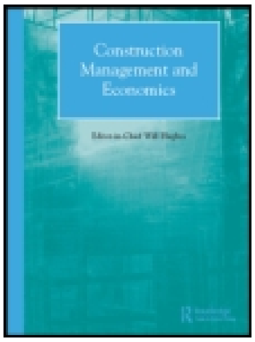

Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

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To cite this article: Heng Li , H.L. Guo , Martin Skitmore , Ting Huang , K.Y.N. Chan & Greg Chan (2011) Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong, Construction Management and Economics, 29:3, 233-245, DOI: 10.1080/01446193.2010.545994

To link to this article: https://doi.org/10.1080/01446193.2010.545994

Published online: 09 Mar 2011.

Construction Management and Economics (March 2011) **29**, 233–245

Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong

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Received 3 March 2010; accepted 4 December 2010

Prefabricated construction is regarded by many as an effective and efficient approach to improving construction processes and productivity, ensuring construction quality and reducing time and cost in the construction industry. However, many problems occur with this approach in practice, including higher risk levels and cost or time overruns. In order to solve such problems, it is proposed that the IKEA model of the manufacturing industry and VP technology are introduced into a prefabricated construction process. The concept of the IKEA model is identified in detail and VP technology is briefly introduced. In conjunction with VP technology, the applications of the IKEA model are presented in detail, i.e. design optimization, production optimization and installation optimization. Furthermore, through a case study of a prefabricated hotel project in Hong Kong, it is shown that the VP-based IKEA model can improve the efficiency and safety of prefabricated construction as well as reducing cost and time.

Keywords: Prefabricated construction, IKEA model, Virtual Prototyping, design optimization, construction optimization.

Introduction

Prefabricated construction has received a great deal of attention from construction industries in many countries over the years. This interest can be mainly attributed to the perceived advantages involved, such as time and cost savings (Warszawski, 1990, 1999; Ting, 1997; Cheung *et al.*, 2002; Gibb and Isack, 2003; Chiang *et al.*, 2005), improved quality (Soubra *et al.*, 1993; Cheung *et al.*, 2002; Korkmaz and Tankut, 2005; Goodier and Gibb, 2007), higher safety standards (Elliott, 2002; Tam *et al.*, 2006) and resource levelling (Leu and Hwang, 2002). These have helped to improve the efficiency and productivity of the construction industry (Chan and Poh, 2000; Chan and Hu, 2001; Chiang *et al.*, 2005). For example, in the United Kingdom, precast concrete construction has been extensively developed since the 1950s to satisfy the high demand for housing following widespread destruction during World War II (Finnimore, 1989). In another case, Singapore's Housing Development Board (HDB) introduced precast concrete technology into Singapore in the 1980s in order to meet its Fifth Building Programme target of checking construction costs, reducing labour costs and improving productivity and quality of workmanship (Wong and Yeh, 1985). In the early 1980s, Hong Kong began to apply precast or prefabrication techniques to public housing (Cheung *et al.*, 2002). This progressed rapidly throughout the decade due to wage increases and a shortage of labour, making conventional construction relatively more expensive.

Despite the successes, the use of precast concrete in the construction industry has resulted in some problems (Wong and Yeh, 1985; Gibb, 2001). These include design problems, production problems, transportation problems, supply chain problems, installation process problems (lack of experience in prefabricated construction), etc. (Blismas *et al.*, 2005). For example, prefabricated components are usually designed, produced and assembled on different sites by various parties, and design errors are often found during instal-

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Construction Management and Economics
ISSN 0144-6193 print/ISSN 1466-433X online © 2011 Taylor & Francis
http://www.informaworld.com
DOI: 10.1080/01446193.2010.545994

lation. After producing prefabricated components (especially precast concrete components), it is almost impossible to modify them, leading to rework, time delays and cost overruns in the event of mistakes. Safety can also be a serious problem when installing prefabricated components. Some precast and prefabricated components are bulky and heavy, leading to difficult and hazardous installation. If the installation programme or sequence is not very clear or realistic, workers cannot generally understand it very well. When the components are installed, accidents are therefore more likely to occur, especially collisions with other components and occasionally even with workers! Unfortunately, such problems are not yet able to be minimized through the introduction of new safety technologies and are currently avoided through the employment of skilled workers and careful monitoring of various critical points. Moreover, more management personnel need to be employed to solve these problems—leading to high management costs.

Research has been conducted in order to solve these problems. Most focus on the optimization of precast production scheduling, e.g. constraint programming-based production scheduling (Chan and Hu, 2002), genetic algorithm-based production scheduling (Chan and Hu, 2001; Leu and Hwang, 2002; Castilho *et al.*, 2007), and production planning and control (Warszawski, 1982), which provide some efficient methods for optimizing production time and cost. Others concentrate on the supply chain of precast components, for example the formalization of information flow for the precast concrete supply chain (Ergen and Akinci, 2008), just-in-time management of precast concrete (Low and Choong, 2001), and the planning of industrial plants (Warszawski, 1972). These researches, to some extent, provide alternatives to solving supply chain problems, but few place emphasis on the issues of design, transportation and installation of precast components. Although BIM (building information modelling) or 4D (four dimensions) technology has been introduced into the construction industry to attempt to solve these problems, achievements are seldom made since BIM and 4D mainly focus on the design of buildings. Therefore, the unavoidable research question is concerned with how these problems can be solved effectively and efficiently. This research focuses on this challenging question and proposes an alternative solution to the problems involved, i.e. to introduce IKEA's manufacturing method (referred to in this paper as the 'IKEA model') and Virtual Prototyping (VP) technology to prefabricated construction.

