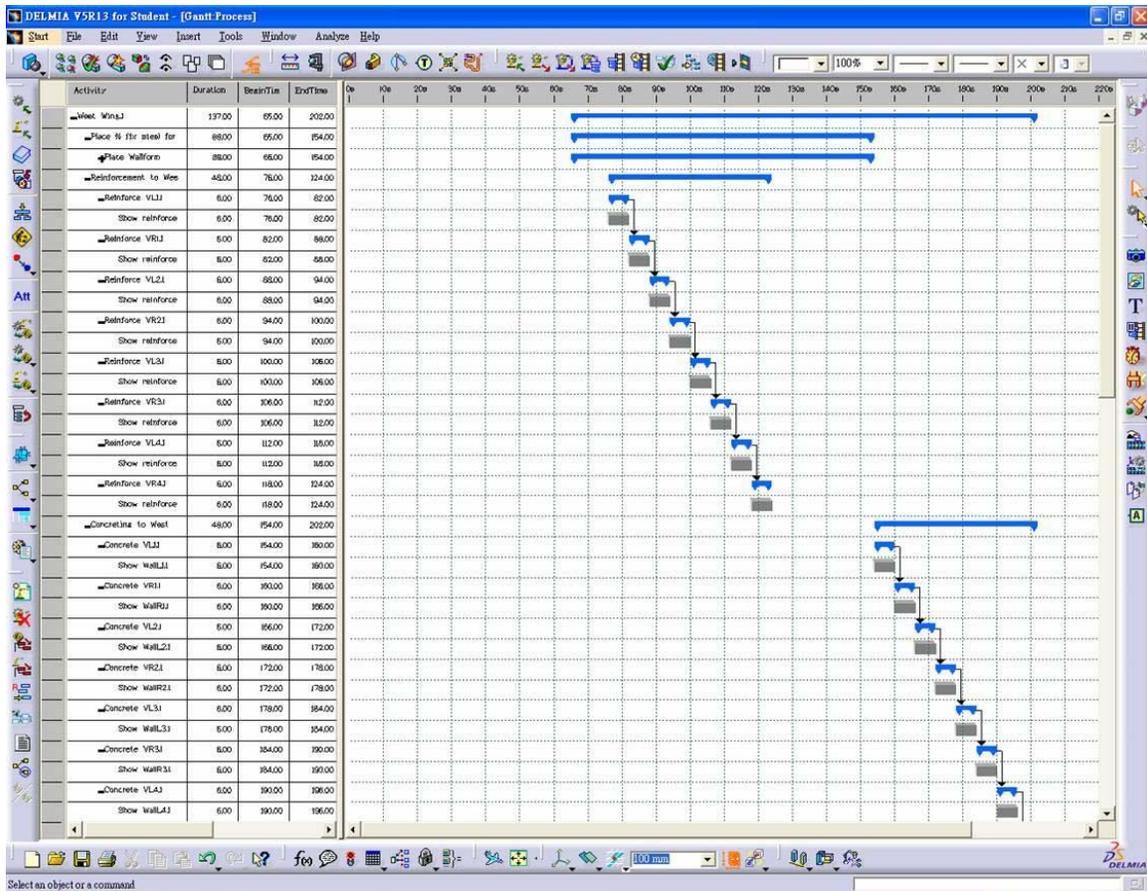


Figure 4: The Gantt chart view

## 4. CASE STUDY

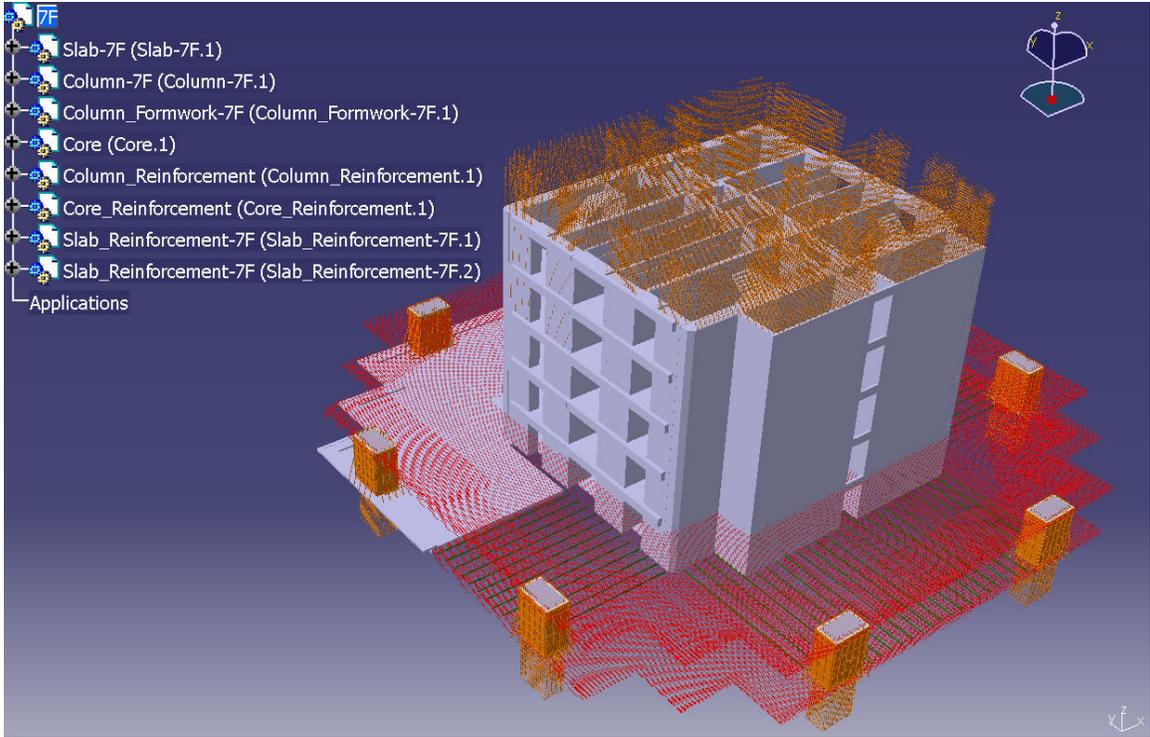
A real-life construction project is presented to demonstrate the applicability of the Construction Virtual Prototyping (CVP) approach. In this case study, the objective is to assist planner, project teams and client to justify the feasibility of shortening the floor construction cycle.

### 4.1 Project description

The project consists of the development of a 70-story office building located in a central business area of Hong Kong. The architectural, structural, and M&E design were made using *Digital Project* from Gehry Technologies. *Digital Project* is developed on CATIA

platform and is specialized for the AEC industry. 3D CAD models of the building were provided as part of tender documents for this project. In order to shorten the construction progress, the client intended to reduce the length of the typical floor construction to a 3- or 4-day cycle. One of the tenderers decided to employ the CVP approach to demonstrate to the client the feasibility of their construction approach and their concern in safety and environmental issues.

In order to visualize the construction process, the construction schedule and site layout were firstly prepared by the project manager and program planner. The locations and utilization of tower cranes, climb forms/ table forms, hoists, and safety screen were then evaluated. The planner proposed that table forms should be adopted as the temporary supports for slab and a proprietary climb form should be designed for core wall construction. Two tower cranes and four hoists were assigned for lifting. In the simulation, a typical floor was extracted from the digital building model and was rearranged according to the construction process. To implement a 4-day floor construction cycle, a floor was divided into four parts which include slab bay 1, slab bay 2, core wall bay 1, and core wall bay 2. The ongoing core wall is four stories ahead of the ongoing slab in the simulation (Figure 5 and 6). The CVP allows the generation of 3D CAD models of resources (i.e., table forms, climb forms, safety screens, tower cranes and hoists) in *CATIA* and assembling them with Product in *PPR* model (Figure 7). The logical sequence of activities in every bay is linked using the PERT chart.



