The Hong Kong Polytechnic University

Department of Building and Real Estate

The Use of Virtual Reality for Visualizing Construction Safety Management Process

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

_______________________________ (Signed)

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ABSTRACT

Construction is a hazardous industry. In Hong Kong, construction has been shown to be responsible for 76 percent of all fatal accidents in the region, a figure which is about ten times greater than that of any other industry. Construction accidents have a significant impact on the economic returns of the industry, and world-wide, a loss of between 7.9 and 15% of the total costs of new non-residential projects has been found to occur. Compensation costs awarded to construction workers can account for up to 3.5% of the total project costs (Coble and Hinze, 2000). Due to the importance of maintaining good site safety, an increasing number of researchers and practitioners have investigated the causes of the above situation and have attempted to find effective methods and tools for managing safety on construction sites. The objectives of this research study are to find and propose alternative approaches for improving the safety performance on construction site. The overall aim is thus to improve the current safety performance by the use of these alternative approaches.

In this research study, a literature review was conducted to examine, 1. the current practice of safety management in Hong Kong and 2. the safety and health system,

suggested by Occupational Safety and Health Administration (OSHA). From the review, weaknesses of these systems and causes of construction accidents are identified, discussed and compared. Complementing these findings are the results of an investigation into the availability and performance of different innovative approaches for safety management, such as the use of advanced information technology as used in other industries, such as the aircraft industry. Reviewed are opportunities for using these technologies in construction industries.

Three new safety management approaches are introduced in this research study, based on a combination of the use of Construction Virtual Prototyping approach and Game Engine approach. The first aims to improve the current hazard identification process by using Virtual Prototyping (VP) skills during early design stage. The method for identifying hazards in virtual basis is briefly introduced. The second aims to improve the current safety training method. This new approach provides a close-to-reality 3D environment for the trainees to practice construction skills without risk. The system allows up to fours trainees to connect and train together. As it is a multi-users platform, the trainees are assigned different roles and are required to cooperate to complete the training. The third aims to provide the users with a 3D assessment platform. The assessment platform introduces not only the use of the 3D format of examination for better illustration of information, but also suggests the use of a better database structure. The assessment platform also resets the basic requirement for working on a construction site. The assessment aims to replace the current certification practice in Hong Kong which only requires the trainees to take a one day training course and to get 12 correct answers out of 20 multiple-choice questions.

The different approaches were tested using case studies conducted on functioning construction projects in Hong Kong. Interviews were arranged to collect opinions, feedback for the purpose of rating the approaches. The collated information was used to evaluate the three approaches.

The results indicate that all three approaches are capable of improving construction safety in various ways. Firstly, the use of hazard identification by VP proved to be useful in identifying construction hazards more effectively than the traditional approach. Secondly, the use of virtual reality (VR) for safety training was successful in improving the performance of the trainees as indicated by the general opinion of those trainees interviewed. Lastly, the use of the proposed assessment method is useful in identifying the weaknesses of the system users.

The value of the new work is as follows: the use of the proposed hazard identification approach improves the construction environment by identifying potential hazard before commencement of work. The proposed training system provides a new training platform and thus improves the safety knowledge of construction workers. The improvement in safety knowledge enhances the workers' reaction to accident and potential hazards and eventually reduces accidents. The proposed assessment approach can verify the construction safety knowledge of the users before they are allowed to work on s ite. The new verification process raises the safety standard knowledge of the users and thus reduces the chances of construction accidents.

PUBLICATIONS ARISING FROM THE PHD STUDY

Refereed Journal Papers

Li, H., Guo, H.L., Skitmore, M., Huang, T., Chan, K.Y.N. and Chan, G. (2011). Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong. *Construction Management and Economics,* 29 (3), 233-245

Huang, T., Li, H., Guo, H.L., Chan, N., Kong, S., Chan, G. and Skitmore, M. (2009). Construction virtual prototyping: a survey of use. *Construction Innovation: Information, Process, Management*, 9 (4), 420-433

Chan, K.C., Li, H. and Skitmore, M. (2012). The use of virtual prototyping for hazard identification in the early design stage. *Construction Innovation: Information, Process, Management*, 12(1), 29-42.

Li, H., Chan, G. and Skitmore, M. (2011). A multi-user virtual safety training system for tower crane dismantling. *Journal of Computing in Civil Engineering*, accepted for publication.

Li, H., Chan, G. and Skitmore, M. (2012). Visualizing safety assessment by integrating the use of game technology. *Automation in Construction*, 22, 498-505.

Referred Conference Papers

Chan, G. (2009). Safety hazard identification by adopting multi-dimensional simulation at early design stage for the construction industry. In: *Proceeding of W099 Confrerence, Working Together: Planning, Designing and Building a Healthy and Safe Cosntruction Industry*, 21-23 October, 2009, Melbourne, Australia.

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CHAPTER 1:INTRODUCTION

1.1 Background of the research

The Construction industry is known to be one of the most hazardous industries in the world (Jannadi and Bu-Khamsin, 2002). In the USA and UK, construction workers are several times more likely to suffer from accidents than workers in other industries (Carter and Smith, 2006). In addition to human physical suffering, economic losses are induced by construction accident. Everett and Frank (1996) concluded that construction accidents have caused total loss of 7.9-15% of the total costs for new non-residential projects. Coble and Hinze (2000) later reiterated that compensation costs from construction workers, due to construction accidents, could account for as much as 3.5% of the total project cost.

Terms related to construction safety is defined before introducing the background of the research in deep and the terms have been defined by The National Safety Council (NSC) as follows. *Safety* is defined as “the control of recognized hazards to attain an acceptable level of risk", a *hazard* is defined as "an unsafe condition or activity that, if left uncontrolled, can contribute to an accident", while *accident* being defined as "an occurrence in sequence of events that produces unintended injury, death, or property damage. Accident refers to the event, not the result of the event.

The industries in Hong Kong with the highest accident rates are manufacturing, catering and construction and of these the construction industry has by far the highest. The accident rate per thousand construction workers is nearly 1.5 times that of catering workers and 4 times that of manufacturing workers in 2007 (Table 1.1). The Hong Kong construction industry has also a far higher fatality rate than that of other industries in the territory, with the number of fatal accidents in that industry representing about 76% of all fatal accidents in Hong Kong in 2007. This is around 10 times more than that of the next highest industry (manufacturing) (Table 1.1).

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
No. of accidents										
Construction Industry	19588	14078	11925	9206	4367	3833	3548	3400	3042	6239
Catering Industry	13011	12549	12621	11914	8527	9410	8902	9294	8876	10149
Manufacturing Industry	6334	5499	5436	4385	2719	2936	2912	2949	2735	3636
Acc. rate / 1000 workers										
Construction Industry	247.9	198.4	149.8	114.6	68.1	60.3	59.9	64.3	60.6	85.2
Catering Industry	73.9	66.9	66.2	61.5	49.6	51.5	47.3	47.2	43.5	54.7
Manufacturing Industry	24	22.2	23.4	20.7	15.7	17.5	17.7	18.4	17.4	18.8
No. of fatalities										
Construction Industry	56	47	29	28	24	25	17	25	16	19
Catering Industry	0	0	2	0	0	0	0	0	0	0
Manufacturing Industry	2	2	3	3	0	2	2	0	6	3
All industries	*68*	*52*	*43*	*34*	*25*	*28*	*24*	*29*	*26*	*25*
Fatality rate/1000 workers										
Construction Industry	0.709	0.663	0.364	0.349	0.328	0.390	0.268	0.422	0.303	0.379
Catering Industry	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Manufacturing Industry	0.008	0.008	0.013	0.014	0.000	0.012	0.012	0.000	0.037	0.019
All industries	*0.102*	*0.080*	*0.066*	*0.053*	*0.042*	*0.051*	*0.043*	*0.053*	*0.047*	*0.045*

Table 1.1: Accident statistics of major industries in Hong Kong (1998-2007)

(Occupational Safety and Health Council, 2007)

The three most common types of accidents which occur in the Hong Kong construction industry are “hitting or being struck by moving objects”, “slipping, tripping or falling on the same level” and “injuries sustained while lifting or carrying objects” – representing 19, 18.3 and 15.3 percent respectively of all the accidents in the industry (Occupational Safety and Health Council 2006). Of these, the average sick-leave induced by the accidents a respective 59, 78 and 98 days. As a result, an estimated 145,000 man-days are lost each year through construction accidents, which is clearly a large amount and costly to all concerned in terms of well-being of employees, reduced income and lost profits for employers. Construction safety is therefore an important issue in Hong Kong and any means of bringing about improvements is likely to be beneficial to the community as a whole.

The recent, advanced technologies and equipment, used in the construction industry has dramatically improved working conditions. As a result, construction accidents are now believed to be due mainly to human failure and organizational factors (Mitropoulos et al 2005). In order to reduce the number of construction accidents, new safety management approaches are required. In the light of this situation, safety officers are now employed to manage construction site safety. This involves two distinct approaches: preventative control and precautionary control. Preventative control aims to eliminate risk by evaluating the risk levels contained in a “method statement” detailing the particular construction activity. Precautionary control is introduced when risk elimination is not possible, the aim being to reduce risk to an acceptable level and provide a reaction plan for use in the event of an accident. Preventative control is comparatively more important than precautionary control as it is usually less risky for construction safety management. For example, fall arrest is a highly effective precautionary control. It prevents fall accident by arresting a worker's fall. It prevents the worker from striking the next level. However, this precautionary control could only minimize the possibility of serious injury but does not guarantee injury-free result. Compared with precautionary control, preventative control if it is effectively carried out, usually guarantees injury-free situations.

Preventative control is usually carried out by conducting hazard identification by safety management teams before the start of particular construction activities. Based on the current level of knowledge of safety management, the level of hazard identification is considerably lower than expected (Carter and Smith 2006). A suggested reason is that the traditional way of identifying construction site safety hazards (through the use of contract drawings issued by consultants or designers) has certain difficulties which impedes the effective visual translation of information into a form suitable for planning purposes (Hadikusumo and Rowlinson 2002). Additionally, drawings can be understood in varying ways (Hartmann and Fischer 2007). Another impediment is that two dimensional (2D) drawings only represent construction components (walls, beams, columns, etc), rather than the specific construction processes involved (Young 1996).

It is understood that hazard identification is almost impossible to identify all potential hazards. Safety management plans are the means used to maintain safety performance of a project. If the safety management plan, that which has been created before the start of construction activity, is not effective, that activity has to be monitored ‘live’ by the safety officer instead. Hence if several unplanned activities are carried out at the same time, the number of safety officers becomes prohibitive.

Without safety officer supervision and an effective safety management plan and training, workers are likely to be at risk because of the hazardous and often unpredictable occurrences in their working environment. Thus, it is advisable for wider based training to be mandatory to ensure knowledge of not only basic skills, but also the more sophisticated such as tower crane erection and the subsequent ability to determine hazards both as regards the working environment and working process.

Despite the importance of the above, there is no formal training in place to improve the almost ad hoc situation. In addition there is no formal assessment to evaluate the workers as regards those safety schemes which may be in place.

Construction workers in Hong Kong are only required to take a full-day course about construction safety and to pass a multiple-choice test at the end of the course in order to gain a certificate to enable lawful work in the construction industry. The existing training process is crude and general and does not address areas of specific skills in which different workers may be involved. Hence a worker with such a ce rtificate cannot be guaranteed to have the necessary awareness of safety skills and practice and also it is likely that they will be insufficiently prepared for the hazards in the specific part in the construction process in which they are involved, with the likelihood of a poor safety performance record

It has been noted that there are three existing problems which could cause construction accidents:

1. The use of only traditional 2D representation of construction information for safety management
2. The lack of training in hazard identification for general construction workers
3. The lack of assessment in safety knowledge and attitude for general construction workers

The above problems underline the need for the development of new approaches, which will improve safety on the construction site. Due to the recent improvement in visualization technology, the approach adopted in this research is to investigate and adopt different virtual reality (V.R.) systems, from both construction and other industries, to improve the poor safety record. Three approaches have been developed to visualize safety information, such as construction drawings, construction sequence and construction method, for conducting hazard identification, safety training and assessment.

