

A Case Study of Applying Virtual Prototyping in Construction

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Abstract—The use of 3D computer-aided design (CAD) models to support construction project planning has been increasing in the previous year. 3D CAD models reveal more planning ideas by visually showing the construction site environment in different stages of the construction process. Using 3D CAD models together with scheduling software to prepare construction plan can identify errors in process sequence and spatial arrangement, which is vital to the success of a construction project. A number of 4D (3D plus time) CAD tools has been developed and utilized in different construction projects due to the awareness of their importance. Virtual prototyping extends the idea of 4D CAD by integrating more features for simulating real construction process. Virtual prototyping originates from the manufacturing industry where production of products such as cars and airplanes are virtually simulated in computer before they are built in the factory. Virtual prototyping integrates 3D CAD, simulation engine, analysis tools (like structural analysis and collision detection), and knowledgebase to streamline the whole product design and production process. In this paper, we present the application of a virtual prototyping software which has been used in a few construction projects in Hong Kong to support construction project planning. Specifically, the paper presents an implementation of virtual prototyping in a residential building project in Hong Kong. The applicability, difficulties and benefits of construction virtual prototyping are examined based on this project.

Keywords—construction project planning, prefabrication, simulation, virtual prototyping.

I. INTRODUCTION

THE use of prefabricated components in residential building is increasing in Hong Kong. The increase is driven by better built quality, faster construction and government support. The shift from on-site fabrication to off-site factory production increases the risk of miscommunication of requirements and design changes, as the inclusion of suppliers of prefabricated components increases communication layers. The use of prefabricated components also introduces additional construction joints which require higher design accuracy. The traditional 2D drawings as a mean for communicating building design and construction operations are found to be not sufficient. Construction planners often realize that they have to rethink the construction project many times because there has been no way to capture best practices and carry them over from one project to another. Thus, there is a need to present building components in 3D and to present construction operations in virtual environment so that the ideas of planners can be captured, communicated and reused.

By implementing virtual prototyping for construction operations evaluation, constructability data can be evaluated

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and captured. The data can be used by construction manager to check design feasibility and provide feedback to the design team. It allows the discovery of constructability problems early in the design stage to minimize cost of change. During the construction stage, constructability data can be used to produce a detailed process plan and generate 3D construction operation instructions for workers and foreman. The data can also be used for future maintenance planning. 3D maintenance and repairs instruction can be built based on the data.

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 [1,2,3]. Traditionally, construction documentation has been normally prepared in standard two-dimensional (2D) format, consisting of plans, elevations, details, schedules, and specifications [4]. These traditional ways of 2D drawings and paper-based delivery processes, however, limited the capability of visualizing and understanding the design and subsequent construction work involved [1]. Members of project teams may develop inconsistent interpretations or imagination of the project images when viewing the 2D drawings, and resulted in ineffective communication [3]. On the other hand, the critical path method (CPM) and bar charts have 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 [3]. 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 [1]. In addition, tougher building codes, higher performance requirements, tighter construction schedules, and the need to deploy innovative construction methods and technologies have forced project teams to seek for new tools to facilitate the better planning and management of contemporary building design and construction.

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 development of the three-dimensional (3D) computer-aided design (CAD) systems have reduced the burden on verbal and written communication, allowing product designs to transcend differences in location and time[5]. A number of software

products have been designed to accomplish the digital design (i.e., Bentley Architecture, Graphisoft ArchiCAD, VectotWorks ARCHITECT, Digital Project and Autodesk's Revit and Architectural Desktop). 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) [1]. 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 [3]. 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 [6], and prompting users to think about all missing details (e.g. site access) [2]. Despite such advancements, 4D CAD model relies heavily on the availability of full plan or schedule information to provide a graphical simulation of the project schedule. The planner mostly uses these tools as means of visualizing and comparing, rather than for implementing different decision alternatives [1]. In addition, 4D CAD systems cannot effectively simulate construction processes in which various resources are used to transform construction from one stage to next of the time-laps. 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).

