Construction virtual prototyping: A survey of use

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ABSTRACT

Purpose –The introduction of Building Information Model tools over the last 20 years is resulting in radical changes in the Architectural, Engineering and Construction industry. One of these changes concerns the use of Virtual Prototyping - an advanced technology integrating BIM with realistic graphical simulations. Construction Virtual Prototyping (CVP) has now been developed and implemented on ten real construction projects in Hong Kong in the past three years. This paper reports on a survey aimed at establishing the effects of adopting this new technology and obtaining recommendations for future development.

Design/methodology/approach – A questionnaire survey was conducted in 2007 of 28 key participants involved in four major Hong Kong construction projects – these projects being chosen because the CVP approach was used in more than one stage in each project. In addition, several interviews were conducted with the project manager, planning manager and project engineer of an individual project.

Findings –All the respondents and interviewees gave a positive response to the CVP approach, with the most useful software functions considered to be those relating to visualisation and communication. The CVP approach was thought to improve the collaboration efficiency of the main contractor and sub-contractors by approximately 30 percent, and with a concomitant 30 to 50 percent reduction in meeting time. The most important benefits of CPV in the construction planning stage are the improved accuracy of process planning and shorter planning times, while improved fieldwork instruction and reducing rework occur in the construction implementation stage. Although project teams are hesitant to attribute the use of CVP directly to any specific time savings, it was also acknowledged that the workload of project planners is decreased. Suggestions for further development of the approach include incorporation of automatic scheduling and advanced assembly study.

Originality/value –Whilst the research, development and implementation of CVP is relatively new in the construction industry, it is clear from the applications and feedback to date that the approach provides considerable added value to the organisation and management of construction projects.

Keywords Construction planning; Communication; Process simulation; Virtual prototyping

Paper type Research paper

INTRODUCTION

The introduction of Building Information Model (BIM) tools over the last 20 years is resulting in radical changes in the Architectural, Engineering and Construction (AEC) industry. One of these changes concerns the use of Virtual Prototyping (VP) - an advanced technology integrating BIM with realistic graphical simulations. The emergence of VP models is due to their digital nature which, coupled with fast and affordable computer processing power, enables the functionality of designed parts to be revised and optimised in a very quick, economic and efficient manner (Zorriassatine *et al* 2003).

Several studies have attempted to apply VP technologies to develop effective dynamic construction project planning and scheduling tools. This has resulted in the identification of five categories of VP technologies of major potential:

(1) *Visualisation.* Visualisation technologies play an important role in communication and collaborative working between customers, developers, architects, managers, engineers, and even fieldworkers. Liston *et al* (2001), for example, found that 4D CAD is commonly used during construction project meetings, with approximately 50 percent of the time being spent using the model to explain designs and a further 20 percent being used to assist in describing construction operations (Liston *et al* 2001). Also, the utilisation of four dimensional (4D) visualisation allows a more intuitive comprehension of the construction process than traditional two dimensional (2D) drawings and schedule information (Bergsten 2001).

(2) *Collision detection.* Collision detection is generally an iterative, time consuming and error-prone process that is expected to benefit from the use of 3D VP. Most commercial solutions from the major software publishers (e.g., Autodesk, Bentley Systems, Graphisoft, Vector Works and Gehry Technologies (Goldberg 2005)) have a collision detection capability. This technology has been already used in building design, especially for prefabricated components and Mechanical, Electrical, Plumbing (MEP) design.

(3) *Testing and verification of functions and performance.* By integrating with detailed geometrical (e.g. centre of gravity, surface, volume) and non-geometrical (e.g. properties such as density, stiffness, etc.) data, 3D solid models can be used to carry out extensive and specialised tests and analysis - such as structural analysis, lighting, acoustic design, energy consumption, and fire simulation. Many researchers have studied the performance of buildings by using VP technologies (Bouchlaghem *et al* 2005; Fischer and Kam 2002; Hamilton *et al* 2005; Soubra 2007).

(4) *Evaluation of manufacturing and assembly operation.* 4D planning provides a new opportunity for the representation of construction scheduling - advancing the principles of planning and the Gantt chart (Richmoller *et al* 2001) - to allow the analysis of construction schedules prior to the construction phase. Advanced 4D tools have been developed to support cost management, quantity survey, and site layout (Akinci *et al* 2000; Chau *et al* 2005; Dawood *et al* 2003; Kelsey *et al* 2001).

(5) *Resource modelling and simulation.* The construction activities may involve lifting materials, fixing formwork or rebar, and concreting by machinery or human operators. Resources including machinery and labour can also be modelled and analysed by VP technologies. The integration of VP with Virtual Reality (VR) enables user interactions with more realistic 3D models. The University of Salford's "Think Lab" is developing immersive tele-collaboration technologies for the construction industry (Brandon 2007).