Recently, the use of VR, such as Building Information Model (BIM), has revolutionarily changed the construction practice. The use of BIM has transformed the traditional use of two dimensional drawings to three dimensional. More information of BIM is available in section 2.7.2. The development of these systems allows the user to manage construction project more effectively. For example, Autodesk (2008) has suggested that the use of BIM can assist coordination between architects, engineers, contractor and owners. The use of BIM can also benefits construction industry by improving the cost and time efficiency of a construction projects. In this thesis, the use of different VR systems, both in construction industry and other industries, are reviewed in Section 2.7 and 2.8. The possibility of using these VR systems to improve construction safety is discussed in chapter 2.

1.2 Scope of the Research

Leung (2010) presented a 4 layers of Protection approach, in using the Swiss Cheese Method, to show the relationship between humans mistake, safety measures and accident. The approach is presented in figure 1.1. Leung (2010) suggested four layers to manage : 1. Design and Engineering; 2. Materials, Plant and Equipments; 3. Process; 4. People. There are weaknesses in each of these layers and the weaknesses form holes on the layer as shown in the figure. Accidents happen as a result of the connection of a series of weaknesses.

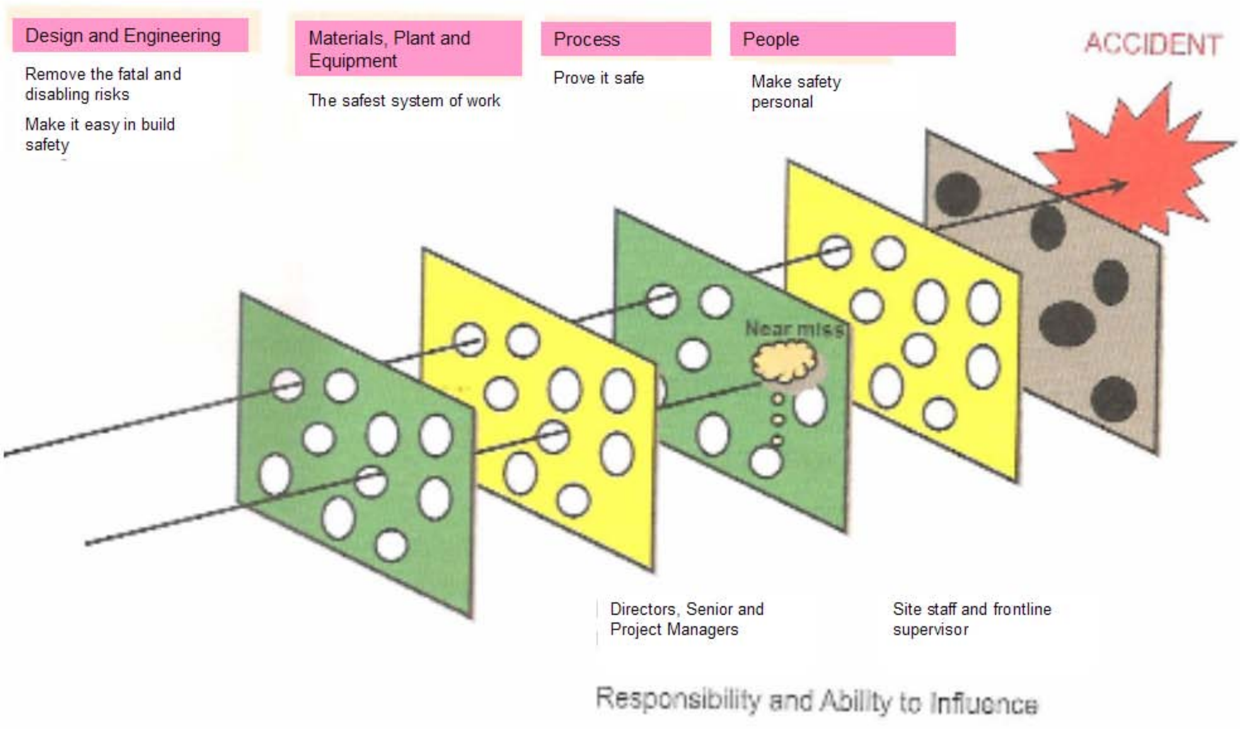

Figure 1.1. The 4 layers of Protection approach by Leung (2010)

In this research, the 4 layers approach is modified according to findings from the literature review in section 2.4, which discuss the factors that affect construction safety and the causes of construction accidents. The four layers are the safety measures that could be applied to a project during different stages. The holes are the weaknesses in safety in different stages. If the construction activity passes thought all weaknesses, accident will be happened. A new picture was formed and it clearly shows the scope of the research in figure 1.2. The four layers are changed to 1) design issue, 2) process issue, 3) management issue and 4) human issue. The four issues are the most important issues, which determine the success of construction safety of a project. The four issues are carried out in different stages of a project and are integrated to manage construction safety. Any "holes" in these layers could easily result in construction accidents. A better safety management system is needed to fill the holes and thus to prevent construction accidents from happening.

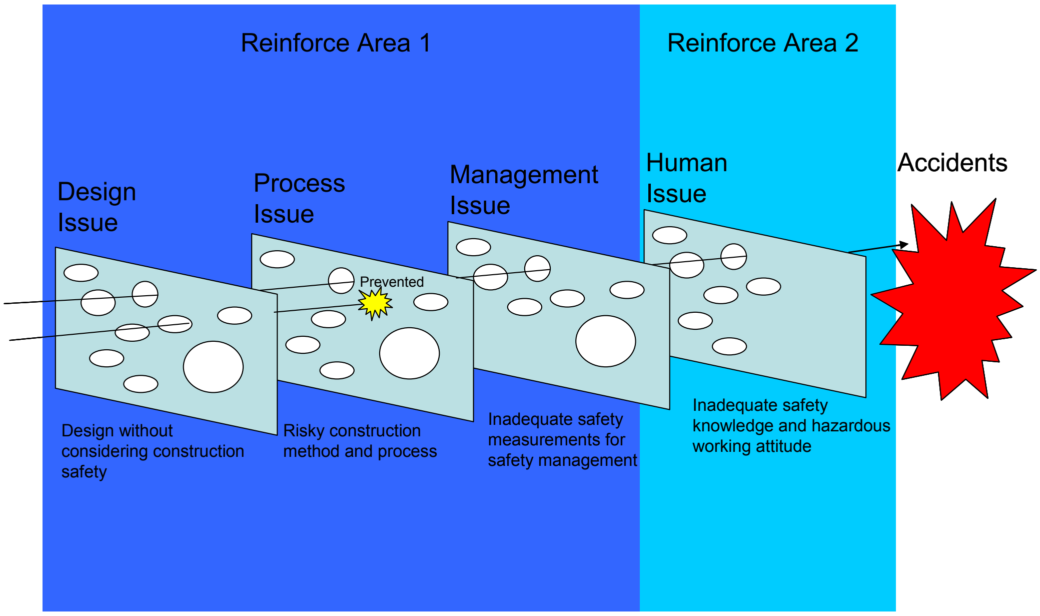

Figure 1.2. The revised 4 layers of Protection

The detail of the current safety practices, such as traditional way of hazard identification, safety training and assessment, is reported in section 2.4. Due to the problems mentioned in section 2.4, this research aims to provide the means by which safety performance can be reinforced and subsequently accident rates can be reduced. Two new different visualization approaches are employed. They are as follows:

1. the development of a tool to identify risk
2. the enhancement of awareness of human issues, such as safety training and assessment. This is the last line of defence against construction accident.

1.3 Research Aim and Objectives

The aim of this research is to propose the use of VR systems to improve the safety performance of the construction industry. The detail of the use of VR technology in the construction industry and other industries are discussed in section 2.6. In order to achieve this objective, the process is divided into different sections and the objectives of these sections are listed as follows:

1) To identify the causes of construction accidents
2) To review the safety management practice in Hong Kong construction industry
3) To review the problems for safety management encountered by construction industry
4) To study the use of VR technology that has been successfully implemented in

construction industry

5) To review the use of VR technology that has been successfully implemented in other industries

6) To propose the use of VR technology and to develop framework for solving safety problems

7) To evaluate the proposed approaches

1.4 Research Strategy

The organisation of the research is shown in Figure 1.3. First, construction accident related literature is reviewed. It includes accidents statistic and causes of construction accident. Afterward, the safety practice in Hong Kong construction industry is reviewed and the problems of the practice are identified. The problems identified are then compared with the causes of accident and the research gap is identified. The uses of V.R. systems to solve the problem are proposed and V.R. systems in both the construction industry and other industries are reviewed. Construction Virtual Prototyping (CVP) approach and the use of game engine are selected because of their success in construction planning and other industries. The framework of the two different approaches are developed and supported by a case study. The case study is designed to identify the feasibility and validity of the developed approaches. Finally, conclusions are drawn and suggestions for future research are discussed.