**Figure 5: 3D CAD model of the typical floor**



**Figure 6: 3D CAD model of the product**

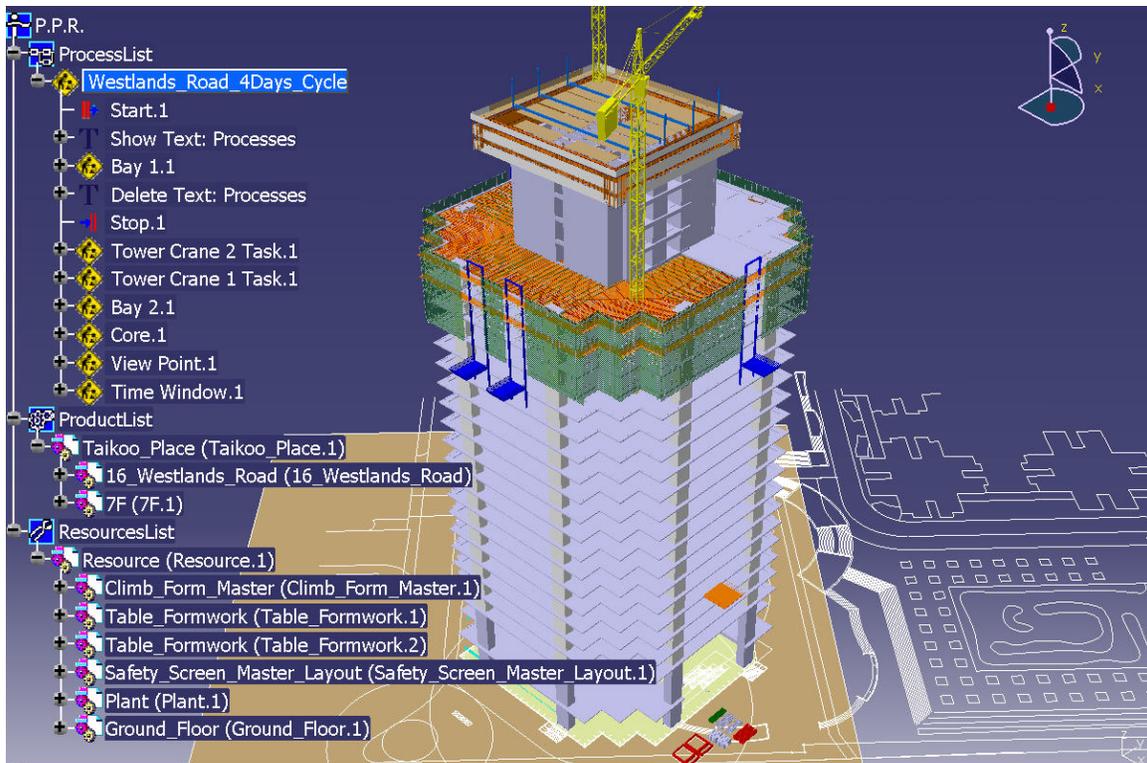


Figure 7: PPR model of the Westlands Road Project

## 4.2 Simulation of construction process

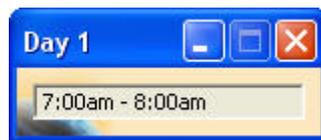
The CVP system can convert 2D engineering design to a 3D construction model, and finally to a model with erection sequences. The 3D CAD models of climb forms/ table forms were built according to the workshop drawings. They can be easily placed to the building structure in the virtual environment in order to check the appropriateness of their dimensions or design. The clearance or collision between climb forms or table forms can be visualized and checked. Reports can be generated automatically to inform the location of collision.

The CVP system produces a precise and detailed planning and scheduling prior to the execution of real construction work giving the ability to observe potential risks and foresee possible problems. For example, two tower cranes with same jib length were initially purposed by the planners for this project, the jib length and location of tower cranes were reviewed and modified by the PPR model of the CVP system. The

visualization of site layout and the two tower cranes suggested that one tower crane can achieve the target of 4-day floor construction cycle, and thus, the planner decided to reduce the number of tower cranes to one. On the other hand, the CVP system provides the planner an opportunity to improve the resource utilization. Two types of resource usage report can be generated automatically from the simulation. The first type of report shows the usage of a particular resource for the activities, while the second type of report shows what resources can be employed for a particular activity. These reports were presented in bar chart or table format to support planning and evaluation of resource utilization. In this example, the idle time of tower crane was identified by the CVP system, and the tower crane can be allocated to lift other M&E components in order to optimize crane usage.

The planning of table form hoisting is another important issue to be considered in this project. More than 150 pieces of table forms were used in one floor. Half of them should be hoisted from the lower story within one day. Due to the spatial constraint, parts of the table forms in the lower floor are removed prior to their installation in the upper floor. The CVP system enables the planner to optimize the table forms installation sequence. The simulation environment also provided an intuitive way to plan floor areas for table forms storage.

In the visualization module, users can view the construction activities at a particular time, and their interrelationship with other activities. The CVP system provides the text windows in the module to explain the work instructions and details of the process (Figure 8 and 9). Pictures were also captured and help the users to present the construction methods (Figure 10). This simulation of 4-day typical floor construction cycle allows an efficient and effective transmission of the proposed ideas of the planner to the client.



**Figure 8: Window of time message**

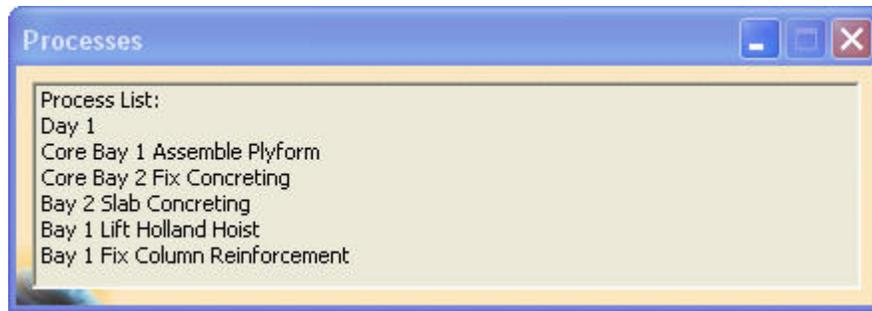


Figure 9: Window of process message

## Construction Methods

- 4-day Floor Cycle – Day 2 (noon)
  - **Slab Bay 1**
    - Set up Table form
    - Bottom re-bars
    - Pre-cast edge beam
  - **Slab Bay 2**
    - Pre-cast column shell
    - Move up Table form
  - **Core wall Bay 1**
    - Concreting
  - **Core wall Bay 2**
    - Re-bar fixing