However, most previous research lacks piloting implementation on real construction projects (Sarshar *et al* 2004). One of the major barriers towards effective adoption and use of IT in the construction industry is its uncertain payoff. Firms are unlikely to employ advanced technologies, such as BIM and VP, until they are reasonable certain of the benefits to be obtained.

VP technology has already been successfully applied in many industries such as automotive, aircraft, shipyards, electrical and electronics, etc. CIMdata (2002) reported benefits from VP implementations to twelve companies in the automotive, aerospace, and shipbuilding industries in the United States, Europe, and Japan. In the case of product and tool design, the users of VP technologies experienced a substantial reduction in the number of design changes (65 percent), greater effectiveness in communications and collaboration (35 percent), savings in tool design (30 percent), and a reduction in overall product design time (10 percent).

Of the few similar studies in the construction industry, Griffis *et al* (1995) conducted research into the use of 3D computer models in the industrial process and commercial power sector of the AEC industry spanning from 1993 to 1995. This study used a survey questionnaire of 93 projects to identify the most common usage of 3D models, the perceived benefits by users, the greatest perceived impediments to the use of 3D in construction, and a statistical analysis of the difference between the use of 2D CAD and 3D CAD. Stanford University's Center for Integrated Facility Engineering (CIFE) also conducted surveys in 2006 and 2007 on the use of Virtual Design and Construction (VDC) and BIM technologies in the AEC industry (Gilligan and Kunz 2007).

In addition, the Construction Virtual Prototyping Laboratory (CVPL) at The Hong Kong Polytechnic University has applied the VP technology to ten real construction projects in Hong Kong in the past three years. Construction Virtual Prototyping (CVP) is the use of integrated product, process and resource models for construction projects to support the construction planning in virtual environment (Li *et al* 2008). This paper describes surveys conducted on several of these projects, in which the CVP approach was used in both design and construction phases.

OVERVIEW OF THE CVP APPROACH

The CVP system was developed by customising an existing third-party solution, DELMIA, from the manufacturing industry. DELMIA is a product of Dassault Systemes (DS) and is one of the most powerful virtual prototyping applications used in manufacturing. It is part of a product lifecycle management application for addressing requirements from design to production and maintenance. The core of DELMIA is a Product, Process and Resources (PPR) model that links up with various applications - 3D model design, process planning, resources planning, discrete and continuous event simulation, 3D visualisation, layout planning and VR - all in the same platform.

The CVP model reinterprets the PPR models of DELMIA for construction use. The first model is the 'Product' which represents the building that is intended to be constructed. 'Resources' is another 3D model which relates to the construction equipment and temporary work to be used for moving or supporting building components. A 'Process' model represents the procedure of how the 'Product' is built by using 'Resources'.

The CVP approach is similar but not the same as the VDC approach proposed by the CIFE. The VDC is based upon a Product-Organisation-Process (POP) framework which purports that a project manager can control three kinds of things: the design of the product to be built, the design of the organization that does the design and construction, and the design of the process that the organization follows (Kunz and Fischer, 2005). This POP framework assumes that VDC can fundamentally change the way to conduct construction projects including the organisation structure and product process.

The primary aim of the CVP approach is to support project teams to improve the constructability of the design, the feasibility of construction methods and the accuracy of construction scheduling. The CVP approach extended 3D models from building components to five different physical planning elements including site, construction components, temporary works, construction equipment and field crew. In addition, using assembly analysis and machinery motion analysis, the CVP approach can be used to study site transportation, equipment access, equipment capacity, and working space. In other words, it is a "nD" approach to simulate important dimensions (or variables) related to a construction project.

To enable project teams to employ the CVP approach, researchers of the CVPL act as process modellers to connect the design and construction teams. The process modeller accepts the BIM model from the designer, and decomposes it into formats required by the main contractor, subcontractors and consultants. At the same time, the process modeller integrates information provided by the construction team into the BIM model to create a VP of the construction processes. Information from the construction team typically includes temporary designs, preliminary planning and costing information. Through an iterative process, the process modeller enables the construction team to conduct 'what-if' analyses of different construction methods in the VP environment, until a satisfactory method is obtained. More details of the CVP approach can be found in Huang *et al* (2007) and Li *et al* (2008).

The CVPL works very closely with main contractors, including China State Construction Engrg., Gammon Construction, the Chevalier Group, and Yau Lee Group in Hong Kong. The Vanke Corp, the leading developer in Mainland China, has also applied the CVP approach in its experiment house. Table 1 lists the projects that have applied this approach and their related risks. In general, the CVP approach started from the construction stage after identifying project challenges with the main contractor. The common characteristic of these projects is the high risks faced by contractors due to constrained sites, tight schedules, new design, or complex structures.