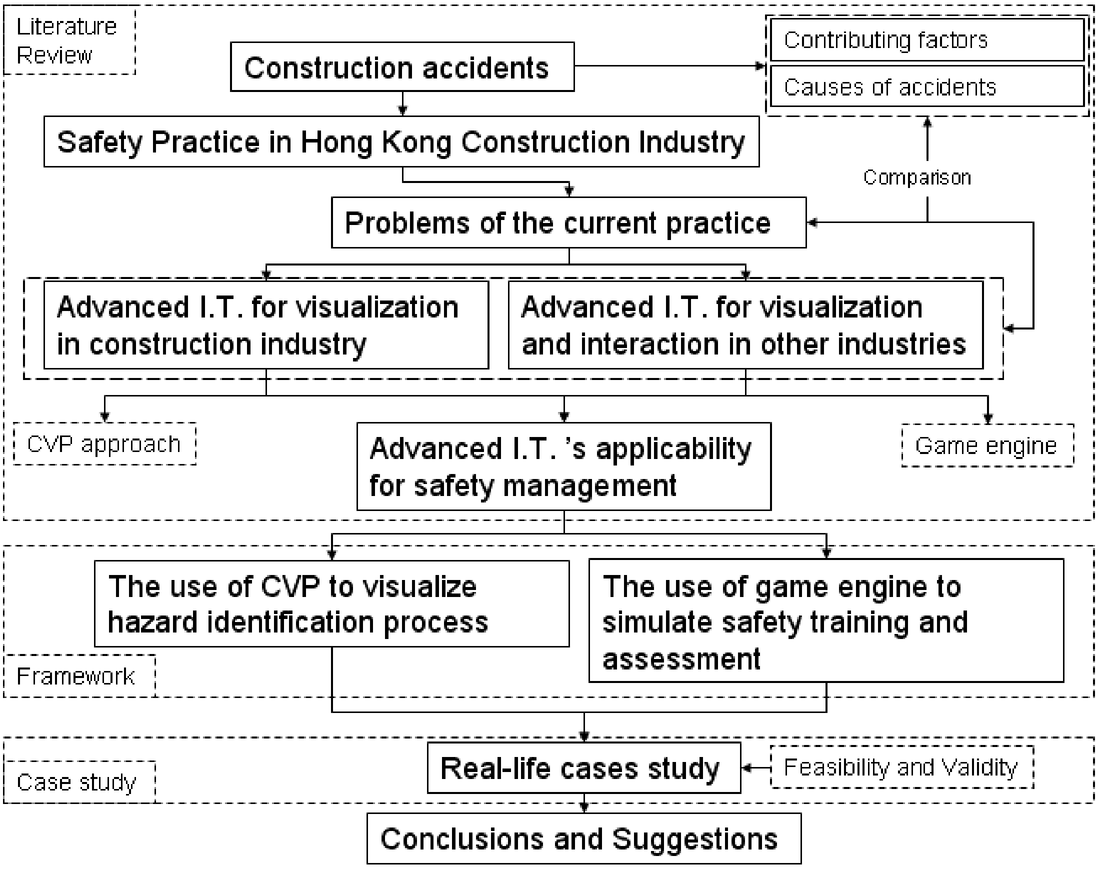

Figure 1.3. The logic framework of this research

1.5 Research Methodology

The research was divided into three parts. The first part was to identify the problems faced by the construction industry in hazard identification. This was carried out by conducting an extensive literature review, which was in previous section. Suggestions were then made based on the ensuing collated and summarized ideas involved. The second part was to study the use of visualization in the construction industry. This involved another literature review to identify previous research. Research on the use of visualization and VP in other industries was also reviewed. This resulted in the selection of Construction Virtual Prototyping (CVP) and game engine because of their previously successful implementation in construction process simulation. A framework was then developed for the detailed implementation of the three approaches. Finally, the three approaches were evaluated by means of a case study, identified after presentation of the approaches to some of the largest construction contractors in Hong Kong. Due to the exploratory nature of the research, focus group interviews were arranged with an expert panel of the contractor's safety specialists and managers – including safety officers, safety managers, project managers and senior project managers involved throughout the life of the projects. Interviewees were selected based on their experience, which is also important for exploratory research (Maxwell, 1996).

In this thesis, four research methods are employed to achieve the stated objectives. The four methods are: 1) Literature review, 2) Comparison method, 3) Case study and 4) Interview. The reasons for selecting the four methods are given below:

Literature review is an important research method to address the existing problems of construction safety management and the management practice, which is the research gap in this research study. The review of literature also provides information such as the use of V.R. in construction industry and other industries. The collected information reinforce the aims and objectives of this study.

The second method employed is comparison. In this thesis, three new safety management approaches are developed. The three approaches involve the use and further of development of V.R. technology. Thus, it is seen that the three approaches developed in this research are different from traditional practice. Comparisons are made between the traditional and the three developed approaches. For example, the traditional hazard identification process is compared with the developed approach by carrying out expert interviews in chapter 3. The comparison was made by interviews.

The interviewees comment on the different based on their experience and opinion. The comparison evaluates the use of the three approaches by pinpointing their strengths and weaknesses.

The third method used is a case study. This method is used to evaluate the feasibility of the new approaches, introduced in chapter 3, 4 and 5. All three approaches were applied in real-life case study. The case study shows the detail procedure of implementing the proposed approaches. In chapter 3, 4 and 5, individual case studies are described.

Interviews are the third method employed in this research. It is an effective way of collecting qualitative data and information. Involved were the collection of the results of numerous of interviews with different construction companies. The details of this procedure are given in chapters 3, 4 and 5. Interviews were conducted to evaluate, separately, the different approaches. As recommended by Naoum (2001), the meetings were semi structured. The group interview method is also acknowledged as "special technique" for information gathering (McQueen and Knussen, 2002).

1.6 Organisation of the Thesis

This thesis consists of six chapters. The content of chapter 2 to chapter 5 is provided as below:

Chapter 2: Literature Review

In this chapter, the background information of construction safety management and its problems are reported. The use of V.R. in different industries is also reported in this chapter (referring to section 1.5). The focus of this chapter is to report such background information to create a platform against which the necessity for the development of new safety management tools is made clear. The use of virtual reality is also highlighted to indicate new ways whereby safety improvements on the construction site can be achieved.

Chapter 3: The use of Construction Virtual Prototyping in Hazard Identification

This chapter reports the development of a new approach for conducting hazard identification by using Construction Virtual Prototyping (CVP). The background of CVP is reported in chapter 2. The detail of the proposed approach is provided in this chapter. The implementation of the approach is demonstrated by a case study, which is a construction project in Hong Kong. The approach is then evaluated by a series of interviews with the project team of the case study project.

Chapter 4: Multi-users Virtual Safety Training System

In this chapter, the development of a new safety training system for the construction industry is reported. The development of the safety training system, named Multi-users Virtual Safety Training System (MVSTS) is created based on an existing game engine. The framework, details and development of MVSTS are discussed in this chapter. MVSTS aims to provide a new training platform for improving the efficiency and effectiveness of the current safety training practice. MVSTS is presented to a group of users of different backgrounds and the effectiveness of the system is evaluated by interviews with the trainees.

Chapter 5: Virtual Safety Assessment system

In chapter 5, a new safety assessment system is introduced by modifying another game engine. The safety assessment system, named Virtual Safety Assessment System (VSAS) aims to assess safety knowledge of workers in a virtual environment. The framework and details of the system are briefly introduced in this chapter. The system is provided to numerous of construction workers, engineers and managers for testing.

Interviews are arranged afterwards to collect information regarding the usefulness of the system.

Chapter 6: Conclusion

In this chapter, the contributions of this research study are given together with the limitation of the study and suggestions for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Construction Safety

The National Safety Council (NSC) has defined the terms related to construction safety. *Safety* is defined as “the control of recognized hazards to attain an acceptable level of risk”, a *hazard* is defined as “an unsafe condition or activity that, if left uncontrolled, can contribute to an accident”, while *accident* is defined as “an occurrence in sequence of events that produces unintended injury, death, or property damage. Accident refers to the event, not the result of the event.” Construction safety is important as construction is one of the most hazardous industries in the world (Jannadi and Bu-Khamsin, 2002). In the USA and UK, construction workers are several times more likely to suffer from accidents than in other industries (Sawacha et al. 1999; Carter and Smith 2006). In 1996, 1,000 construction workers dead at work and 350,000 workers received disabling injuries in the USA (*Accident Facts* 1997). From 1997 to 2004, the U.S. Bureau of Labor Statistics (2004) reported that over 1,100 workers lost their live at work consistently. Barnard (1995) reported that about 120 people are killed on construction sites and about 3000 workers received major injuries in the UK. These accident figures could be dramatically higher if unreported near-miss accidents are included, such as Heinrich (1959) found that a large number of near-miss accidents exist. The high accident rate has brought huge economic loss to the construction industry and personal loss to the workers. The cost of construction accident is discussed as follows.

2.2 Cost of construction accidents

In construction related accidents it is not only construction workers who suffer. According to Sawacha et al. (1999), report under RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrence Regulations) state that one member of the public, including children, is killed on average each month due to construction related accidents. Health and Safety Executive (1985) reported that over 370 million working days is lost due to incapacity at work and more than 15 million days are lost as a result of industrial injuries. Construction accident induces more than hospitalisation and compensation. Early in 1941, Heninrich (1941) itemised accidents' cost and what he referred to as an accident cost iceberg and accident triangle. The accident cost iceberg relates to direct and indirect costs of an accident while the accident triangle shows the relationship between all different kind of accidents (fatal accident, non-fatal accident, property damage accidents and near miss accident).

The direct and indirect cost listed by Heninrich (1941) are categorised as follows:

Direct costs:

- Sick pay
- Personal injury claims and Public liability claims
- Repair of buildings, plant and equipment
- Replacement of product
- Overtime payments

Indirect costs:

- Lost time of injured employee
- Lost time of other employees who stop working
- Lost time of executives employees

- Lost time of first aid attendant and other related staff
- Cost of damage to machinery, tools, property and materials
- Cost of wages of injured worker
- Cost of reduced worker productivity
- Cost of idle equipment
- Cost of subsequent injuries
- Cost of interference with production
- Cost of overheads (utilities, heat, rent, *etc*)

Later in 1994, Hinze (1994) reported that the indirect costs are double the direct costs if liability claims are taken into account. Similarly, Crocker (1995) reported that every £1 of an accident cost induced, a further £5 to £50 indirect cost the latter including product, material and legal costs, to the contractor. The accident cost is always a hindrance to the development of the industry and explains the importance to maintain safe environment inside construction site.

2.3 Factors affecting construction safety and causes of construction accidents

The high cost of construction accidents reviewed in the previous section has raised the attention of researchers. Different research studies have tackles the construction safety in various ways in an attempt to achieve improvement. The two main ways have been used by researchers to address safety problem.

1. The determination of factors that affect construction safety. Some factors improve construction safety such as good management practice while others, such as job pressure undermine it. By addressing these factors, specific focus is placed on the matter of improving safety performance and hence makes a move to eliminate construction accident. The mentioned factors affect construction safety but do not directly cause construction accident.

2. The identification of the causes of construction accident. The causes of construction accident are different from those factors given above. Some causes are hard to eliminate due to the nature of construction industry.

Both approaches are reviewed below.

2.3.1 Causes of construction accident

Managerial factors are one of the most important factors that affect construction safety. The majority of researchers try to address the importance of managerial factors. Levitt (1975) addressed the importance of top management's attitude toward safety. Different researchers had pointed out the relationship between human resource management and safety performance, such as The effect of turnover (Hinze 1978), job pressure and competition (Hinze and Parker 1978). Other researchers investigated the effect on safety caused by working practice. For example, the relationship between practice of superintendent and safety was studied by (Hinze and Gordon 1979; Levitt and Samelson 1987). Others practice, such as job control (Hinze and Panunllo 1978), working relationships (Hinze 1981), safety techniques (Liska et al. 1993), safety climate (Mohamed 2002) and organization culture (Molenaar et al. 2002), were all studied. Some researchers argued that the size of company affects its safety performance. Hinze and Harrison (1981) studied the performance of safety program in large company. The size of projects was also regarded as one of the potential causes, such as appropriate way to maintain safety on large projects (Hinze and Raboud 1988) and safety performance in different project sizes (Hinze and Figone 1988a; Hinze and figone 1988b). The responsibility of owners, such as owners' strategies in selecting and monitoring safety performance of contractors (Samelson and Levitt 1982) was also considered by researchers. Jaselskis and Anderson (1996) carried out a comprehensive research study and tried to find the most important organizational factors which could affect the safety performance of construction industry. More than ten previous papers between 1976 and 1993 were summarized during this work. They divided the factors into company related factors and project related factors. These factors are given below:

1. Upper management support
2. Time that company safety management team spend on project
3. Informal safety inspections
4. Meeting with site staff
5. Detail of safety program
6. Safety expenditures
7. Project manager experience level
8. Less project team turnover

Numerous managerial factors were identified, and thus highlighting the difficulty of safety management on a construction site. Cooperation between designers, managers, engineers and workers is required to achieve the best result, making the safety problem almost impossible to be solved by the use of advanced information technology.

However, it was clear that the details of safety programs and informal safety inspections are among the key factors which affect site safety. These factors existing in the industry today undermine the current practice and are further discussed below.

In the early stage, researchers tried to study the cause of accident by investigating the accident record. By examining accident records, information such as types of accidents, accident related trade and the occurrence of accidents can be categorized (Fullman 1984; Goldsmith 1987; Culver et al. 1990, 1992; Davies and Tomasin 1990; La Bette 1990; MacCollum 1990; Rietze 1990; Helander 1991; Peyton and Rubio 1991; Hinze 1997). Huge effort was spent and these research findings provide important information about occupational accident occurrences and therefore a platform to encourage further investigation regarding construction safety improvements.