The aim is to minimize prefabricated construction costs (i.e. rework cost, management cost) and time, and improve construction safety and quality by applying the IKEA model and VP technology to the project delivery process. In the following sections, the considerations made for selecting an appropriate research method are discussed, the research framework and research methods are presented, and the approach for applying the IKEA model to prefabricated construction work is described. A real-life prefabrication project using the IKEA model in Hong Kong is presented to demonstrate the method's feasibility and effectiveness for use in prefabricated construction work.

Considerations for selecting the research method

Selection of the IKEA model

The characteristics of prefabricated construction were mainly taken into consideration when selecting the IKEA model. The prefabricated construction idea originates from the manufacturing industry, with buildings expected to be built in the same way as assembling a car or a piece of flat-packed furniture. To a great extent, the characteristics of prefabricated construction are similar to those of production in the manufacturing industry. However, the efficiency of prefabricated construction is very different from that of manufacturing production. The manufacturing industry has a very effective design-production management method, while prefabricated construction does not yet have such an efficient method. Therefore, the research endeavours to apply the design-production management method of the manufacturing industry to prefabricated construction in anticipation of solving its associated problems.

The production of IKEA furniture provides a typical example of the method. The IKEA Group has obtained great success from its manufacturing method—the most important aspect being a reduction in the total cost for each customer who buys IKEA products (Barthelemy, 2006). During the process of assembling a piece of IKEA furniture, for example, there are no design errors or constructability problems as the design is checked in a 3D environment and the assembly process is guided by 3D easy-to-read instructions (Mather, 1992), thus avoiding any rework costs. Moreover, as the assembler is provided with detailed step-by-step instructions, there is no need for any additional management personnel to supervise/manage the assembly process. Therefore, management costs are also avoided. As the world's largest (and arguably most successful) furniture retailer, the IKEA Group and its methods have been studied by many researchers from several perspectives and its integrated logistics system (Klevas, 2005), unique strategies (Barthelemy, 2006) and management system (Weisbord

Table 1 Main similarities between precast building and IKEA furniture

Item	Component	Production means	Production site	Material and component supplier	Assembly
IKEA furniture	Prefabricated	Standardized production line	Off site	Over one	On site
Precast building	Precast or prefabricated	Customized production line	Off site (usually) or on site	Over one	On site

and Jandoff, 2005) have inspired other industry sectors to achieve greater efficiency.

The prefabricated construction process also has many similarities with the production process of IKEA furniture (Table 1). Whether IKEA furniture or prefabricated buildings, all or most of the components are prefabricated by offsite production lines. These components are transported to sites and then assembled or installed. Of course, this similarity suggests that IKEA's design-production management method has the potential to improve prefabricated construction processes.

Selection of VP technology

Although the prefabricated construction process is similar to the production process of IKEA furniture, prefabricated buildings have their own unique characteristics that are very different from those of furniture. First, the prefabricated construction process is often bespoke and irreversible and the production of components cannot easily be repeated. An appropriate design/construction approach is needed. After the building is finished, it is difficult to completely apply its design and construction method to other projects. For prefabricated construction to be similar to the production of IKEA furniture, it is necessary to find an appropriate design/construction method before actual construction commences. This involves testing different design/construction methods and, without a virtual environment, also attracts a high cost. VP technology provides such an environment for designers/builders to test and compare different design/construction methods.

Secondly, prefabricated construction is fragmented and involves multi-parties. For a prefabricated building, both design and construction need multi-party collaboration. As is well known, however, such collaboration is not effective and efficient and design errors and construction problems frequently occur in practice. VP technology, on the other hand, provides an effective and efficient collaboration and communication platform (Huang *et al.*, 2007; Li *et al.*, 2008).

Thirdly, the components of prefabricated buildings, e.g. precast façade, precast slab, etc., are usually larger and heavier than those of furniture and thus accidents easily occur during the transportation and installation process. Owing to the repeatability of furniture production, the same type of furniture can be easily produced and assembled using the same methods. Furthermore, small furniture elements make the process easier than for prefabricated building. This reduces many safety problems. However, the large size of prefabricated construction components makes their transportation and installation riskier. Detailed and clear instructions for transportation and installation are needed. To save time and cost, transportation and installation trials need to be conducted in advance in a virtual environment.

Research framework

Based upon the two methods described above, the framework of the research is presented in Figure 1.