SURVEY METHODS

The overall objective of the questionnaire survey was to assess the operational effectiveness and functionality of the CVP approach. The matrices used in the questionnaire have been designed and developed based on the Case Study Protocol developed in CIFE (Fisher and Gao, 2004). This involved seeking information concerning:

1. General Information and Project characteristics. This comprised information relating to the respondents' organisation, position, and work experience.
2. Operational Effectiveness of the CVP approach. This involved respondents' rating the operational effectiveness of CVP on a five-point scale ranging from 1-not effective at all to 5-highly effective.
3. Lessons Learned and Recommendations. Here, respondents were asked to give their recommendations for the improvement of the CVP approach.

After piloting, the questionnaires were sent to four projects - the Ho Tung Lau Development Project, Island East Project, TKO Sports Ground and Vanke Experiment House. These four projects were chosen because the CVP approach was used in more than one stage in each project and all the key participants - including client, architect, main contractor, and subcontractor – were involved in the application. Table 2 lists the stages and participants involved in these projects. Of the 50 questionnaires sent to the participants of the projects, 28 valid responses were obtained. Figure 1 shows the distribution of respondents for each project.

In addition, several interviews were conducted with project team members when the superstructure construction of the Island East project was almost finished. These involved the project manager, planning manager (APM) and project engineer and aimed to collect feedback on the utilisation of CVP technology. Questions were asked relating to their own experiences of the software functionality and the benefits on project performance. Each interview lasted 30-50 minutes and was recorded with permission and transcribed for subsequent analysis.

It is necessary to note that the ratings of the time, accuracy and other performance improvements listed in the questionnaire are not direct conversion of quantitative measures, but rather qualitative assessments of the respondents. To supplement this, interviews have been conducted to gauge quantitative data of these performance improvements.

FINDINGS

This section reports the findings of questionnaire survey and interviews.

Background of respondents

The developed framework and the process of CVP aims to help the construction planning process and implement process for general contractors. Other participants are not directly served by the CVP approach but they share information and use the results, so their feedback is also important for the further development of the CVP approach. Therefore, responses were obtained from the four key process players, namely, architects, client/owners, general contractors, and subcontractors. Figure 2 shows the number of respondents specialising in these various roles and services that make up the process of design and construction of buildings. All the participants gave a positive response to the CVP approach. However, the various participants' feedbacks were not analysed individually due to the limited numbers involved.

Overall ratings of the effectiveness of CVP

Because the CVP approach is used in different stages of construction projects, respondents were asked to give an overall rating of the effectiveness of CVP for each stage. The average ratings are presented in Figure 3. This shows the design stage to be the most highly rated. Although a complete BIM was not built for these projects, the amount of rework was reduced by detected collisions – resulting in savings for the contractors and client/owners. The feasibility stage and construction stage also receive the high rating. Comments from the interviews indicated that applying the CVP approach in the early stage of project, such as feasibility stage or design stage, provides more benefits to client/owners and architects, while general contractors obtain more benefits from the CVP approach if the delivery method of the project is Design and Build (D&B). On the other hand, the CVP approach provides little benefit to engineering consultant during the engineering consultant stage because of the specialised knowledge or experience required. Although the CVP approach has not been applied to the operations and maintenance stage yet due to the need to reorganise the BIM for this stage, it is believed by some client/owners that a complete BIM of a building will provide useful information for this stage.

The CVP approach provides some functions including visualisation, planning, analysis and communication to the project participants. The respondents were asked to rating these functions accordingly. As Figure 4 shows, the most useful software functions are considered to be visualisation and communication. The CVP approach enables both project design and construction method to be visualised. Visualisation enables planned schedules to be reviewed intuitively and provides a communication platform to all participants. The visualisation and communication functions were also highly praised during the interviews. Although the CVP approach was developed for construction planning, this function was not fully acknowledged due to the CVP's role being limited to assisting the planners' work instead of providing a full automation.

Improvement in communication

The respondents were asked to rate which aspects were improved between different participants as a result of using the visualisation platform. Figure 5 shows that most respondents think that the CVP approach improves communication efficiency, decision-making promptness, and client/owner satisfaction.

The interviewees estimated that the CVP improves collaboration efficiency among the main contractor and sub-contractors by approximately 30 percent. The meeting time for presentation of construction plans and schedules was also reduced by approximately 30 to 50 percent (Figure 6). As revealed during the interviews, communication with unspecialised participants such as developers is traditionally more difficult and the CVP approach enables substantial improvements in communication efficiency with developers of approximately 50 percent.