The screenshot shows a 3D model of a building under construction. The model is color-coded: orange for slabs, green for core walls, and blue for columns. A yellow crane is visible on the left. The software interface includes a toolbar at the top and a 'Processes' window on the right, which matches the content of Figure 9.

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Figure 10: Presentation of 'Construction Methods' with captured picture

### 4.3 User feedback

A number of interviews were made with the project team members including project manager, planning manager and project engineer to collect feedback on utilizing virtual

prototyping technology in the tender stage construction planning. Questions were asked in the areas of software functionality and benefits on project performance. The overall feedback was on the positive side.

The project team members think that the most useful software functions are visualization and clash detection. Visualization allows them to review their planned schedule intuitively and it facilitates modification to the schedule. They find clash detection an indispensable tool in analyzing work sequence in confined area, especially when the work involves installation of large prefabricated element. The drawbacks of the employed virtual prototyping facilities are tedious data input and the difficulty to modify the simulation. Planners find these tasks too time consuming and difficult to cope with the tight tender preparation time. The average rating of the effectiveness of virtual prototyping in different areas are listed in Table 2. A rating of 5 represents highly effective and a rating of 1 represents not effective at all.

Table 2: Effectiveness of virtual prototyping

Virtual prototyping as a visualization tool	4
Virtual prototyping as a planning tool	3.4
Virtual prototyping as an analyzing tool	3
Virtual prototyping as a communication tool	3.7

A number of benefits are identified by the project team members in the area of project performance. They think that virtual prototyping increases the accuracy of their project schedule and their ability to predict and plan construction tasks. The most important benefits of virtual prototyping in this tendering process are its ability to impress client and well define the project scope. It increases client satisfaction and the project team on the case study project thinks that it is one of the reasons for being awarded the construction contract. They predict that utilizing virtual prototyping in construction stage will help them to reduce rework and change orders, and improve coordination and communication effectiveness.

The project team members have some concern on the time required for building all the detailed 3D models of building, temporary work and plant, as it takes long time to build the detailed and accurate models. This is a problem that has to be faced by the first virtual prototyping project, but it can be alleviated in the future project as those common 3D parametric models can be reused directly from library or just slightly be modified to suit the new project condition.

These views were supported from data collected on three other projects where the same virtual prototyping software had been used. There was full appreciation to the ability provided by the system to visualize the construction process but concern with respect to the time taken to collect and input the data required to present the simulation. Where the client had stipulated the need to present the construction process in this way its importance to securing the project was recognised. For one major construction organisation there was the recognition that, if the benefits of the technology are to be realized at this time then there must be specialist input to the project team to facilitate the virtual prototyping process. The potential for benefits to both the design and construction process was clearly recognised by senior management who indicated the potential for savings in time and cost as well as co-ordination. There were other benefits, e.g. Virtual Prototyping models were considered to improve the effectiveness of meetings between the client and the construction team. For Virtual Prototyping to be more widely accepted and used by construction personnel feedback indicated requirement for improved facilities for the time analysis of construction tasks. Time Analysis features should more closely replicate the time analysis facilities within existing planning software. The ability via a library of model data to reduce the time taken to build the models would clearly assist the task.

## **5. Conclusions and further studies**

This paper presented the Construction Virtual Prototyping (CVP) approach for modeling and visualizing the construction processes based on the Dassault Systemes solutions. The framework enables the users to rehearse and simulate construction process virtually prior to the commencement of a real construction project. The example illustrated in this study

showed that the CVP enables the users to visualize the constructability of the proposed construction approach. The CVP system also assists the project team to design a precise construction schedule so as to remove any potential unproductive activities. The rapid prototyping of the CVP system can be enhanced by improving the existing process and resource optimization, constructability and safety evaluation.

From the feedback of planners and our past experiences of developing industry specific IT applications, DELMIA should be further customized to satisfy the demand of construction process planning. For instance, arranging activities is tedious and too time consuming. Gantt chart interface is not user-friendly for construction planning. Some construction specific activities are also needed. We are currently working collaboratively with the Dassault Systems in order to develop an AEC specific version of the DELMIA system.

## **6. Acknowledgements**

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