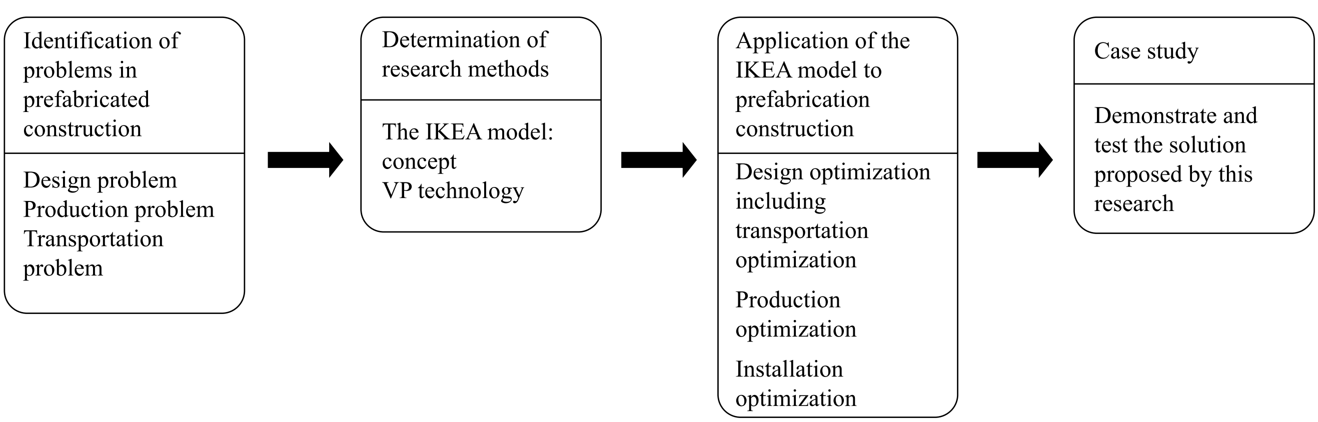

Figure 1 The framework of the research

The IKEA model and VP technology

The IKEA model

IKEA is a globally recognized brand of home furnishings, with a vision to 'offer a wide range of well-designed, functional home furnishing products at prices so low that as many people as possible will be able to afford them' (www.ikea.com). The purpose of the IKEA model is to fulfil this vision. Figure 2 provides a schematic view of the philosophy and process involved, showing that time and cost are saved in each of the four phases of design, production, transportation and assembly.

Design

With regard to *design for manufacturing* (DFM) and *design for logistics* (DFL), the designer's work is to carry out the design of furniture and identify integrated ways of making production and transportation feasible (Mather, 1992) and uncomplicated. With this system, possible design collisions or errors are found and removed in advance. At the same time the production sequence is also identified. As a result, the design is more appropriate, thus increasing the efficiency of production and transportation. This reduces rework and transportation costs and saves production and transportation time.

Production

In addition to the identification of a clear production sequence from the design phase, a wide collaborative suppliers' relationship helps IKEA attain low-cost material globally and thus reduce raw material costs. Multi-region production lines, on the other hand, make low labour costs possible and close-to-store production sites. This not only enables a low-cost production average but also reduces the cost of transporting raw materials from source to factory, and products from the factory to IKEA stores.

Assembly

After the design and manufacture is completed, a 3D assembly instruction for each kind of furniture is offered by the IKEA Group and an attractive catalogue of products is also provided. The 3D assembly instruction is so clear as to be understandable by almost all customers. Customers are therefore able to use the catalogue to find the furniture they want, collect their components and assemble them by themselves by referring to the 3D assembly instructions.

The functions of the IKEA model are summarized as follows: *design optimization* (DFM and DFL), *production optimization* and *assembly optimization*. Note that the design optimization involves design for production and transportation.

Virtual Prototyping technology

Virtual Prototyping (VP) is a computer-aided design process concerned with the construction of digital product models (virtual prototypes) and realistic graphical simulations. These address the broad issues of physical layout, operational concept, functional specifications, and dynamic analysis under various operating environments (Pratt, 1995; Xiang *et al.*, 2004; Shen *et al.*, 2005). VP technology arises from the manufacturing industry. Dedicated VP technology has been extensively and successfully applied to the automobile and aerospace fields (Choi and Chan, 2004). VP technology has also been applied in the construction industry in the form of construction process simulation, with the Construction Virtual Prototyping Laboratory (CVPL) of The Hong Kong Polytechnic University (see www.cvptl.com for more information) being a prominent leader in the field

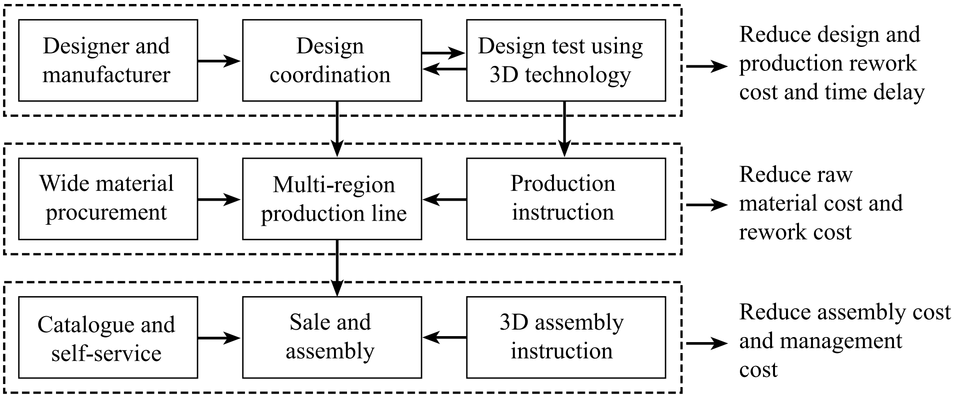

Figure 2 The IKEA model

(Huang *et al.*, 2007). It has been identified as having considerable potential for the design of structural steelwork (Slaughter and Eraso, 1997), site planning (Tawfik and Fernando, 2001) and construction project management in general (e.g. Hobbs and Dawood, 1999; Sarshar Christianssen, 2004; Riese, 2006).