Design check

The design check is the main function of the BIM. In the Island East project, the BIM was built by the 3D model team and the general contractor estimated about 30 percent of design errors were detected before the construction. The same general contractor, China State Construction Corp., also adopted the CVP approach in the Ho Tung Lau Development Project and the TKO sports ground and the project teams thought they received more benefits from the latter – a D&B project. In the Vanke Experiment House project, the project teams considered clash detection to be an indispensable tool in analysing work sequence in confined areas, especially when the work involves the installation of large prefabricated elements.

Visualised construction method statement at tendering stage

Only two projects, the Ho Tung Lau Development Project and the Island East Project adopted the CVP approach during the tendering stage. In the former, three different construction methods were visualised on the virtual platform. Interviews indicated that these visualised construction methods speeded up the decision-making process and were easier to explain to the client/owner. Also, the most important benefits of VP at the tendering stage are its ability to impress client/owners and well-define project scope. It increases client/owner satisfaction and is thought to be one of the reasons for the general contractor being awarded the construction contract.

Construction planning

The respondents were asked to rate the aspects that are improved by CPV during the construction planning. The results are summarises in Figure 7, which shows the most important benefits at this stage are improved accuracy, shorter planning time, and improved safety and constructability.

The interviewees estimated that there is an approximate 40 percent reduction in planning time for typical floor cycle and more than 50 percent reduction in planning time for non-typical outrigger construction. The interviewees also considered that the CVP application, at its present stage of development, may be more suitable for multistory buildings with plenty of repetition of floors, since a saving of even a 1/2 day per floor is a great contribution to the project. In addition, the interviewees also thought that some major or key items - such as outrigger or steel trusses - are more worthy of the CVP approach, as these are critical and high risk for the contractor.

In the Island East Project, the total saving in outrigger floors was 24 working days. Despite such successes, the project teams are hesitant to attribute the use of CVP directly to any specific time savings as nobody knows the cost or delay that would have happened without the CVP approach. For example, although the CVP enables "try before build" and the early identification and resolution of potential problems that may result in delay, many of these potential problems would have been identified later anyway and not necessarily have impacted on the construction period. To possible ways exist to conclude on this more objectively. One is to use a benchmark project. The other is to use statistical analysis to measure the significance of the different effects between projects with and without the CVP approach.

Workload of planners

The influence on the workload of planners needs to be considered in judging the success of the CVP application. Although the CVP framework and process do not require planners to create models or simulations, they do need provide more information for the CVP modelling process. For example, to carry out collision detection, original design drawings from designers or subcontractors are needed. While this does not significantly increase the workload of planners, if any collisions are identified, a response is needed from the relevant designers or subcontractors. This iterative process requires the planners to delivery updated drawings to the 3D modellers, otherwise the troublesome modelling process is worthless.

To simulate the sequencing or verify the construction methods, the planners provide the initial planning information. Furthermore, since process modellers are not usually experienced in construction planning, the planners have to help interpret the information. This again is an iterative process that continues until the construction planning is correctly replicated by the simulation.

In response to questioning, interviews indicated that the CVP approach *decreases* the workload of project planners. The planners indicated that the virtual work instructions save them considerable time in preparing sketches. Although the planners have to prepare detailed construction plans before passing information for simulation, they believe the extra effort is worth while and one of the reasons for more accurate schedules being produced.

Construction implementation

The respondents were asked to rate the aspects that were improved by CPV during the construction stage. Figure 8 shows the most important of these to be concerned with *instructing fieldwork*, followed by *reducing rework*.

During the interviews, one of the site managers also indicated that the virtual work instruction improves the cooperation between project planners and site managers. In previous projects, the planners tended to work alone and their scheduling was often regarded as inappropriate by the site managers. With the CVP approach, the planners are able to develop a more reasonable and understandable schedule to site managers and also improve their degree of collaboration as a result.

The amount of time and cost reduction was rated rather lower. One of the reasons is that, as mentioned earlier, project teams are hesitant to attribute CVP use directly to any specific time and cost savings. The interviewees also indicated that the CVP approach had the potential to optimise planning and scheduling further and therefore was expected to directly reduce time and cost in the future.

Barriers and deficiencies

The survey also obtained further recommendations for the future. Of these, some interviewees suggested that the CVP system should be developed further to automatically perform some planning tasks or optimise resource utilisation by the introduction of Artificial Intelligence (AI) to replace the current dependency on the planners' experiences. It was also pointed out that manufacturing tolerance and assembly tolerance is inevitable and that some allowance for this needs to be made in the CVP system in the study of prefabricated components.

CONCLUSION

This paper reports on the experiences of using CVP in several major projects in Hong Kong to establish the effects of adopting the new technology and obtaining recommendations for future development. All the participants gave a positive response to CVP approach, with the most useful software functions being considered to be visualisation and communication. It was estimated that the CVP approach improve the collaboration efficiency of the main contractor and sub-contractors by approximately 30 percent, and with a concomitant 30 to 50 percent reduction in meeting time. The most important benefits of CPV in the construction planning stage are the improved the accuracy of process planning and shorter planning time. The most important benefits in the construction implement stage are in instructing fieldwork and reducing rework. Although project teams are hesitant to attribute CVP use directly to any specific time savings, it was acknowledged that the CVP approach decreases the workload of project planners. Suggestions for further development of the CVP approach include incorporation of automatic scheduling and advanced assembly study.