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 [7,8,9]. Dedicated VP technology has been extensively and successfully applied to the automobile and aerospace fields [10]. 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. The production line in the manufacturing industry is almost constant and stable as the machine's operation is predictable; whilst the construction project is human-dominated, involving various construction parties and uncertainties.

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. Researchers at the University of Teesside (UK) developed the VIRCON (VIRtual CONstruction) as a prototype application for evaluation, visualization, and optimization of construction

schedules within a virtual reality interface [2]. The Virtual Design and Construction (VDC) method was also 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 [11]. 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 [12]. Waly and Thabet [1] developed an integrated virtual planning tool called the Virtual Construction Environment (VCE) which allows the project team to undertake inexperienced rehearsals of major construction processes and examine various execution strategies in a near reality sense before the real construction work.

II. METHOD

Case study is the method used in this research. The residential building project that implements virtual prototyping consists of constructing two 41th floors building blocks with 16th flats per floor. The structure of these building blocks are made up of more than 60% of precast components ranging from load bearing wall and slab to toilet and kitchen units. Figure 1 shows the layout of a building blocks in the virtual prototyping environment. This project is pioneering in adopting large percentage of precast construction in residential building of Hong Kong. Major concerns of the contractor are on the capability of tower cranes in lifting all the precast components, materials and temporary work facilities, and the sequence of installing precast components. The objectives of virtual prototyping in this building project are to verify and optimise the 6-day floor construction cycle in the areas of resources utilization, space allocation, sequence of works, and design of temporary work facilities and precast components. The expected outcomes of this virtual prototyping are reduced construction schedule variances, avoidance of unbuildable or ergonomically unsafe conditions, minimised change orders after design completion, and shortened response time to changes and unplanned conditions in construction site.



Fig. 1 Building block layout in virtual prototyping environment

III. THE IMPLEMENTATION OF VIRTUAL PROTOTYPING

There are three main phases in implementing virtual prototyping. They are project requirement collection phase, 3D models building phase, and process simulation phase. Table 1 depicts the tasks, information, and people involved in these three phases. They are discussed in detail in the following sections.

A. Project Requirement Collection Phase

In the project requirement collection phase, major project challenges are identified and these become the basis for defining the scope of works. The challenges can be divided into design related and construction related. Design related challenges come from coordination of building components and temporary work facilities design details to ensure a harmonized building design and construction operations. The major design challenges in this building project are coordination of welding joint and reinforcement layout of precast components, and coordination of working platform design. Construction related challenges come from uncertainty in method of construction, duration of an activity, and level of resources utilization. The major construction challenges in this project are ensuring not to overload tower cranes, and preparing the best sequence of installing precast components to streamline other construction works like concreting, rebar fixing, formwork fixing, etc. The information required in this phase include a preliminary construction method statement, architectural drawings of major building components, a master construction program and a preliminary floor cycle program. The people that usually involved in this phase include the architect, engineer, project manager of main contractor, and representative from major sub-contractors.

TABLE I THE THREE PHASES OF VIRTUAL PROTOTYPING IMPLEMENTATION

	Project Requirement Collection Phase	3D Models Building Phase	Process Simulation Phase
Tasks	Identify design and construction challenges; Define scope of works.	Create 3D models of building components, temporary work facilities and plants; Carry out digital mock-up to check dimensional conflict.	Simulate planned construction process; Validate construction sequence; Find time space conflict; Check and optimize resources utilization; Try alternative construction plan.
Information Required	Preliminary construction method statement; Architecture drawings of major building components; Master construction program; Preliminary floor cycle program.	Workshop drawings and layouts of building components, temporary work facilities and plants; Detailed floor cycle program showing divided working bays.	Detailed process program; Productivity rates of different activities; Safety plan.
People	Architect;	Project planning	Project planning

Involvement	Engineer; Project manager of main contractor; Representatives from major sub-contractors.	team of the main contractor; Suppliers of building components and temporary work facilities.	team of the main contractor; Representatives from major sub-contractors.
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B. 3D Models Building Phase