The VP technology adopted in this study comprises computer software developed by the CVPL. Through customizing two software systems, CATIA V5 and DELMIA V5 of the DASSAULT SYSTEMES, and adding construction-specific functions, the VP technology provides a digital mock-up of construction processes and activities. It extends current technologies, such as 4D CAD, which just represent construction progress based on 3D models of a building project and construction schedule, by providing the capacity to simulate not only the three physical dimensions and time, but all important dimensions of a construction project such as safety, logistics, resources and productivity (i.e. nD). nD modelling is defined as an extension of building information modelling (BIM), which focuses on the establishment and application of a 3D model integrating with useful information related to the life cycle of a building project (from design and construction, to maintenance and demolition). BIM can provide useful information to support various analyses relating to a building project, for example design analysis, structural analysis, solar analysis, energy analysis, environmental analysis, etc.; while to some extent, VP (or nD) integrates the functions of BIM by which foundational models and relevant information are provided for VP to simulate and optimize construction processes.

nD has attracted some research. For example, Aouad *et al.* (2005) and Marshall-Ponting and Aouad (2005) have examined nD modelling applications, including crime, accessibility, acoustics and environmental impact and propose its use as a communication platform for designers and contractors. An nD prototype tool was initially developed to demonstrate its application for the collaboration of designers. However, although this approach mainly focuses on design it is also useful in building construction. The VP technology employed here has been successfully used in the whole life-cycle management of many real-life building projects, not only for design but for construction (Li *et al.*, 2008; Guo *et al.*, 2010) and has been shown to improve the whole process of building projects.

Application of the VP-based IKEA model to prefabricated construction work

The IKEA model functions—*design optimization* (DFM and DFL), *production optimization* and *assembly (installation) optimization*—in prefabricated construction are proposed to improve the management of prefabricated construction work. Owing to the differences between prefabricated construction projects and IKEA furniture, the application of some functions of the IKEA model need to be modified for the special characteristics of prefabricated construction.

Design optimization

The design of a building includes its architecture, structure and building services (BS), each carried out by different parties and assembled for completion. Since different participants seldom communicate with each other except for formal exchanges of main shop drawings, some collisions inevitably occur when the components are installed. After production, prefabricated components generally cannot be modified. Therefore, if design errors occur, related components must be reproduced, dramatically adding to cost and time. Also prefabrication design has a direct influence on production, with unrealistic or inefficient designs often making it difficult to produce prefabricated components. In addition, rework transportation costs are incurred due to the usual offsite production of prefabricated components and the need for them to be transported to the construction site. For example, construction projects in Hong Kong are often located in regions where transportation infrastructure is minimal. Likewise, major problems can occur if the entrance to the construction site is narrow or limited in height—restricting the entry of prefabricated components. As rework costs resulting from design problems amount to around to 12% of total cost (Love *et al.*, 1999), it is clear that these problems should be solved during the design phase and not passed over into the construction process, creating cost increases and time delays.

The idea of 'design coordination' (DFM and DFL) in the IKEA model is employed to enhance prefabrication design, production, transportation and installation. VP technology is adopted to provide a collaborative platform for all participants and interest groups, including architects, structural engineers, BS engineers, owners and contractors. All these participants are able to use VP technology to conduct and update the design in real time in a virtual 3D main model (termed here a digital mock-up) (see Figure 3). This digital mock-up is a parameterized 3D model which consists of not only the geometries of all parts of a building but their formulated dimensions. As an example Figure 4 shows the length l of a semi-precast slab is parameterized with the distance w between two precast façades and the distance c between each façade and the slab. This makes it possible to modify any part

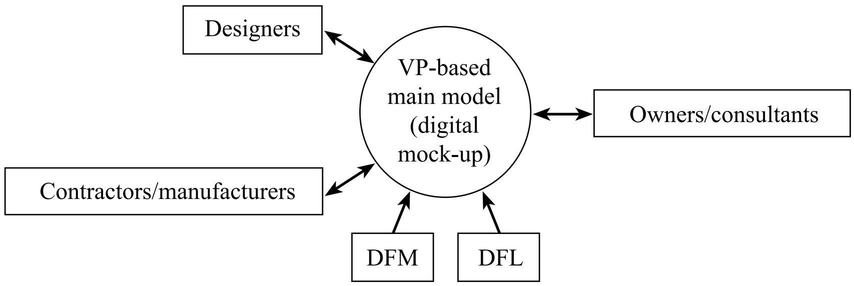

Figure 3 Design coordination for prefabricated construction

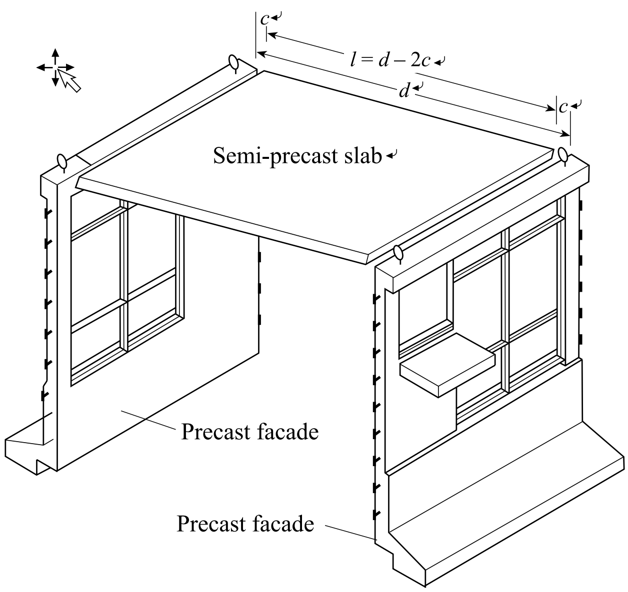

Figure 4 A parameterized 3D model

of a building and reduces errors caused by this modification since the dimensions of related parts will be automatically updated. The vivid nature of the 3D main model also makes it easy for each party to identify problems existing in the design, issues extending to design errors, collisions, constructability, etc., in advance through the use of the design error auto-check of the VP technology. Following problem identification, discussion can follow and solutions proposed via the real-time communication provided by the VP technology. This means rework is reduced and relevant cost and time are saved during design, production and installation. Additionally this facilitated communication saves both communication time and cost and ensures the quality of the prefabricated component to all the parties involved.