However, although a platform was so provided, the above research did not further investigate the precise causes of accidents. In addition, the research centred on the whole picture of occupational accidents i.e. those of all industries. McClay (1989) identified hazards, human actions and functional imitations as three key elements of industrial accidents. Others conducted research to find the relationship between accident and specific factors, such as ergonomic factors (Ramsey, 1985), human error (Reason, 1990) and system factors (Sanders and Shaw, 1988). These studies helped the industries to understand more about the cause of accidents, but none focused solely on the construction industry. As a result, the data does not perfectly match with that of the construction industry.

In light of this situation, the possible causes of construction accident, were addressed by researchers. Hinze (1996) introduced a distraction theory which argued that workers could be distracted from work, resulting in the probability of an increase in accidents as a result of production pressure. Hinze et al. (1998) and Abdelhamid and Everett (2000) conducted research which identified the root causes of construction injuries and accidents. Suraji et al. (2001) and Toole (2002) have carried out comprehensive research into the causes of construction accidents.

Abdelhamid and Everett (2000) suggest three root causes:

1. an unsafe working environment - failure to identify an unsafe condition before an activity starts
2. worker interaction with an unsafe environment - decision to work in unsafe conditions
3. unsafe worker behaviour - decision to behave unsafely regardless of the work environment.

Suraji et al. (2001), on the other hand, classified the root causes as:

1. inappropriate construction planning,
2. inappropriate construction control,
3. inappropriate construction operation,
4. inappropriate site condition and
5. inappropriate operative action.

Yet a further classification is that of Toole’s (2002) eight roots causes of:

1. lack of proper training,
2. deficient enforcement of safety,
3. safety equipment not provided,
4. unsafe methods or sequencing,
5. unsafe site conditions,
6. not using provided safety equipment,
7. poor attitude toward safety and
8. isolated, sudden deviation from prescribed behaviour.

Based on the above, it appears that the causes of construction accidents are similar to those found and defined by McClay's (1989)

• *Unsafe site conditions*. A physical environment, unsuitable for work; an environment that violates safety standards; or a construction workplace that is more hazardous than is normal. Poor housekeeping, broken working platforms plus any other mal functioning are also included as deficient conditions.

• *Unsafe worker behaviour.* Lack of proper training can be a contributory in this respect. Workers who are not well trained tend to be weak in both recognizing and avoiding hazardous activities. Such deficient behaviour can also apply to well trained workers, particularly those with a negative attitude safety towards.

- *Unsafe working methods or sequencing*. Inefficiently planned construction tasks can be or even are likely to be hazardous to carry out, especially if the work involved is of an unusual nature. Such inefficiency may be due to such as inadequate method statements, temporary works design, layout plans, schedules or site investigations.

It is obvious that the three causes of construction accidents identified above could be prevented if safety management is effectively carried out (the detail of safety management is discussed in section 2.3.3). The existence of the three general causes makes clearer the reasons for the ineffectiveness of the current practice. In this study, it seems reasonably certain that a new tool to modify existing I.T. systems is necessary, the aim being to improve the effectiveness of the current safety management practice.

2.4 Construction safety management measures

2.4.1 Regulation and legislation of safety management

In recent years, new safety legislations have been put into practice in various countries, such as the United Kingdom, Hong Kong and Singapore. These legislations emphasize the importance of safety management. Safety management system, such as BS 8800 (BSI 1996), OHSAS 18001 (BSI 2000) and CP 79 (PS 1999), are similar. All these documents and legislative statements agree that risk management processes are key to the success of safety management. As construction accidents are random events the causes of which are numerous with some created by human error, it is important to manage risk (Chua and Goh, 2005). Safety and health programs focused on r isk management are the most useful means of controlling site safety. Reese and Eidson (2006) identified numerous facts that could influence the accidents rate and find that the promotion from top management is one of the most important facts, which could lead to as much as 470% less accidents. This finding indicates that without implementation of well-structured safety and health program, accident rates rise dramatically,. Reese and Eidson (2006) suggest seven approaches in the safety and health program from OSHA's handbook as a mean to improve construction safety. These approaches are widely adopted the construction industry. In the following, the details of the seven approaches are introduced. After introducing the seven approaches, which is common safety practice in Hong Kong, the problem of these approaches are discussed. The seven approaches are:

1) Toolbox talks

Toolbox talks are short succinct meetings, which last five to ten minutes prior to the workday. The talks should cover current concerns or information including, but not limited to changes in work practices, shortening training modules, accident or injury facts, job instruction, policies, construction procedures, rules and regulations.

2) Safe operation procedures (SOPs)

The Safe operation procedures (SOPs) show the steps of how to conduct a task or procedure safely. The use of SOPs is useful to teach new workers correct working procedures as well as refreshing the memory of experienced workers. The use of SOPs is popular in many industries, such as pilot training.

3) Training

Training is believed to be one of the most basic but important measure to ensure construction safety. Training is important to both newly hired worker and should provided for all new working procedures and the use of new equipment. The training should cover the necessary skills as well as safety knowledge. Trained workers have been found, in general, to be more productive and safer. Evaluation of any training systems is necessary to ensure the training's adequacy and also to develop such training further.

4) Hazard identification

Hazard identification is conducted by breaking down a specific job into a step-by-step sequence. Potential hazards are then identified at every step, with each step being reviewed as many times as necessary to ensure the identity of all hazards. Periodic inspections are also useful in identifying existing or potential hazards. During the process, hazards that currently exist and hazards that could occur due to changes are considered.

5) Accident investigation

An accident investigation technique is used by the National Mine Safety and Health Academy in West Virginia. The technique was later adopted in the construction industry due to the similarity between those two industries. The causes of construction accident regarding the causes of accidents include the following:

- location of accident
- time of accident
- type of Accident
- victims' information
- type of injury suffered
- equipment involved in the activity and related
- related materials
- cause of accidents

6) safety procedures observed

Accident investigation is a basic approach which allows the related personnel to study how a task or job is done in detail. The investigation is usually carried out by watching a person performs his job. During the process, the observer, who is usually safety supervisor, detects unsafe behavior and unsafe condition. The safety supervisor must be well trained before they are sent to the site. The success of the observation depends on the experience of the supervisors in the recognition, evaluation and hazard control. The observation process is useful as it can also be the mean of checking the effectiveness of training.

7) Safety audits

Safety audits are an important procedure to ensure the safety quality of a project. It starts with determining the content to be audited. The audit process then includes a check of compliance with company rules, regulations and OSHA rules. The safety and health performance of supervisors and workers are also evaluated. The effectiveness of new processes or procedures is studied and progress is also evaluated. There are different types of audits. They include continuous, ongoing, planned, periodic and intermittent audits.

Similar to the suggestions made, the Hong Kong construction industry employs a similar safety management system to maintain construction site safety. The details of training in Hong Kong is discussed as follows.

2.4.2 Safety training

Besides the seven mentioned approaches, there is a Green Card induction training system in Hong Kong. The induction training system requires a new worker to receive a basic orientation in construction site safety. All construction workers are required to pass the test at the end of the training before they are eligible to work in construction site.

Besides Green Card induction training, the Construction Industry Training Authority (CITA), which is the main provider of craft training for the construction industry, offers a range of basic craft courses to the industry practitioners. The following nine basic streams, which consist of both one-year and two-year courses, are offered by CITA:

- Bricklaying, Plastering and Tiling (two-year)
- Carpentry and Joinery (two-year)
- Painting, Decorating and Sign-writing (two-year)
- Plumbing and Pipe-fitting (two-year)
- Marble-laying (two-year)
- Metal Works (two-year)

- Construction Scaffolding Works (one-year)
- Construction Plant Maintenance and Repair (one-year)
- Electrical installation (one-year)

The training consists of both practical training in workshops and classroom lectures. For two-year courses, the trainees can acquire working experience through site practice. All trainees are also required to attend theoretical lessons at other institute such as CICTA and Hong Kong institute of Vocational Education. A Basic Craft Certificate is awarded to trainees who have completed the training. After completion of the training, all workers under 19 years of age must enter into apprenticeship contracts with their employers. On-the-job training and continue education are provided during the apprenticeship. After the apprenticeship, a qualified craftsman certificate is issued to the worker. CITA also offers safety related courses of different natures. Nineteen safety related courses, which include certificate of different roles (e.g. competent person, certified worker, *etc*) for different scenarios (confined spaces, drainage service works, *etc*) are arranged by CITA.

It is required by Government policy that several construction activities can only be carried out by certified workers. Typical example is temporary suspended working platforms, according to section 17 of the Factories and Industrial Undertakings Regulation. In order to obtain the certification, CITA offers certification course to meet the requirement of the policy. The certification process has helped the industry to improve the quality of workers. However, the training course can only guarantee the attendance, but not assuring that the trainees have learnt from the course.

2.4.3 Problems of current construction practice

The current safety practice for construction was discussed in the previous section. Obviously, some problems of the current practice have undermined the situation. In this section, the problems of current practice are discussed.

2.4.3.1 Contradictory with project management

Despite the importance of site safety, construction safety management is separately managed from construction project management (Hare et al. 2006). The prime goal of construction project management is to complete the project within limited time with limited resource. However, health and safety program are sometimes recognized by the project team as paperwork and a deterrent to productivity (Reese and Eidson, 2006). Similarly, Mitropoulos *et al* (2005) listed five limitations of the current safety approach. The authors believe one of the limitations is that the safety effort does not add value to production and even conflict with production. Besides productivity, Prichard (2002) also argued that the use of safety programs, such as training and inspection, increases the cost of noncompliance, while the violations approach, suggested by OSHA, is labeled as costly and does not ensure safety. It is found that previous research had indicated that the existence of health and safety program is contradictory with the prime goal of a construction project.

2.4.3.2 The difficulty in measuring construction safety

Mohamed (2004) mentioned another problem which is the incapability to measure safety performance in its current form. The problem is caused as safety is usually the responsibility of every involved party. Different to the suggestion made by Hinze and Wiegand (1992), who believed that safety is the sole responsibility of contractor, the roles for maintaining safety of owners, designers and academia are also discussed by different researchers (Huang and Hinze, 2006; Hinze *and* Wiegand 1992; Hinze 2000). The complex relationship between the cooperation of all these parties has made it nearly impossible to measure safety accurately. While Montgomery and Runger (1999) mentioned that it is no guarantee that two situations with similar characteristics will have the same outcome. Thus it is nearly impossible to evaluate the safety program by measuring the different between applying the safety measurement and vice verse.

2.4.3.3 The structure of construction industry

Construction is also pointed out as less structured when comparison is made to other industries, such as nuclear and airplanes (Rasmussen 1997). The structure together with the dynamic nature has limited the effectiveness of reactive approach.

2.4.3.4 The proactive safety management approaches

Mitropoulos *et al* (2005) believe that the violations approach is a reactive approach which is not as good as a proactive approach. Benner (1985) also suggested that OSHA's violations approach is weak in its ability to identify construction accident root causes. Despite the weaknesses in reactive approach, there is only limited proactive approach available. One of the most common proactive approaches for managing safety in construction site is to conduct hazard identification before commencement of work. However, there are numerous of problems exist in the current hazard identification practice. Carter and Smith (2006) briefly presented the procedure for establishing hazard identification in the UK. They questioned the effectiveness of traditional hazard identification and believe that only small proportion of potential hazards is identified during safety risk assessment of the method statements. The use of two dimensional engineering drawing can be one of the reasons of the ineffectiveness. Hadikusumo and Rowlinson (2002) explained that the traditional way of identifying construction site safety hazards involves obvious visualisation difficulties in translating two-dimensional (2D) information for planning purposes. Also, different people interpret drawings in varying ways (Hartmann and Fischer 2007a). Two dimensional (2D) drawings represent only construction *components* (walls, beams, columns, etc), rather than the construction *processes* involved (Young 1996). As a result, it is almost impossible to identify all hazards before the start of construction.