It is interesting to note that our results concur with and reinforce the VDC survey conducted by Gilligan and Kunz (2007). Specifically, it has been identified that the construction industry has placed significant attention to developing digital design and construction capabilities in all stages of design and construction processes. The most important benefit of using digital design and construction is the reduced effort in preparing construction documents, and the ability to coordinate design and construction work closely enough to bring meaningful reductions in the number of personnel and materials on site.

Whilst the research, development and implementation of CVP is relatively new in the construction industry, it is clear from the applications and feedback to date that the approach provides considerable added value to the organisation and management of construction projects, especially those with a high degree of repetitive elements and potential for prefabrication. The key to its further success lies in the increased use of automation, probably through the extended application of AI. Being based on the BIM, it would seem the BIM would benefit from increased automation too, as it currently absorbs a great deal of time for preparation in advance of the CVP itself.

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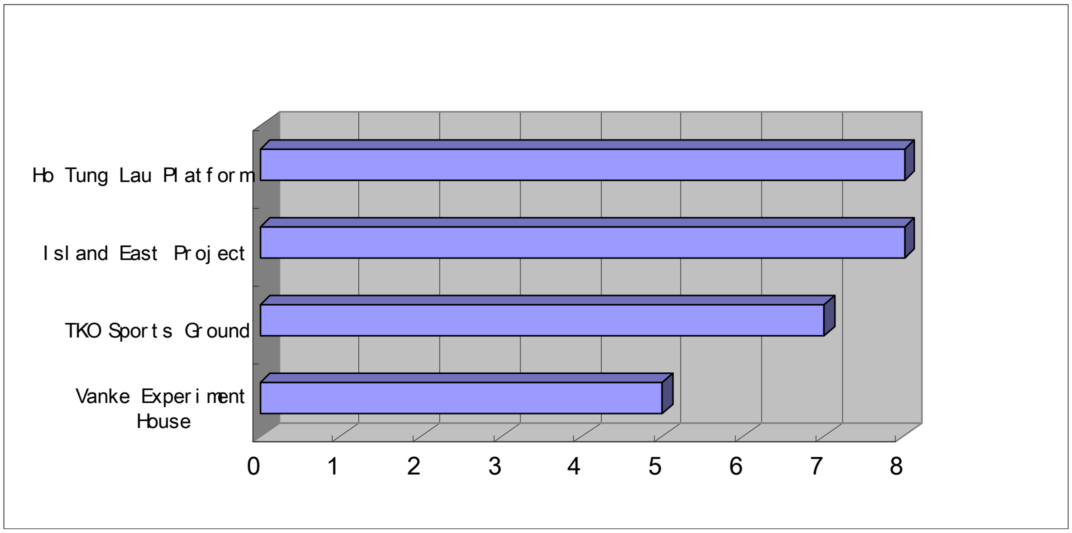