DFL is also conducted at the design coordination stage to reduce transportation problems. Because of the large volume or atypical shapes of some prefabricated components, the feasibility of their transportation is another issue for designers. On the one hand, the decomposition of prefabricated components should facilitate transportation. Some components, such as columns or beams, can be easily transported in batches, which reduces transportation cost and time. On the other hand, the design of prefabricated components should take into account the location and layout of the construction site in order to conveniently transport the components to the site and place and install the components. This is difficult to deal with using traditional design methods but easily handled by VP technology. In the virtual environment provided by VP technology, the feasibility of transporting prefabricated components can be tested in advance. This applies not only for transportation vehicles but for the location and space layout of construction sites to determine the appropriate size of prefabricated components. Prefabricated components can be put into vehicles in a virtual environment to check the feasibility of the dimensions and shapes of the components for transportation. The prefabricated components can also be transported to the construction site in the virtual environment to test whether or not the entrance of the site is wide or high enough for the components' entry and that the space layout is suitable. All parties can identify transportation problems and solve them as soon as possible by using the virtual platform ahead of the real construction process to ensure efficient construction progress.

Using the VP-based IKEA model, the process of design coordination optimizes the design process of prefabricated components and improves their constructability and transportation. Note that as VP technology is not yet widely employed in the design of buildings, a third party process modeller (e.g. CVPL) is needed in practice (see Figure 5). The third party works with all the other parties, uses the VP technology to transfer all 2D drawings provided by the different design parties to 3D models, conducts the analysis related to design, and provides suggested improvements. The third party also participates in the production and installation of prefabricated components in the following sections.

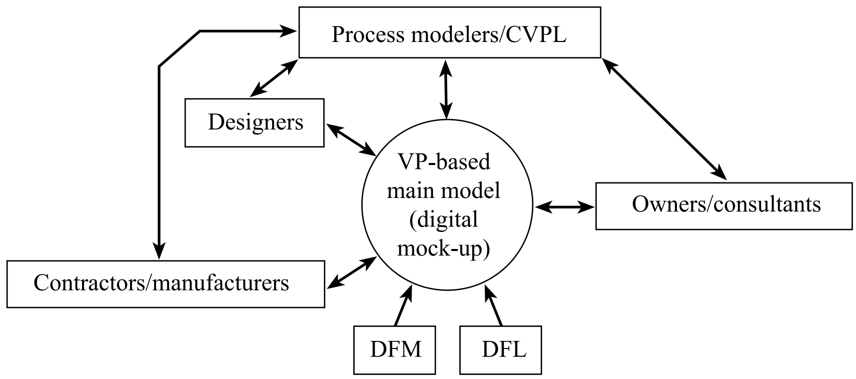

Figure 5 Design coordination for prefabricated construction based on third party

Production optimization

While prefabricated components are produced both on site and off site, all types of production require feasible design decomposition, as unrealistic design affects production ability. This problem was presented and a solution offered in the previous section. In addition to realistic designs, a 3D production instruction is also needed to support a smooth production process. This is because prefabricated components have to be produced and supplied in a timely, logical sequence in order to satisfy the requirements of the construction process. Although most production workers are skilled, it is difficult for them to follow the often complicated requirements of projects, especially in complex project situations, and construction time is often delayed.

A vivid step-by-step 3D production instruction with a production schedule can help improve production efficiency through the use of VP technology. The procedure of producing and using this on a production site is shown in Figure 6. After the master programme for a prefabricated building is sent to the factory, the project manager of the factory develops a production schedule for all kinds of prefabricated components to be used in the building. Foremen then identify complex and/or non-typical prefabricated components and work with the third party process modellers to test and compare different production methods in the virtual environment to find which is the most appropriate. Based on the production schedule and method, 3D production instruction manuals and/or videos are produced by the process modellers. This 3D instruction provides production information, i.e. the time when the prefabricated components need to be manufactured, the method of producing the components, etc., and is used to guide the production of the prefabricated components. This makes the production processes run more smoothly and reduces time in prefabricated construction.