2.4.3.5 Difficulties in job safety observation

There are also problem associated with the use of job safety observation. It is very difficult, if not impossible, for a contractor with 10 to 20 persons to manage the safety of hundreds of workers who are working on m ore then 10 di fferent activities in different places and at the same time. Safety management teams find it more difficult to control and assess the degree of risk for certain trades as only a limited amount of information is available before the start of construction. At a result, hazardous working environment exists, which eventually causes construction accidents and fatalities. Therefore, the ability of individual workers to identify hazards is extremely important.

2.4.3.6 Short-coming of safety training system

Numerous of problems exist in the safety training at the same time. Rowlinson (1997) points out that there are a few scopes that construction industry needs to address in order to improve the training quality. The problems include the lack of co-ordination between safety training and education bodies, the lack of certification system in some of the trades such as some of the plant and equipment. It is also pointed out that both the policy and programme should be better planned to improve the situation.

2.5 Previous research effort in safety management

Traditionally, construction management is usually separated from safety management (Hare et al. 2006). The separate management practice is questioned by numerous of researchers, who believe the integration could benefit the overall outcome (Kartam 1997; Gambatese and Hinze, 1999; Saurin et al. 2004; Chantawit et al. 2005; Navon and Kolton 2006; Hare et al. 2006). Gambatese et al. (2007) agree the same idea by stating that the planning and design phrase is the golden opportunities eliminate hazards.

2.5.1 Safety management in design phrase

Various approaches were suggested to integrate safety into construction process during different phrase such as design, planning and control. For example, Gambatese and Hinze (1999) suggested developing a database which contains hazards and relative suggestion to eliminate the hazards. Thus, the tool can assist the designer to reduce hazards during design stage. Gambatese et al. (2005) investigated the viability of considering safety during design and pointed out key changes which are needed. The changes include: change in designer mindset, motivation of safety design promotion, improve designers' knowledge of safety, develop design for safety tools and guidelines. Hare et al. (2006) explored the critical success factors for the safety integration. Their research provided a foundation for achieving a better result of integration between safety planning and design planning. The importance of safety is usually overlooked during design process. At 2007, t he Construction Design and Management Safety (CDM) Regulations reinforced this idea by requesting better coordination between overall management and safety management throughout a construction project.

As the design of construction project affect the choice of construction method, the role of designers in early design stage is stressed by Behm (2005) and Gambatese et al. (2007). Baxendale and Jones (2000) also believed that safer designs can reduce or even avoid construction accident. In spite of the importance of designers' role in safety, Gamabatese et al. (2005) have urged the need for a new tool which could assist designers in safer design Besides Gambatese and Hinze's (1999) tool, Hidkusumo and Rowlinson (2002, 2004) developed a new system called " design-for-safety-process" (DFSP) to capture and share safety knowledge for design within virtual reality.

The design-for-safety-process-tool consists of 4 m ain functions stated by

Hadikusumo and Rowlinson's (2002):

1. Collision detection. This allows the user to walk through any of the components inside the technology.
2. Terrain following. This function defines different elements at terrain. For example, once the floor is defined as terrain, the function enables the user to maintain a walking plane. When the user starts a 3D walk through, this function enable the user to walk on this defined terrain. It also enables the simulation of falling objects when objects are placed beyond this defined area of terrain.
3. Geometry picking. This allows the user to pick anything inside the virtual environment, link to the database and report any incidents found. For example, the user can pick up temporary material storage and place at another location. Reason for re-locating the item could be reported to the database as a record.
4. 3D tape measurement which allows the user to measure the distance between objects or dimension of objects.

Hadikusumo and Rowlinson (2004) further investigated the possibility of applying the design-for-safety-process-tool in capturing knowledge for construction safety – concluding that it is likely to be successful as:

- The representation of 3D models allows the user to have better understanding of the situation to be reviewed than he would from traditional 2D drawings.
- The simulation of construction processes can better educate the user than reading texts and 2D drawings.
- The tool contains a database which assists safety engineers recall their previous experiences of safety hazards and precautions.

The design-for-safety-process-tool is powerful but some limitations exist. In particular, the system is not able to simulate. This means that, the tool can only simulate the safety in an pre-defined 3D environment. It is impossible for the tool to simulate safety for real-construction project by importing the 3D environment of the project.

2.5.2 Safety management in the planning and control phrase

Benjaoran and Bhokha (2010) believe that, due to the nature of construction work, construction hazards are almost impossible to completely eliminate. As a result of this contention, other researchers have investigated further ways of dealing with safety problems such as factors related to the planning measurement and control phrase, which is discussed below. The importance of considering safety during planning was stressed by Kartam (1997). In his research study, Kartam (1997) tried to integrate safety activities into Critical path method traditionally used as a planning tool in the construction industry. A framework for integrating safety planning with Critical path method for both long-term and to short-term construction planning was developed by Saurin et al. (2004).

Other researchers have proposed a new approach during the control phrase. For example, Saurin et al. (2004) suggested a three-level monitoring system to control the effectiveness of safety performance. Cheung et al. (2004) developed a web-based safety and health monitoring system which could automatically assess the safety performance of a project. The system suggests corrective actions from knowledge base known at the same time. Carter and Smith (2006) have developed a system Total-Safety which aims to determinate the risk level. The use of similar safety analysis software is not common in construction industry. Wang et al. (2006) developed a simulation-based model to express the degree of hazard in terms of accident cost. Critical factors are reported from the result of simulation. The safety management team can reduce accidents rate by controlling these factors. Another study, conducted by Navon and Kolton (2006) suggested the use of sensors and transmitter devices to control safety. These expensive devices were to be installed at the guardrail and alert the users when uninstalled guardrails are misplaced.

Numerous research studies in safety management during the design, planning and control phrase are reviewed in this section. The reviewed approaches all contribute to the improvement of construction safety, but several limitations remain, which leave the workers still vulnerable to hazards.

For example, the use of design-for-safety-process-tool can assist the designers to learn safety design, the design process is not assisted however. It is difficult to assure the improvement of designers from the tool. Despite having the above-mentioned approaches, it is still believed that a tool is needed for managing construction safety throughout the construction process (Hare et al. 2006), which is the aim of this thesis. In the following paragraph, the use of advance Information Technology (I.T.) and its potential application on s afety will be discussed.

2.6 Advanced I.T. in the Construction Industry

The construction industry has recently adopted numerous new approaches as a result of the rapid development of information technology (I.T.). The use of these approaches focus on different areas in the construction field, one example being, project management. In the following section, some of the applications, which have made a huge impact on the construction industry, are reviewed. The potential to convert or directly employ these I.T. applications for safety purpose is also discussed.

2.6.1 Building Information Model (BIM)

2.6.1.1 Definition of BIM

The concept of BIM emerged in the early 2000s from the development of the combination of these ideas. There is no standard definition for BIM and varying definitions were given by different professionals and organizations. Autodesk (2008), one of the most popular BIM commercial software developers, defines BIM as:

"BIM is an integrated process built on coordinated, reliable information about a

project from design through construction and into operations. By adopting BIM, architects, engineers, contractors and owners can easily create coordinated, digital design information and documentation; use that information to accurately visualize, simulate, and analyze performance, appearance and cost; and reliably deliver the project faster, more economically and with reduced environmental impact."

Similarly, another BIM commercial software developer, Bentley's (2008), which has a huge part of the market share, believe that:

"*BIM is a new way of approaching the design and documentation of building projects. It does so by applying information and model-based technology solutions in order to allow the automatic generation of drawings and reports, the analysis of design, the scheduling of simulation, facilities management, and more – ultimately enabling the building team to focus on the information and their decisions, rather than the documentation tools and process.*"

Besides developers, different definitions are given by national associations. National Building Information Model Standard (NBIMS) defined BIM as:

"*BIM is a computable representation of all the physical and functional characteristics of a building and its related project/life-cycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the lifecycle of a building*" (NBIMS, 2006)

The US General Services Administration (GSA, 2007) gives a similar definition to BIM:

"*the development and use of a multi-faceted computer software data model that not only documents a building design, but also simulates the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback on and improvement to the facility design.*"

On the other hand, Associated General Contractors Guide (AGC, 2007) defines BIM as:

"*a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility.*"

American Institute of Architects (AIA, 2009) may have given the shortest but equally important definition to BIM:

"*a model-based technology linked with a database of project information*"

Being a l eading experts and academics for BIM, Eastman *et al* (2008) interestingly identify the technology that has following features as not "BIM"

- Models that only contain 3D data (Without object attributes)
- Models that do not support behavior
- Models that require the users to adjust the dimension respectively in different views
- Models that are composed and combined by 2D CAD reference files

In this thesis, of the many available, only definitions of BIM given by international recognized associations are recorded. In order to discuss the further use of BIM, it is important to give a definition to BIM. These definitions are given to provide a basis for that adhered to in this study and given below:

"BIM should consist of but not limited to the following features:

1. The model should be in 3D format
2. The model should be enabled to written in attributes / data
3. The model should be easily handled by all parties (Architects, engineers, clients, e.t.c.)

2.6.1.2 Development based on BIM

BIM contains more than only a 3D model, it also includes different building information which could be used during any construction stage. Stated above is the fact that ineffectiveness in hazard identification results from the use of 2D drawings. The use of BIM provides more dimensions than 2D drawings, embedded also building information such as the details of different building services, which enables improvements to be made in the area of documents management. The rapid development and obvious potential of BIM has attracted the interest of many researchers. Alshawi et al. (2007) and Vries et al, (2004) had suggested and developed the use of BIM as the core of visualization technologies and developed an interactive learning environments for education and training purposes. For monitoring of construction conditions, Sorensen et al. (2009), Hakkarainen et al. (2009) and Golparvar-Fard et al. (2009) have all investigated the use of RFID, mobile and augmented reality technologies to control safety. These approaches focus on comparing real-time data from construction sites with that on plans with the aim of determining differences. In term of communication, Mahalingam et al. (2009) has found that BIM practices are significantly beneficial to the construction industry. Numerous researchers have also pointed out that BIM is useful for communications in relation to safety on site (Heesom and Mahdjoubi 2002; Khanzode and Staub-French 2006; Suermann and Issa 2007; Eastman et al. 2008;). Mourgues and Fischer (2010) have recently developed an automatic system for work instructions. A group of researchers have developed new approaches which integrate safety analysis with BIM. Hu et al. (2008) suggested analyzing construction procedures with 4D simulation, so acknowledging that simulation could reveal potential safety threats. Research has also been conducted into the relationship between BIM and safety risks caused by the dynamics of different size operations (Rozenfeld et al. 2009). The recent study also developed a rule-based hazard identification from 4D CAD models (Vacharapoom and Sdhabhon 2009). Huge research effort was put in integrating the use of BIM with safety and management. It can be concluded that the potential for integrating the use of BIM to manage safety is immense.

2.6.1.3 Limitation of BIM

Despite positive research evidence to the contrary, the use of BIM in the construction industry is still limited. It was reported by Gu and London (2010) that few examples of real world projects have been recorded. Despite the rapid development, BIM is not widely adopted in the Architecture, Engineering and Construction (AEC) industry. Gu and London (2010) suggested a few factors, which may be at the route of this problem. They include:

1. lack of awareness and training of practicing personel (Bernstein and Pittman 2004)
2. fragmented nature of the AEC industry (Johnson and Laepple 2003)
3. reluctance to change current work practice (Johnson and Laepple 2003)
4. unwillingness to learn new technologies
5. lack of clarification of role
6. distribution of benefits and responsibility

Bazjanac (2002, 2004) suggested that data incompatibility, software limitation, file exchange problems, poor quality of some software and high hardware requirement may also exacerbate the problem. Most importantly was the suggestion regarding the lack of aid for end users. Hartmann and Fischer (2007b) suggested the two main drivers who promote the use of BIM in construction industry are contractors and owners. But the promotion has not been highly successful as the distribution of benefits is not defined clearly enough to impact the industry.