Figure 1: Distribution of respondents

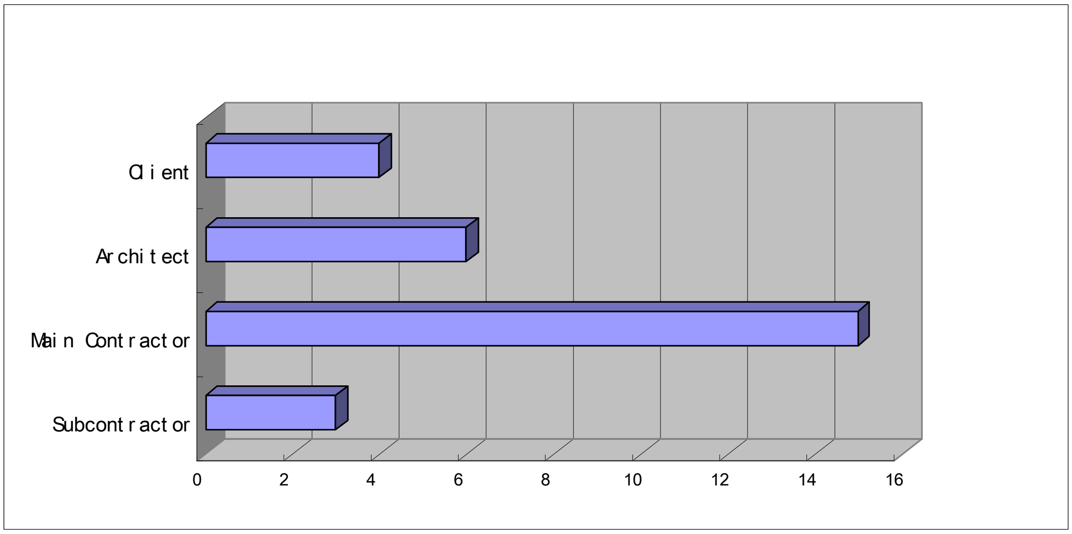

Figure 2: Number of respondents specialising in the various roles and services

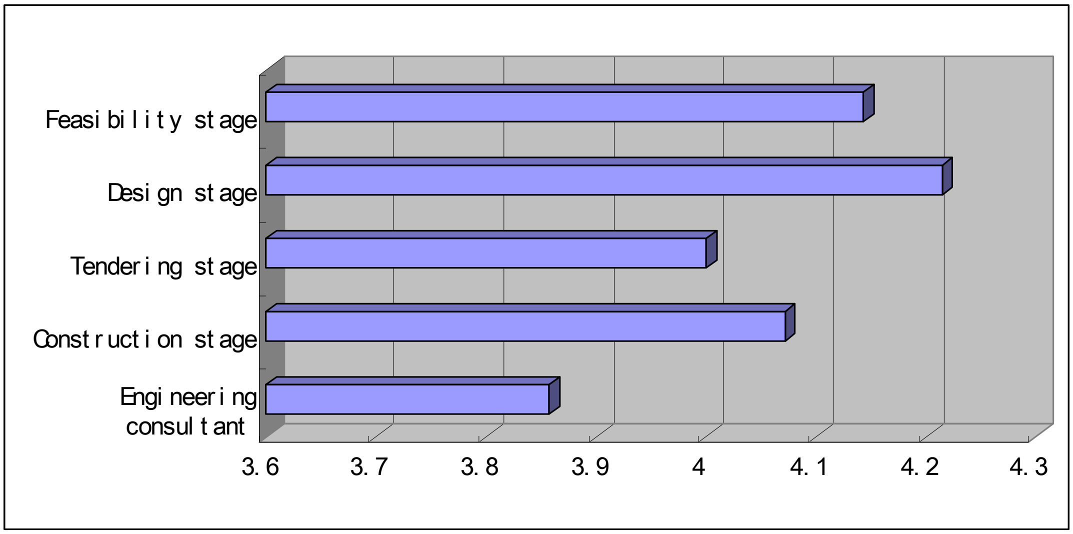

Figure 3: Overall effectiveness of virtual prototyping for different stages

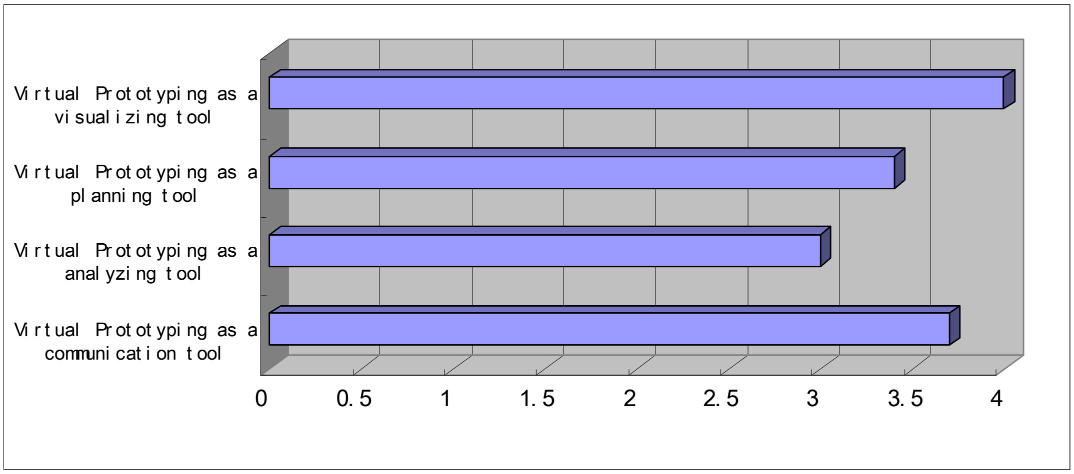

Figure 4: Overall effectiveness of virtual prototyping for different functions

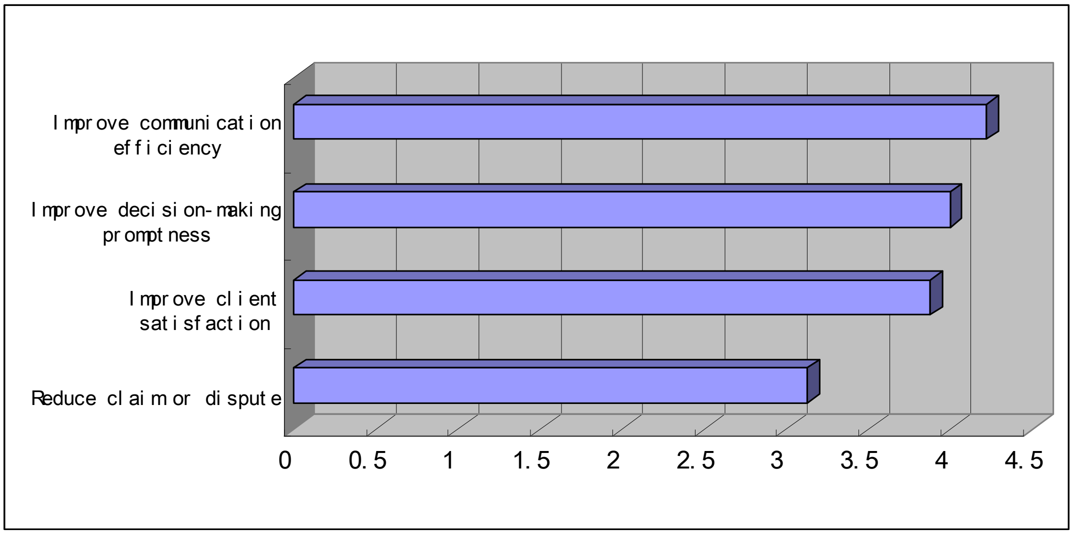

Figure 5: Improvement of communication between different participants

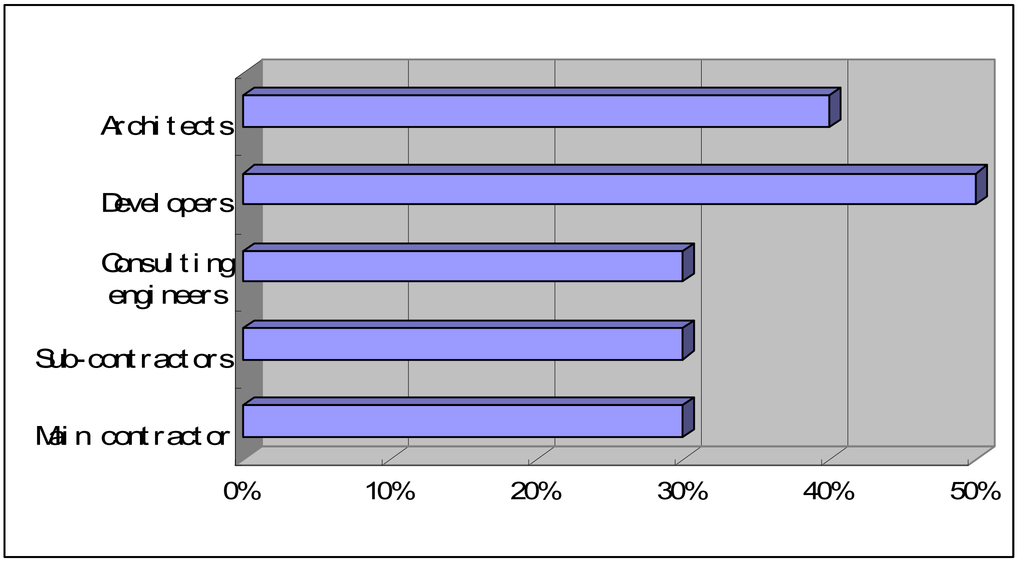

Figure 6: Percentage improvement of communication effectiveness

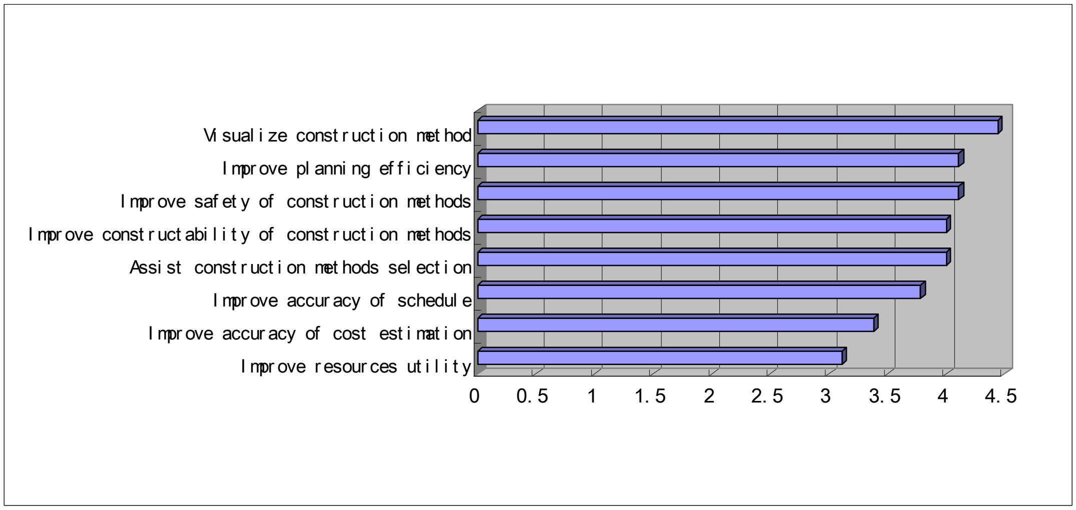

Figure 7: Improvement of the construction planning process

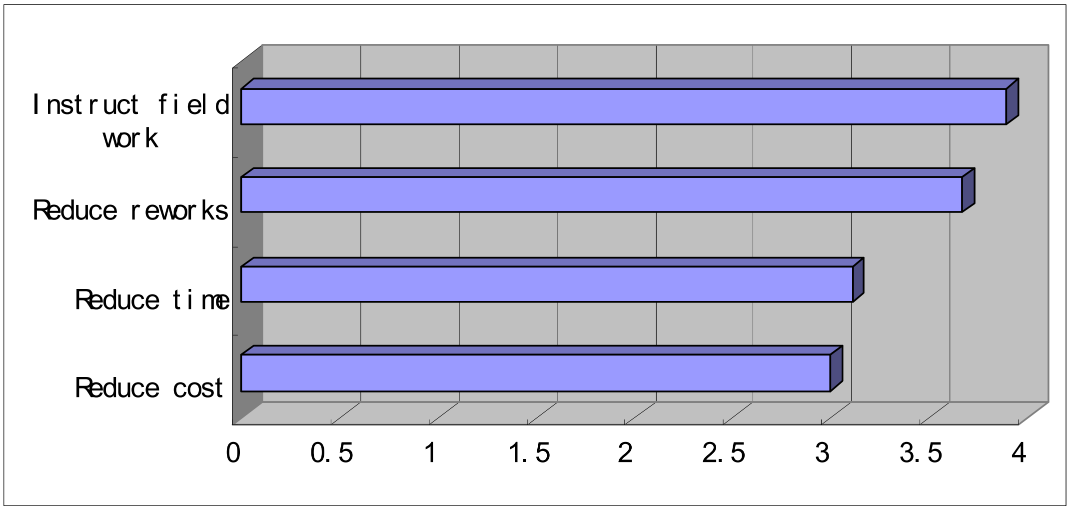

Figure 8: Improvement of construction implement

Table 1: Main risks and CVP tasks in the real projects

Project	Delivery methods	Main risks	CVP task
Kwai Chung Public Housing Project	Design-bid-build	The high ratios of precast elements in this project will change the traditional construction sequence. The contractor needed to verify the new construction sequence to fit for a six day floor cycle.	Simulate and optimise the six-day floor cycle construction