In the 3D models building phase, 3D CAD models of building components, plants and temporary work facilities are built according to the need for tackling design and construction challenges. Building components, including both precast and in-situ parts, have to be broken down into small unit that suit simulation of construction operations. For instance, the slab reinforcement and in-situ concrete have to be broken down into units that fit the divided working bays. The level of details of the 3D models has to be discussed in this phase so that the models can reflect the situation that need to be examined. It is obvious that we cannot build 3D models into every bolt and nut details. The models just need to be built to the details that can reflect both dimensional and space conflicts, and sometimes enough for examining safety issues. The plants in virtual prototyping can have its physical properties like degree of freedom in movement, speed and acceleration of movement and association between different mechanical joints. Physical properties are set for evaluating reachable area, travelling time and viewing angle of plant operator. The 3D models prepared in this building project includes precast components, reinforcement and in-situ concrete components, conduits and boxes, steel wall and beam formworks, shoring, struts, working platforms and tower cranes. After creating 3D models, digital mock-up will be arranged for checking dimensional conflict between building components, between temporary work facilities, and between building components and temporary work facilities. Figure 2 and 3 shows dimensional conflict checking between working platforms and between wall formworks and precast slabs respectively. The works in this phase have to be done after producing the first version of workshop drawings and before manufacturing of building components and temporary work facilities, so that dimensional conflicts can be rectified before manufacturing to reduce reworks in the actual construction. The information required in this phase include workshop drawings and layouts of building components, temporary work facilities and plants, and a detailed floor cycle program that shows divided working bays. The people involved in this phase include project planning team of the main contractor, and suppliers of building components and temporary work facilities.

C. Process Simulation Phase

After building 3D models and validating design of building components and temporary work facilities, the next process simulation phase is to simulate planned construction process, validate construction sequence, find time space conflict, check and optimise resources utilization, and try alternative construction plan. Construction processes are simulated to tackle identified construction challenges. The process as

detailed as every movement of a human or plants can be simulated in the virtual prototyping environment.

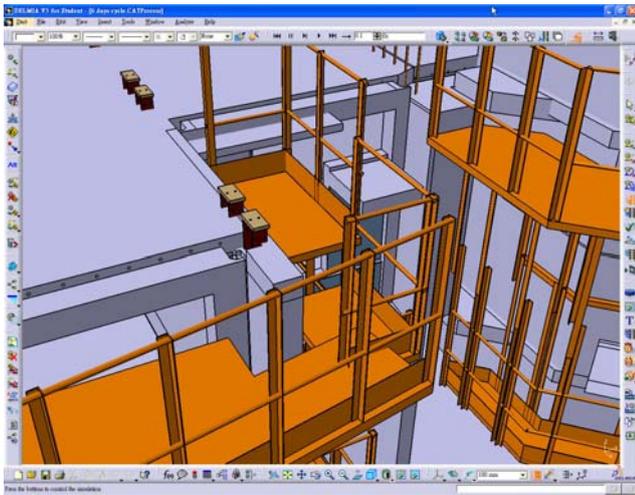


Fig. 2 Digital mock-up to check dimensional conflict between working platforms

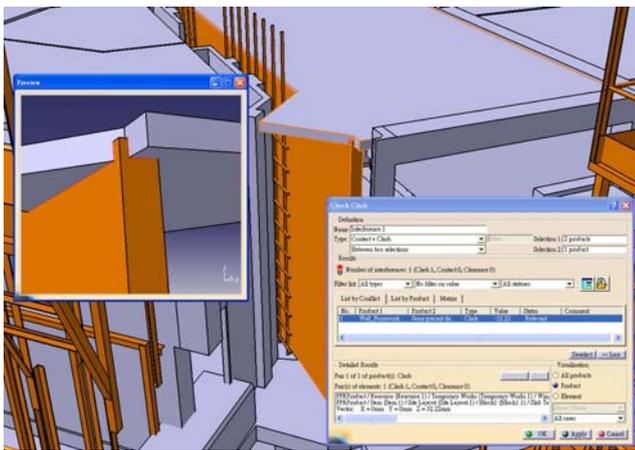


Fig. 3 Digital mock-up to check dimensional conflict between wall formworks and precast slabs

provide more detailed productivity and planning information, which sometimes are difficult to get due to limitation in time and information. The information required in this phase include detailed process program, productivity rates of different activities, and safety plan. The people involved in this phase are contractor's project team and representatives of major sub-contractors. A floor construction cycle involves the works of different sub-contractors. It is necessary to collect information on resources deployment, productivity rate, and work sequence from them in order to produce the simulation.