2.6.1.4 Summary

BIM is an innovative concept to manage construction project by simultaneously storing and visualizing construction data. Due to its benefits, numerous research studies have been conducted regarding BIM integration for different purposes. Despite the apparent slow start, and perceived hindrances, researchers and construction personnel are optimistic that BIM will become increasingly popular in the construction industry.

A 4D construction simulation approach, based on BIM but with a time component, is discussed in the following section.

2.6.2 4D Construction process simulation

2.6.2.1 Development of 4D simulation

The advent of *Virtual Reality* or *Four Dimensional(4D) simulation* in the early 1990s, first for the benefit of potential client/users for virtual walkthroughs of computer simulated projects in advance of their construction (eg., Funkhouser *et al* 1996), and later, the simulation of the construction process itself (eg., Retik 1996). 4D is defined as a geometry-based construction process visualization technique by Koo and Fischer (2000) and it is also generally recognized as the combination of 3D models and time. The first generation of 4D-CAD can be tracked back to 1996, This was in the form of a research prototype that generate 4D movies by CAD geometry and construction activities (Williams 1996). Collier and Fischer (1995) developed a similar 4D-CAD by use of a commercial tool. The development of CIFE 4D-CAD by McKinney et al. (1996) even allowed the user to operate the construction schedule separately from the 4D-CAD. The first library-based 4D-CAD was introduced by Adjei-Kumi and Retik (1997) who provided a platform for the user to plan and visualize a construction project. The CIFE was later modified by Liston et al. (1998) and it was further enabled by the addition of annotation, directly to visualize planning information. A criticism from McKinney and Fischer (1998), concerned the lack of descriptive information within the 4D-CAD, was improved by a 4D annotation approach. CIFE later carried out a 4 D application with Walt Disney Imagineering (Haymaker and Fischer 2001). The tool was then used for designing the Disney Concert Hall in Los Angeles (Goldstein 2001).It was reported to be useful for coordinating subcontractors and for presenting the idea to the board members, who were not familiar with the construction process (Goldstein 2001). The tool allowed the board members to understand the challenges of the project and the selection of construction methods.

After the publication of the first generation 4D-CAD approaches, the use of 4D-CAD was put onto the market by commercial software developers. Heesom and Mahdjoubi (2004) compared available commercial 4D-CAD software, which included *Bentley Schedule Simulator, SmartPlant Review, Project Navigator, FourDviz, Common Point 4D* and *Visual Project Scheduler*. The details of each software package were also discussed in their paper. It was concluded by Heesom and Mahdjoubi (2004) that the use of 4D CAD has significant potential and could have positive impact during pre-construction and construction stage. McKinney and Fischer (1997) believed that the use of 4D could encourage the planners to share more complex and creative ideas. It is also found that the use of 4D made possible, improvements in the relationship between designers and contractors (Barrett 2000).

Recent 4D research into the process of project construction has covered topics listed as follows: the use of 4D to present spatially and chronologically accurate construction operations (Kamat and Martinez 2001, 2002), the development of information resource bases (Dawood et al 2003), 4D management approach for planning and space utilization (Chau et al. 2003), 4D modes for planning and management (Wang et al. 2004; Ma et al. 2005; Chau et al. 2004), integrating design and construction (Li *et al* 2008) and optimising planning schedules (Li *et al* 2009).

The use of 4D-CAD is not limited to improving construction planning and management, Akinci et al. (2002) investigated the potential of detecting time-space conflicts between activities.

2.6.2.2 Summary

Bergsten (2001) claimed that 4D visualization allows a more comprehensive presentation of the construction process than the traditional way of presenting information. It is clear that the use of 4D-CAD has the potential to improve construction safety by different techniques, such as improving communication between different parties, providing more information for safety management and providing information about working space.

However, there are also several limitations to the use of 4D. For example, few commercial tools consider the importance safety management in the area of temporary structures and storage. Effective tools and policies are limited. The change in the working environment is also one of the difficulties in the consideration of the above in construction industry. As a result, the use of the 4D-CAD not specifically dedicated to safety management appears, at present, to have brought little benefit to the this aspect of the construction industry. The use of 4D-CAD could be more successful if commercial software was available on the market.

2.6.3 Virtual Prototyping (VP)

The concept of Virtual Prototyping (VP) has been adopted by different industries. There are various definitions given in the literature and by the industry. Gowda et al (1999) defined VP as a new technology involving the use of Virtual Reality (VR) and other computer technologies to create digital prototypes. Song et al (1999) believe that VP refers to a process which simulates, in the software, the user, the product and their interaction at different stage. During this process, the product design and the performance analysis is carried out. The use of VP can build the structure or apparatus of a model which can be used for testing, evaluating, design check, performance test, study and training (Li et al, 2008).

The application of VP mainly aims to improve the construction process by visualization. Visualization is effective as a communication tool. Koo and Fischer (2000) proposed using 4D modeling as a visualization tool. The study found that this technique was useful in improving the effectiveness of communication between different parties. More research was then conducted in studying the effectiveness of enhancing communication between different parties. Burkhard (2004) regards visualization tools as one of the communication tools for knowledge, enabling insights, experience, attitudes, values, perspectives and opinions to be shared between different parties. Other than a tool only for communication purposes, Barsoum et al. (1996) believe that by using VP modes, the project planners are reminded of any missing details. These details may include site safety and site access. Boussabine et al. (1997) suggested the adoption of VP as a tool for site layout and planning. At 1999 Ye et al. (1999) studied the potential benefits of using VP in the planning process by conducting experiments, such as supporting assembly planning. They found that project planners tend to spend less time to complete their work in the VP environment than they do in the traditional working environment. After conducting appropriate experiments and analysing results, it can be seen that the positive contributions can be made by the adoption of VP in the construction industry. The success of the previous studies encouraged the subsequent development of VP integration with construction industry.

2.6.3.1 VP applications in construction industry

In 2004, vi rtual workspaces were developed and applied in the DIVERCITY project. Sarshar et al. (2004) showed that the application of virtual prototyping can simulate the construction process in the four-dimensional (4D) aspect. More than simulating 4D process, only, lighting design, acoustic design, energy consumption, site planning and safety issues could also be simulated

A year later, Immersive Virtual Environment (IVE) was introduced by Yerrapathruni et at (2005). IVE can visualize the construction plan in virtually and thus enhance the project planning process. Visualization is believed to also enhance project planning development and improve the understanding of the construction schedule. The technology enables different construction approaches and strategies to be tried and tested within the virtual environment built by it instead carrying out these activities at the commencement of the real construction.

At the same time, another VP application named The Virtual Design and Construction method was proposed by Kunz and Fischer (2005). This application is applied to the construction industry by constructing multidisciplinary performance models for design-construction projects. These models include the product, facilities, organization of the project team and work process. The product can assist the user to integrate buildings and plant within the virtual environment. The user can also design, construct and operate the product by VDC. Kunz and Fischer (2005) believe that this technology can improve the construction project strategy, constructability, productivity and also as a rapid identification and solution of time and space conflicts.

A brief introduction of SIMCON is given by Naji (2000, 2005). SIMCOM is a 3D virtual environment developed to give insight into construction projects during the pre-construction stage. This tool can simulate equipment-based construction processes. For example, material handling, earth removing and crane simulation can be simulated as a real time process.

SIMCON contains two main components. They are internal Scheduler and Simulation manager. The 3D visual simulation is managed and controlled by these two functions. The internal Scheduler engages the user in the simulation when the application is launched. The Scheduler consists of three elements: 3D CAD Database, Process Control module and Building Assembly Module. The 3D CAT Database defines building components and stores as AutoCAD (dxf). 3D definitions, 3D terrain definitions, labour objects and objects representing temporary site facilities. Materials can also be applied to the objects. All components / objects built by the tools can be stored and reused by different projects.

The study (Naja, 2005) conducted an experiment on an office building project. The tool investigated the working safety during different construction periods of the project. This study was mainly conducted to analyse the effect on safety by site space. The analysis was achieved from carrying out collision tests.

Similarly, more VP applications were introduced. They are the Virtual Environments (VE) firstly be introduced at 1996 (Faraj and Alshawi, 1996; Kamat and Matinex 2001) and constructive visualization interactive 3D (i3D) by Aouad et al (1997)

2.6.3.2 CVP applications in the construction industry

In order to more adequately reflect the construction process, Li *et al* (2003) developed Construction Virtual Prototyping (CVP). The development of CVP, which aims to provide a full simulation of the construction process, has made remarkable progress in Hong Kong in recent years.

2.6.3.2.1 Definition of CVP

According to Li *et al* (2003), the development of CVP was based on a modification of existing software CATIA (Computer-Aided Three-Dimensional Interactive Application) V5 and DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) V5. CATIA V5 is a computer-aided design/engineering software that allows users to design and manipulate a product in a virtual environment. It is a 3D interactive platform which enables Computer-Aided Design (CAD), Computer-Aided-Management (CAM) and Computer-Aided-Engineering (CAE). It is a leading software development for the manufacturing industry due to its capacity to complete product management in an integrated and associative manner (Karam and Kleismit 2004).

DELMIA v5 is described by Dassault Systemes (2002) as a solution for comprehensive product life cycle management. It is used for 3D design validation, 4D simulations, human ergonomic simulations, material flow simulations and monitoring manufacturing processes. DELMIA allows users to experience detail planning of model assembly with geometry created by CATIA and other CAD systems. The assembly process is integrated with “collision test” function and the integration allows the user to manage the assembly process and paths simultaneously.

2.6.3.2.2 Development of CVP

Due to the success of Virtual Prototyping in other industries, Huang *et al* (2007) felt it n ecessary to explain that the software, developed for the manufacturing industry has been modified to suit the needs of the industry employing it,:in tis case the construction industry. The modified system (CVP) contains a library of parametric 3D models of construction plant, temporary work facilities and building components. The CVP system allows users to construct and modify digital models of temporary works and building components (i.e. columns, walls and slabs) in the CATIA environment. Users can then employ these models to define and simulate the construction process in the DELMIA environment. As both CATIA and DELMIA are built on the same platform, the two systems share the same database and interface.

The benefits of CVP are well known. Design constructability and anticipated shortages and pitfalls are able to be identified and rectified before the real-time execution of construction work (Huang *et al* 2007) (The use of CVP for safety is discussed in Chapter 3). CVP therefore assists project planners in modifying the design and decision making process related to constructability problems during the early design stage. Li *et al* (2008) also present a case study conducted to specifically to investigate the effects of CVP, the result of which shows that the project team members are generally satisfied with the enhanced performance resulting from its use. Li *et al* (2009) also demonstrate a brief implementation of CVP technology in planning. The research clearly identifies CVP's ability to enhance construction planning in the early design stage.

In the area of safety knowledge, most are familiar with the interactive 4D flight simulators for air pilot training. This tool tests and helps develop pilot skills in reacting to and managing high risk situations. Perhaps less well known is that similar technology also exists for hazard perception in motor car driver training and testing (eg., Dumbuya 2005), with tests on learner drivers, now mandatory in some Australian States such as Victoria and Queensland.

Clearly, such approaches have potential applications for construction site safety, with the potential of adapting existing 4D technology for construction processes for use in testing worker safety knowledge within a computer simulated environment.