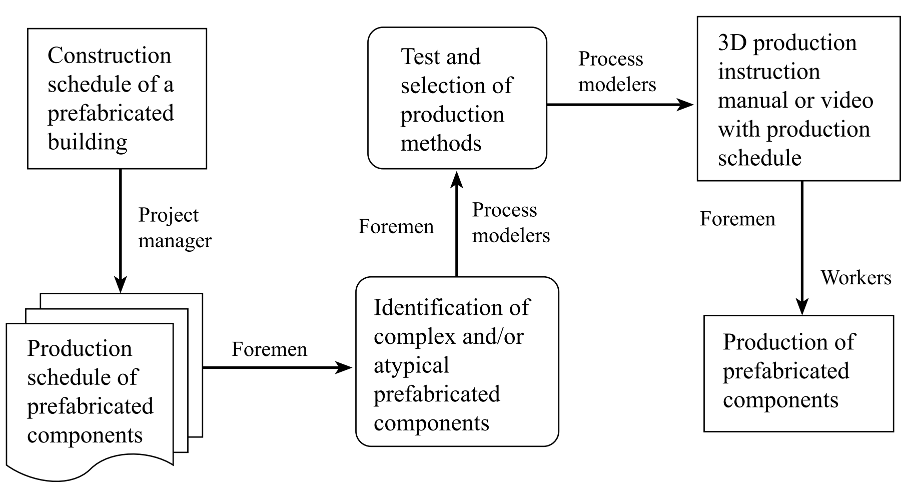

Figure 6 Procedure of producing and using 3D production instruction

The choice of an appropriate location for the component production line is also important and is directly related to production cost and construction time. Several factors need to be taken into account, including the raw material cost, labour cost and transportation cost and time. Since construction sites are distributed in different locations, multi-region production lines are encouraged to reduce whole cost and time. This is not discussed further in this paper.

Installation optimization

Since most prefabricated components are installed in large, complex projects, some of them are very heavy and bulky. Many types of equipment are therefore used for their installation. In order to avoid construction time and cost overrun and maintain quality, a reasonable and clear installation sequence or procedure is needed in the assembly stage. However, at present, the progress of construction projects is often guided only by the application of a Gantt chart, with the installation procedure being predominantly based on the site foreman's experience. Reliance on this is insufficient for most prefabrication projects and usually leads to work delay, collisions among prefabricated components or equipments, and even safety breaches and accidents. Small contractors in particular lack experience in prefabricated construction (Gibb and Isack, 2003; Blismas *et al.*, 2005). Furthermore, many more technicians, foremen and safety officers are needed to manage and support the installation, thus adding management costs of up to 13% of total cost to this stage of the project (Li *et al.*, 2008).

Adoption of a vivid 3D assembly instruction manual and/or video similar to that used for IKEA furniture assembly can show the detailed step-by-step installation procedure of all prefabricated components, including the kind of equipment needed and installation schedule. The procedure for producing and using such a 3D instruction (see Figure 7) is similar to, but more complex than, that for the production of components, since this involves many construction sequences and a variety of equipment. The whole project needs to be broken down into parts, each of which is simulated to find an appropriate installation method. First, the project manager identifies the complex and/or non-typical or typical installation work, and then collaborates with the foremen on the installation methods involved. The foremen test and compare different methods for each installation and further optimize and determine an appropriate method in a virtual environment with the aid of the process modellers. During this, a 3D installation instruction for each part is produced. This allows all workers to understand the installation sequence better than by relying on Gantt charts and experience alone. Workers can easily follow the instructions to install prefabricated components, smoothing holistic installation processes and lowering the risk of accidents. Furthermore, some problems, including collisions, safety and other issues can be checked in the 3D assembly instruction before the real construction commences—allowing management and technicians to combine. This helps optimize the management activities of construction projects and reduce management costs.

The following section provides a case study of a semi-precast building project to demonstrate the process of applying the VP-based IKEA model to

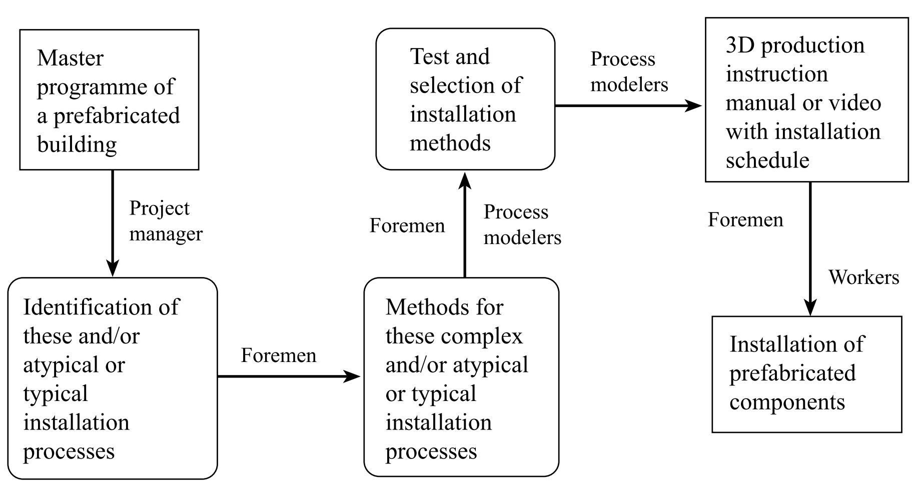

Figure 7 Procedure of producing and using 3D installation instruction

prefabricated construction management and also review its validity.

Case study

The case study concerns a semi-precast construction hotel project in Hong Kong sponsored by the Hong Kong Polytechnic University's CVPL. As the third party, the CVPL's function is to analyse the design and installation of the precast components based on the IKEA model and VP technology. In order to make this case study easily understood, a precast toilet unit in the hotel project is selected as an example. Owing to the onsite precast nature of the project, the case study focuses on the design, production and installation of the precast bathroom unit to illustrate how the VP-based IKEA model can be successfully applied to prefabricated construction, demonstrating both its feasibility and effects. Note that the toilet unit is assembled on the ground prior to installation on an appropriate floor level.

Design optimization

Transferring 2D drawings to 3D model

2D drawings of the toilet (including components such as wall, slab, ceiling, glass partition, building services and temporary support), were gradually transferred by CVPL personnel to a 3D model (i.e. main model) as the design progressed. Figure 8 shows the 3D model and two components (i.e. bathtub and cabinet). At the same time, the participants communicated with each other and discussed any problems arising through the 3D model.