Ho Tung Lau Development Project	Design-bid-build	The confined site of works is covered by live track and high voltage overhead cables, portal frames and many other railway facilities.	Simulate and verify the different construction methods.
Sha Tin Housing Project	Design-bid-build	The constraint site forced the contractor to use one set of wall panel for two construction buildings. The contractor needed to verify the new construction sequence to fit for a six day floor cycle.	Simulate and verify the site layout and four-day floor cycle construction.
Island East Project	Design-bid-build	Tight construction schedule and high-risk erection of outrigger steel members.	Simulate the four-day floor cycle and the outrigger construction sequencing.
HKCC	Design-bid-build	The constraint site forced the contractor to change the in-stu columns and beams into the precast elements. The contractor needed to verify the design and new construction sequence to fit for a four day floor cycle.	Check the collisions among reinforcement and simulate the four-day floor cycle construction
TKO Sports Ground	Design- build	Design and build project. Potential collisions between underground pile and pipes. High-risk erection for huge V-column and steel roof trussed.	Check the collisions and simulate the erection sequencing.
Vanke Experiment House	Design-bid-build	A new precast system was tested. The developer needed to verify the precast elements' design and the new construction sequence to fit for a five day floor cycle.	Check the design errors and test the erection sequencing.

Table 2: Served stages and involved participants in the chosen projects

Project	Served stages	Involved participants
Ho Tung Lau Development Project	tendering stage, construction stage	Client, Architect, General Contractor, Subcontractor
Island East Project	design stage, tendering stage, construction stage	Client, Architect, General Contractor, Subcontractor
TKO Sports Ground	design stage, construction stage, consult engineering stage	Client, Architect, General Contractor, Subcontractor
Vanke Experiment House	design stage, feasibility stage, construction stage	Client, Architect, General Contractor, Subcontractor