2.6.4 Game technology

2.6.4.1 Definition of Game engine

According to Lewis and Jacobson (2002), the game engine is the collection of modules of simulation codes which have no specification on the game's behaviour or game's environment. The engine usually includes modules handling input, output, and physics for the game world. These available modules allows reuse by the users, thus time is saved and the amount of programming work is reduced. Game engine allows user interaction to be integrated into virtual environment. A virtual environment does not only contain a 3D environment. It is a platform which allows the user to create different functions by computer programming. For example, Smith and Hart (2006) suggest that user interaction should also be integrated into the virtual environment, for example collision detection. Available virtual environment development toolkits may provide a subset of tools for building a complete virtual world.

2.6.4.2 Game technology for training

The use of game technology and game engine is a promising area of training research. The first application of game technology in this area of research was found in aircraft industry. The use of the Microsoft Flight Simulator and Flight Simulator for teaching purpose dates back to 1991 (Moroney and Moroney, 1991). The student did not only learn the capability of the simulator, but they also learned the psychology and engineering in relation to Aviation According to Hampton (1997), there were as many as six different personal-computer based flight simulators. These simulators were designed as instrument flight trainers, and made available to individuals with a pilot's certificate. Koonce and Bramble (1998) summarized the benefits of adopting PC-based flight training device. They pointed out that the use of this approach can dramatically save the flying time in the actual aircraft, which represented a significant cost benefit.

Lindheim and Swartout (2001) developed a new simulation technology, which integrates United States Army training with game engines. The project is called Mission Rehearsal Exercise (MRE). It aims to create a v irtual reality training environment to the soldiers. The soldiers can confront different pre-defined dilemmas. They are required to make decisions in real time under stress and various conflicts. The soldiers are then presented with the consequences of their decisions, in the simulator. By gaining experience within the virtual environment, the soldiers are expected to be better prepared when they experience similar dilemmas in the real world.

The success game training in the aircraft industry and the United States Army has raised interest from different industries. Visualization through a virtual environment is one of the generally investigated areas. Trenholme and Smith (2008) summarized the use of game technology for achieving visualization in different industries. The summary is shown in the Table 2.1.

Previous research studies indicate that the use of game engines can achieve more than mere visualization, vital information for a given field can be so collected. The use of game engines to simulate particular scenarios is investigated by Lewis et al. (2007), Wang et al. (2003), Bell and Fogler (2003) and Refsland et al, (2002). The use of game engines in different research studies has indicated that the game engine is capable of achieving the proposed implementation in term of technology. Perhaps less well known is that similar technology also exists for hazard perception in motor car driver training and testing (eg., Dumbuya 2005), with tests on learner drivers now mandatory in some Australian States such as Victoria and Queensland, as stated in Section 2.6.3.2.2. More recently, the use of game-engines was adopted by the construction industry with Yan et al. (2011) suggesting the integrated use of BIM with a game application to develop real-time interactive architectural visualization. A similar approach was taken by ElNimr and Mohamed (2011), who aim to visualize simulated construction operations by game-engines. Juang et al. (2011) also try to simulate the physics of a forklift by a game-engine - the simulation of a forklift providing a foundation to further develop equipment simulation by game-engines in the near future. For construction safety, Lin et al. (2011) and Dickinson et al. (2011) both propose the use of the 3D game environment for education purposes. The result shows that students are interested and therefore further motivated in the given topic by game environments.

The reason behind the success of game engine applications can also be explained by its edutainment nature. Leopouras and Vassilakis (2005) summarized previous efforts in edutainment. Generally, this technique enhances the user’s motivation in learning. Chen et al. (2003) introduced a new virtual environment for middle school students to learn from digitized museum resources and the result reinforced this idea. Lepouras and Vassilakis (2005) also pointed out that game engines offer an affordable virtual reality for research purposes. They believe that game engine provides a sophisticated, interactive environment with 3D graphics and immersion capabilities to the users.

Bylund and Espinoza, 2001 O'Neill et al., 2007	Context-aware system evaluation
Berger et al., 2007	e-Tourism
Silverman et al., 2006	Human behaviour model testing
Laird, 2002 Laird et al., 2002	Human-level AI research
Lewis et al., 2007 Wang et al., 2003	Human-robot interaction simulation
Kot et al., 2005	Information visualization
Cavazza et al., 2002	Interactive storytelling
Bell and Fogler, 2003	Laboratory accident simulation
Herwig and Paar, 2002	Landscape visualization
Refsland et al., 2002	Large-scale real-time ecosystem simulation
Bouchard et al., 2006 Robillard et al., 2003	Phobia therapy
DeLeon and Berry, 2000	Photorealistic environment walk-through
Frey et al., 2007	Psychological experimenting
Mac Namee et al., 2006	Serious game
Lepouras and Vassilakis, 2005	Virtual museums

Table 2.1. Summary of previous research in the scientific use of game engines

2.7 Summary

The background of construction safety management was introduced at the beginning of the section. The figures show that construction industry is by far one of the most risky industries. The cost of construction accidents was reviewed and the huge burden clearly identifies that hazardous working conditions have, to an extent, hindered the development of the construction industry. As a result, typical examples of safety management in construction industry have been reviewed. The weaknesses of the current practice, both in Hong Kong and suggestions from OSHA, were pointed out. Previous studies related to construction safety have been reviewed and the identified weaknesses compared.

Advanced I.T. in the construction industry and other industries were then reviewed. In this research study, focus has been on visualization technology. Two different approaches, the CVP approach and the game engine were selected .The literature covered in the above chapter gives background information on the two parts of the main research study: the study of the use of the CVP approach for visualizing the hazard identification process and the use of game engine for training and assessment purpose.

CHAPTER THREE: THE USE OF CONSTRUCTION VITURAL PROTOTPYING (CVP) IN HAZARD IDENTIFICATION

3.1 Introduction

As indicated also in Chapter 2 there are two major approaches to maintenance of safety on c onstruction sites: the preventative approach and the precautionary approach. Many practitioners consider a preventative approach to be the most important means of bringing about safety improvements. As indicated in Section 2.6.3, computer simulation technique is one of the current approaches to be adopted in this regard. Hence, the focus of this research is the use of such techniques to create virtual environments where users can explore and identify construction hazards.

Specifically, virtual prototyping technology was deployed to develop typical construction scenarios in which unsafe or hazardous incidents occur. In this section a new application is described and illustrated involving the use of a multi-dimensional simulation tool - Construction Virtual Prototyping (CVP). The use of CVP for process simulation is previously discussed in section 2.6.3.2. In this chapter, the framework of using CVP for safety management is developed. A case study, which demonstrates the implement of the CVP for safety, was conducted. In this case study, the performance of the approach was evaluated by the responses to incidents within the virtual environment and the effectiveness of the computer simulation system established though interviews with the safety project management team.

3.2 Framework for integrating CVP tool on Safety Management

The CVP system is a tool that provides structured simulations for the construction team to predict construction hazards and unsafe working practice. Its ability to simulate workers' working posture can assist the safety management team to assess the suitability of the methodology and construction program by predicting possible hazards and their outcome. The simulation considers construction workers and construction resources, precisely, and hence reflects close-to-reality construction processes. This important feature has not been achieved by previous 4D simulation studies. The use of the CVP system can change the current working practice from a reactive approach to a proactive approach, a change which would benefit the industry.

As the CVP system employs “Product”, “Process” and “Resource” models, the integration between these three elements explains how such a system can achieve hazard identification virtually. The logic framework of the CVP system is shown in figure one. Three steps are involved:

1. The virtual construction environment is constructed according to drawings which include all temporary work facilities (i.e. temporary support and formwork), building components (i.e. wall, slab, and beam) and machinery (i.e. tower crane and hoist). The building components are stored as “Product” within the system, while others (i.e. temporary work facilities, machineries, and virtual humans) are stored as “Resource”. By applying the walk-through function, the user can perform a virtual site investigation and validate safety measurements. For example, as all safety related temporary work is also included in the virtual environment (as with engineering drawings), users can check to see if the boundary areas are properly fenced off.

2. The construction process is simulated according to the construction program of a construction project. As the CVP system employs the “Product”,

"Process" and "Resource" models, the simulation is carried out by integrating all of the elements. The user has to instruct the system which "Resource" is needed to enable a particular "Process" to be carried out The "Process" may, for example, refer to the transport of several precast façades (i.e. "Product). The system automatically calculates the transport time and path once the user has determined the starting and final location. The simulation process allows the user to experience a 4D construction simulation, with the level of detail involved, relying on t he amount of available construction information in the form of drawings and method statements. By applying the walk-through function, the user can investigate every detail of the process from various viewing angles.

3. After simulating the correct construction sequence, the user can verify safety measurements by simulating specified consequences through a "what-if" approach. For example, the user can simulate a p articular construction activity that does not have safety measure. The user can then design and validate different safety measures, and select the most suitable for use within the virtual environment.

4. One of the most significant contributions of the CVP approach is the ability to simulate the working behaviour of construction workers. Involved is the development of the physical structure of a virtual human with appropriate angles of movement for different joints. The CVP tool has a total of 46 different and adjustable segments. Each segment has the degree of movement similar to that of a real human and is also limited in the same way.

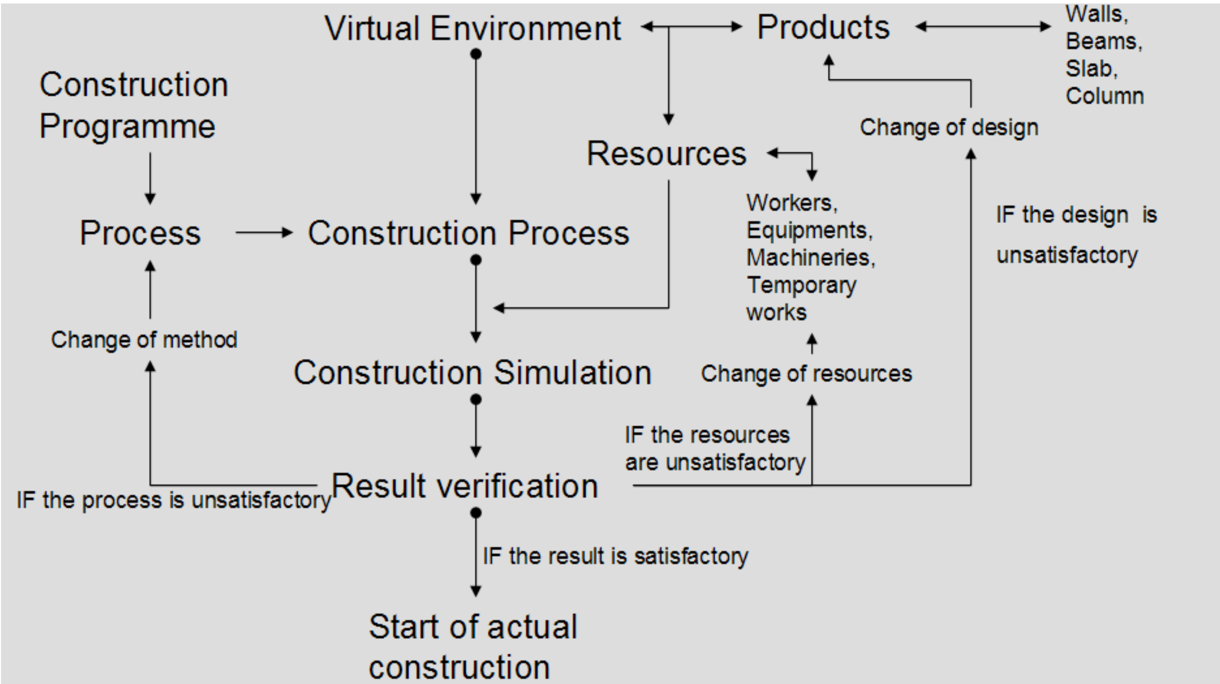

Figure 3.1: Logic framework of CVP

The simulation of the human working posture is illustrated in Figures 3.2 and 3.3. After setting Figure 3.2 as the initial posture and Figure 3.3 as the final posture, the CVP tool automatically calculates the link movements necessary for movements between each posture. Simulating the working behaviour of construction workers allows the user to investigate the working posture within the working environment, more preciously. Eventually, the CVP tool could help the user to study the working posture so as to prevent injury.