The process simulation phase usually starts at the construction project planning stage and stops at the actual construction stage. Process simulation helps contractors to tackle construction challenges in the planning stage. The simulation can then be used as 3D work instructions for communication among the project team members and for giving guidelines to workers. During construction stage the actual productivity data are recorded and compared with that of the simulation. Adjustment to the simulation will be made if there is any discrepancy. The adjusted simulation will serve as a knowledgebase for reference by future projects.



Fig. 4 Human movement simulation in detailed process analysis

Fig. 4 shows simulation of a worker moving a table formwork to its final position for slab concreting, and figure 5 shows the mobilisation of workers when installing precast building components. Sometimes it is not necessary to simulate behaviours of workers or every detailed work process, but just to highlight building components that are under construction. Figure 6 shows simulation of fixing wall reinforcement by using blue colour highlight. The level of details of the simulation depends on the nature of the construction challenges we need to tackle. For tackling workspace related problem, we probably need to simulate every step of a construction process and the movements of both human and plant involved. But for reviewing overall work sequence or resources utilization of a floor cycle, using colour highlight can be good enough to reflect the physical conditions of the construction site. Higher level of details require more effort from the virtual prototyping team to make the simulation, and also from the contractor's project team to

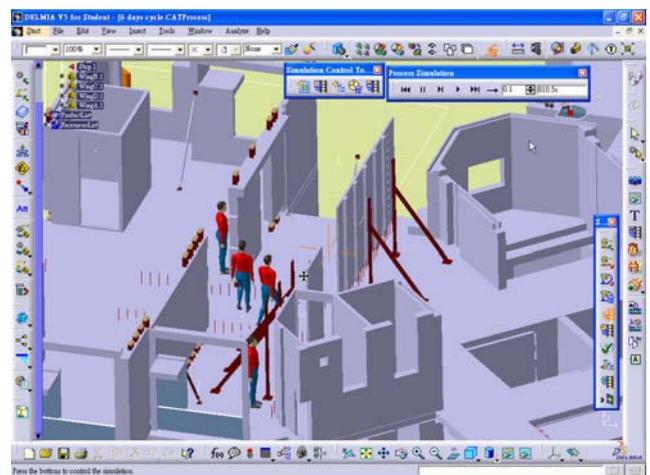


Fig. 5 Simulation showing mobilisation of workers

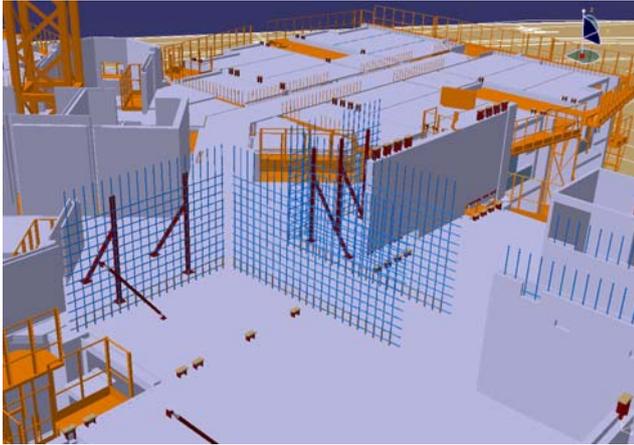


Fig. 6 Simulation of reinforcement fixing process

IV. BENEFITS OF VIRTUAL PROTOTYPING

Through the process of virtual prototyping, the 6-day cycle, which was initially planned by the main contractor, was incrementally improved and optimised through a loop of try and error process. The finalised plan is a 6-day cycle with every aspect of constructability and safety examined and confirmed by the virtual prototyping process. During the process of constructing 3D models of all prefabricated cast-in-situ components, over 10 design errors, which can contribute to over 40% of rework, have been identified and corrected. In addition, the virtual prototyping process has also identified a number of “unsafe” spots where possible human-machine interaction can occur, which will result in severe accidents.