Design error checking

Based on the main model, the design was checked automatically in real time and errors notified to the designers. The design-check process was iterated until no errors remained. Checking rules can be set so as to satisfy the users' own requirements. After the elements needed to be checked are selected, the checking process was conducted based on the rules involved. For the design of the precast toilet, a total of 11 design errors were found, including dimensional discrepancies, incorrect junctions, collisions, etc. (see Table 2). After the design errors were removed, the main model was also updated. This reduced not only the time and cost for the design but that for construction since most of the design problems had been solved before actual construction commenced.

Production feasibility checking

For the design of prefabricated components, the manufacturers checked that components could be conveniently produced and stored. For the precast toilet, the production feasibility, including its formwork system, was tested in advance in the virtual environment.

Production optimization

The onsite production of precast toilet components meant that optimization at this stage focused solely on production processes. A step-by-step 3D production instruction was developed to instruct the holistic production process of the units. This indicates when and how to concrete precast toilets (erecting formwork, configuring drainage, concreting, etc.), assemble the toilets and other prefabricated bathroom components

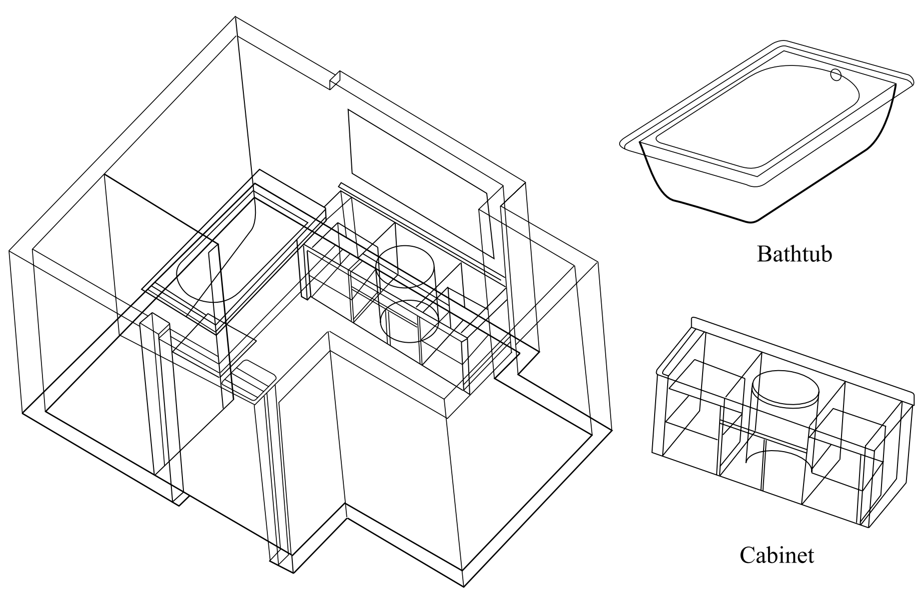

Figure 8 3D parameterized model of precast concrete toilet

Table 2 Types of design errors in the precast toilet

No.	Items	Type of errors	Value
1	Wall cabinet	Dimensional discrepancy	10.24mm
2	Drainpipes	Incorrect junction	16.14mm
3	Bathtub Drainpipe	Collision	12.45mm

(e.g. bathtub, cabinet, glass partition). This makes the whole production stage quite smooth. The production stage of the toilet components is thus achieved while effectively controlling cost and time.

Installation optimization

The physical installation of precast concrete toilets was a major challenge for the project as the toilet is a complete concrete unit comprising bathtub, partition, cabinet and drainage and as a whole is very heavy and large. With conventional installation procedures, collisions or accidents easily occur in manoeuvring the sheer bulk involved. After hoisting a toilet unit to the desired floor, it is particularly difficult to move to its specific final resting place. A further challenge is to connect the drainage with that of other toilets above and below. The slab under the toilet must be prepared in advance in order to provide working space for the connection between drainage systems and with the exact location and size of holes provided to avoid cost and time delays.

Before the physical installation of precast toilets commenced, the installation sequence was repeatedly tested in a virtual environment provided by VP technology until an appropriate installation procedure was achieved. Concurrently, a detailed step-by-step 3D installation instruction was built. This is briefly presented as follows: (1) hoist toilet to a design floor; (2) move it via a rolling footing; (3) move it to the design location; (4) remove rolling/installing footing; (5) connect drainage; and (6) fill holes for drainage. With the instruction, onsite workers were first trained and then carried out the installation work. This made the construction process smooth, ensured safety and reduced installation time and rework costs. According to the project manager, the time saved was up to 15%—estimated through comparing the time really used with the planned time.

In addition, safety and technical problems were solved in advance, the need for additional safety officers and technicians was greatly reduced, thus reducing the management cost of the project. For example, the foreman and assistant foreman roles were combined into a single general foreman. As a result, the amount of management personnel on site was reduced by up to 30%.