In addition to the tangible benefits, the main contractor accepts that the virtual prototyping system is an ideal platform to capture and manage knowledge and expertise of the main contractor. As the virtual prototyping system provides a rich environment to capture all properties and attributes needed to represent construction processes and sequences, the simulated construction processes eventually become the most valuable knowledge asset to the contractor, and the virtual prototyping system becomes an effective knowledge management tool to the firm. With the incremental accumulation of simulated construction projects, it is possible for the contractor to try different what-if scenarios within the virtual prototyping environment, and to achieve incremental improvement of efficiency and productivity over time. Arguably, this is how the car industry has managed to achieve over 10% productivity improvement annually over the last decade or so.

V. DIFFICULTIES OF IMPLEMENTING VIRTUAL PROTOTYPING

The difficulties of implementing virtual prototyping in construction project come from three major areas: 1) computer hardware requirement, 2) information collection and dissemination, and 3) communication of virtual prototyping ideas.

Virtual prototyping applications compute activities sequence and illustrate the activities in a real time 3D virtual

environment. It requires massive computational power to drive the simulation. Even the workstation computer with a very fast CPU and graphics acceleration card can just simulate construction of a typical building in acceptable speed. The contractor has to purchase workstations dedicated for the virtual prototyping works. This can become the hurdle for contractors as they need to invest in the start up. Currently the virtual prototyping applications are run on 32-bit version of Microsoft Windows XP which allows it to use 2 GB of physical memory at maximum. This amount of physical memory is sometimes not enough for simulating complicated scenario. Adjustment to the 3D models is needed to reduce memory usage. An alternative is to use 64-bit version of Windows XP which does not have this memory limitation.

Difficulties in information collection come from conflict of interest. The main contractors in Hong Kong usually sublet major works like concreting, reinforcement fixing, building services installation, system formwork, etc. They usually do not have a comprehensive database of productivity rates of different trades. In order to accurately simulate construction process, productivity rates and number of workers for different trades have to be collected from sub-contractors. However sub-contractors usually refuse to give this information due to confidentiality and protection of their interest. The main contractor has to make their own estimate based on experience in the planning stage and then make measurement of it during actual construction. Difficulties are also encountered in disseminating simulation information to the workers, as the communication chain from the main contractor end at the leader of the sub-contractors but not the workers. It is up to the worker leader on how or whether to disseminate the information to workers. Similar to the manufacturing industry, the effectiveness of virtual prototyping will be largely hampered if not all people involved in the construction works understand the results of simulation.

In order to produce a practical and thorough simulation of construction works, input from the planning personnel of main contractor and sub-contractors is necessary. Their ideas have to be collected in the initial simulation planning stage and also in the simulation review stage. However it is found that calling up all the parties to attend meeting for virtual prototyping works is difficult due to the lack of interest of sub-contractors. It is necessary to persuade sub-contractors on accepting benefits of virtual prototyping at the very beginning.

VI. CONCLUSIONS

This paper presented an implementation of virtual prototyping in a residential building project in Hong Kong. The framework and process of implementation are discussed, and benefits and difficulties identified. The implementation framework presented in this paper can be used as a basis for future virtual prototyping works. In addition to the project presented in this paper, the virtual prototyping technology has been applied to other 5 construction projects including 2 office building, 2 sports stadiums, and 1 infrastructure project. Concurrent studies are currently conducted by team members

of our Construction Virtual Prototyping Laboratory to calibrate the accuracy between the simulated construction processes and those in real-life, as well as to measure tangible time and cost savings brought by the use of the virtual prototyping technology. In addition, discussions and preparatory work are underway to work closely with a well-known virtual prototyping software provider to develop a construction-oriented commercial system of virtual prototyping.

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