Discussion

The case study shows that the design optimization, production optimization and installation optimization of prefabricated components can be conducted with the aid of VP technology and the processes of design, production and installation of prefabricated components have been improved. The application of the VP-based IKEA model enables improved design coordination, rapid design progress, ensures productability and constructability of design before real production and construction commence, and provides visual production and construction or installation instructions which not only ensure their feasibility in advance but increase the smoothness of production and construction processes. Therefore rework costs and time is reduced to a great extent in the design, production and construction stages. Through the practice of using the VP-based IKEA model, this also proved to be the case in other several building projects. After every project is completed, a questionnaire survey is conducted to evaluate the performance of the VP-based IKEA model. Table 3 summarizes the time and cost savings made in applying the VP-based IKEA model to the construction stage. Note that these data are provided by project managers and may not always be accurate due to estimation difficulties. As Table 3 shows, the construction cost and time is reduced by approximately 10% and 5–17% respectively. Although the data are mainly concerned with the construction stage, they do provide at least an indication of the effects of using the VP-based IKEA model.

Some lessons have also been learnt from this case study. During the course of design optimization, design coordination is an important and difficult task. Design coordination is related to the productability and constructability of prefabricated components. Designers commonly focus on the function and appearance of a component and care little about its production or installation, while producers or builders mainly pay attention to the production and installation processes involved. In order to ensure

Table 3 Cost and time savings in the construction phases of real-life projects in Hong Kong

Project name	Cost saving	Time saving
Kwai Chung Public Housing	Unclear	About 17%
Hotel	Unclear	About 15%
HKCC	Unclear	Unclear
Ho Tung Lau	About 12%	About 5%
TKO Sports Stadium	About 2.5 million HKD	About 1 month

productability and constructability, a sufficient level of design coordination is needed between designers, producers and builders during the design stage. When a component is designed, it is passed on to the producers and builders in time to evaluate whether this design is suitable for future production and installation. If it is available then the production and installation processes will be considered; or relevant responses will be sent to the designers in time for revisions to take place. By repeating this process, a feasible design option can be rapidly achieved. Therefore, the efficient implementation of design coordination has an important influence on the design's feasibility.

Although the concept of 'design coordination' has been developed for many years, it is not yet accepted by the construction industry. Almost all parties in the hotel project did not understand the concept well and many hope that their traditional working methods will not be changed. They have formed a habit of independently implementing designs and then passing them on to the next stage for production or construction. Design modifications are only made when there are design problems. They completely resist changing their working ways through the introduction of design coordination. Additionally, a VP technology which assists design coordination has also not been used widely to date. Almost all the practitioners in the hotel project had no knowledge of VP technology prior to working with the VP-based IKEA model. All of these factors contributed to the difficulties involved in the design coordination for the hotel project. Therefore, before conducting design coordination, it is necessary for all parties to undergo necessary training in design coordination and VP technology. Furthermore, for a successful project, owners and main contractors need to pay attention to design coordination. Fortunately, the owner and the main contractor in the case study provided great support, and VP technology also provided a visualized design environment which made design coordination easier.

Another difficult problem concerns the use of the 3D installation instructions. Through repeated trials and tests, a smooth and feasible 3D construction instruction can be achieved. A video illustrating the instruction can be provided for the main contractor and subcontractors to train workers and guide the real construction work. However, this video does not always display enough of the detailed construction processes. This is because not enough detailed information can be provided or the project manager thinks the visual instruction is sufficiently detailed at the time of its preparation. As a result, workers do not always understand the instruction very well. In order to solve this problem, the CVPL personnel also need to participate in the training of the workers and provide some support with the instruction. When necessary, the CVPL personnel also assist project managers or foremen in guiding construction on site. In order to achieve a better performance in using 3D construction instructions, it is suggested that the project manager or foreman could make an appropriate evaluation of requirements for use in guiding the production of an appropriately detailed construction instruction.

Additionally, it is unnecessary to produce 3D installation instructions for all construction sequences of a whole project. Building projects, including the hotel project, consist of typical construction sequences and non-typical construction sequences. The construction sequences for different typical floors in a building are almost the same and therefore only an appropriate typical construction sequence and relevant instruction are needed. The sequences for non-typical floors are different however, and thus need more appropriate instructions. This not only meets the requirements of the project, but reduces time wasted in simulating all construction sequences and producing their visual instructions. Therefore, before a construction sequence is simulated and optimized and its 3D instruction is produced, it needs to be identified and classified as one of these two kinds. Only one 3D instruction for each kind of sequence is necessary, as illustrated in the installation of the precast toilet in the case study.

Conclusions

The IKEA model and VP technology can be applied to prefabricated construction to solve such major problems as time and cost overruns. Through the application to a Hong Kong hotel project, it is demonstrated that the VP-based IKEA model can improve the efficiency of prefabricated construction through optimizing design, production and installation processes. As a result, the time and cost of design, production and installation can be saved and construction safety enhanced. Some lessons were also learnt that will benefit future research and practice of prefabricated construction. Although the case study project is an onsite prefabricated hotel, the experiences that occurred as a non-typical building are still worthy of consideration.

Prefabricated construction is being strongly encouraged by many governments, especially by the Hong Kong government. The research indicates that the IKEA model has the potential to be of central importance to the future productivity of the construction industry, especially where prefabrication technology is involved. This adds impetus to the application of prefabricated construction at least in Hong Kong.

Additionally, although the logistics system is an important aspect of prefabricated construction, it is immature at present. From our experiences to date, the IKEA logistics system clearly offers some improvement and is worthy of being a major focus for future research.

Acknowledgements

The research is supported by a research grant from the Ministry of Science and Technology of the PRC (Grant No. 2007BAF23B04). The authors acknowledge China Overseas Holdings Limited, Gammon Construction Limited and other participants for their support during implementation of the proposed model and data collection.

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