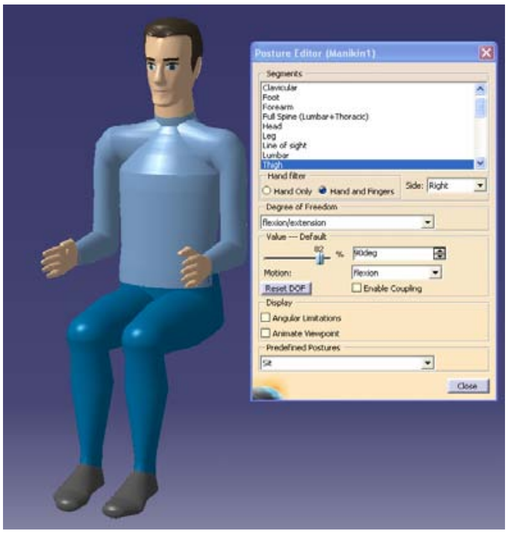

Figure 3.2: Different postures of the virtual human (1)

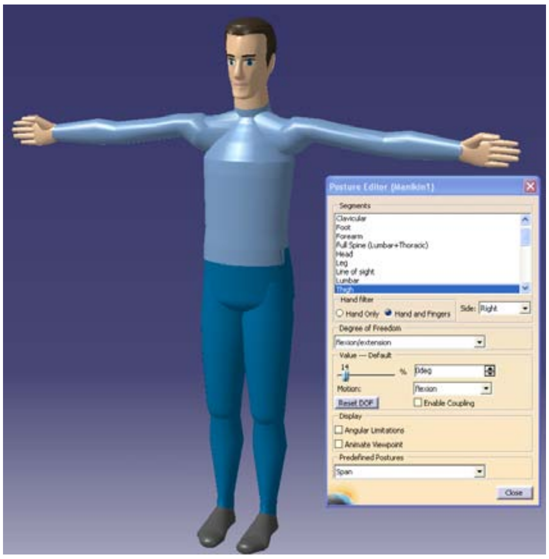

Figure 3.3: Different posture of the virtual human (2)

3.3 Case Study

A real-life construction project is used to demonstrates the approach proposed in this study. As previously indicated, the objective is to assist safety management teams to justify the safety performance of the construction methods used.

3.3.1 Background of the Project

The project consisted of the construction of the mega structural work of an exhibition hall extension, located in the central business area of Hong Kong. Due to the uniqueness and difficulty of the installation progress for this and hence to structure to avoid the possibility of construction accidents, the project team, had the intention of carrying out hazard identification during the early design period . At this point, the client decided to employ the CVP system to investigate the suitability of the safety measurements of their construction approach.

The construction activity selected was the installation process involved in connecting two mega trusses (Truss A and B). The layout of this activity is shown in Figure 3.4. Both mega trusses were constructed from reinforced steel and produced off-site. Two metal splice plates were to be fixed next to the opening of mega truss A. Mega Truss A was to be built first, on a concrete column using a tower crane, while Truss B was to be held at a location adjacent to Truss A by a second tower crane. One construction worker was to place himself inside Truss A. The splice plates, which were fixed next to the opening of Truss A, were then to be loosened and moved by the worker to a place in-between the two trusses. When the plates were moved in-between the two trusses, the worker was to fix the plates to the trusses with bolts and nuts.

The splice plates weighed over one tonne, and hence were identified as a potential threat to the worker. Within the enclosed area, the worker was only able to move the plates to the designated position by simple hand tools. Any unpredicted movement of these plates could lead to serious accident. The potentially hazardous mature of this activity raised the need to study the situation by the CVP system.

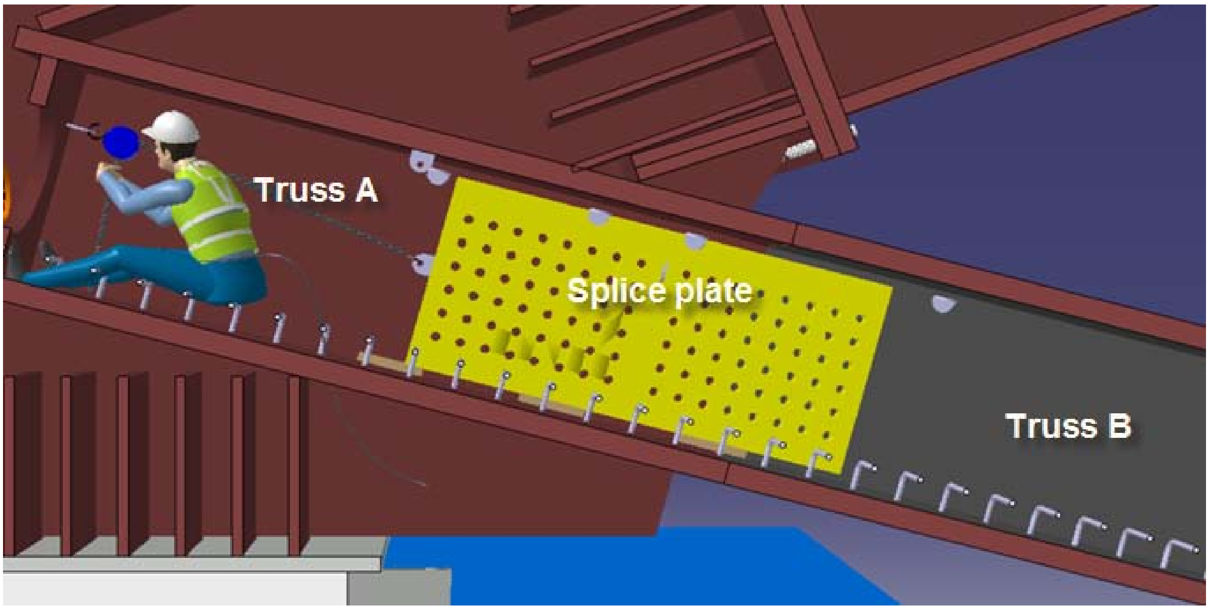

Figure 3.4: The working environment of the studied activity

3.3.2 Data collection

All data used for the case study - including the construction program, related two dimensional drawings and interviews with on-site safety officers - were obtained directly from one of the largest construction contractors in Hong Kong. Such data is commonly available on most construction sites. During these interviews, photos, 3D models and videos of simulations were first presented to the interviewees. Then the interviewees were asked to express their opinions concerning the use of CVP, to compare the traditional practice of hazard identification with the additional assistance of CVP and to rate the CVP approach.

The method of information collection was based that used by Huang *et al* (2009), who studied the use of CVP in construction process management. In doing this, the ratings of time, accuracy and other performance measures involved seeking information on the following:

1. The operational effectiveness of CVP for safety management during the early design stage. The interviewees were requested to rate this on a five-point scale ranging from 1 (not effective) to 5 (highly effective) to evaluate the CVP approach from the view of the interviewees.

2. The possibility of accidents. The interviewees were asked to estimate the chance of an accident occurring without the use of CVP to justify the effectiveness of the approach according to the interviewees' experience.

3. Recommendations. The interviewees were requested to give recommendations on the use of the CVP approach for safety management.

The findings of the interviews were analyzed and presented in sections 3.4.6.

3.3.3 3D Environment for investigation

The CVP system was used to convert the 2D engineering design to a 3D construction model (Huang *et al* 2007). After the 3D environment was completed, the analysis of possible hazards began, with the safety managers and project officers contributing to the process. The managers and officers first performed a walk-through within the 3D environment in order to measure the dimensions of all objects and distances between objects. As a result, the safety management team expressed their concern regarding the inclined working environment (Figure 3.5) as the inclined metallic floor could potentially be slippery and the worker could accidentally slide to the end of truss B, resulting in an accident. While it was impossible to change the working environment due to the construction design, the safety management team suggested the use of a safety belt to protect the worker.

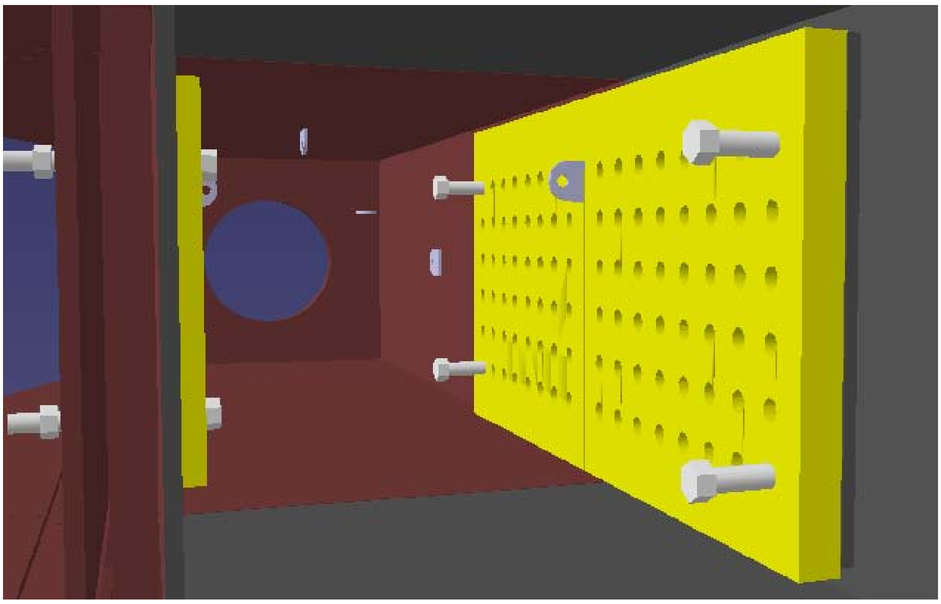

Figure 3.5: The inclined metallic floor working environment

3.3.4 Construction process for investigation

The CVP system virtually assembled the 3D CAD models according to the PERT chart, and the user then linked the logical sequence of construction activities to form a 3D simulation. Similar to a process simulation, the user has to define different activities for the human and link the activities in the PERT chart, in order to simulate the behaviour of the construction worker. The DELMIA system, which is previously described in section 2.6.4.2.1, provides basic control functions for a virtual human, such as ‘walk’, ‘stand’, ‘crouch’ and ‘sit’. For more complex activities, such as working on a construction site, the system requires the user to define the detail of every movement.

In this case study, in order to simulate the construction activity, it was vital to simulate the construction worker inside the truss. The process of installing splice plates between the two trusses was simulated with the given hand tools. The working procedure and specification of the hand tools, provided previously, by the safety management officers during an initial meeting, illustrated the working posture, working location and also the required hand tools. The researchers then converted this information into the DELMIA system and conducted a simulation of the construction activity. The simulation was then presented to the safety management team during the next meeting.

The following hazards were identified during the meeting:

1. Improper design of temporary support to the splice plates during installation. The design to hold the splice plates by angle cleats and timber blocks (Figure 3.6) was found, by the safety management team, to be hazardous. In order to improve the efficiency optimize the design, additional simulations were necessary for the safety management team.

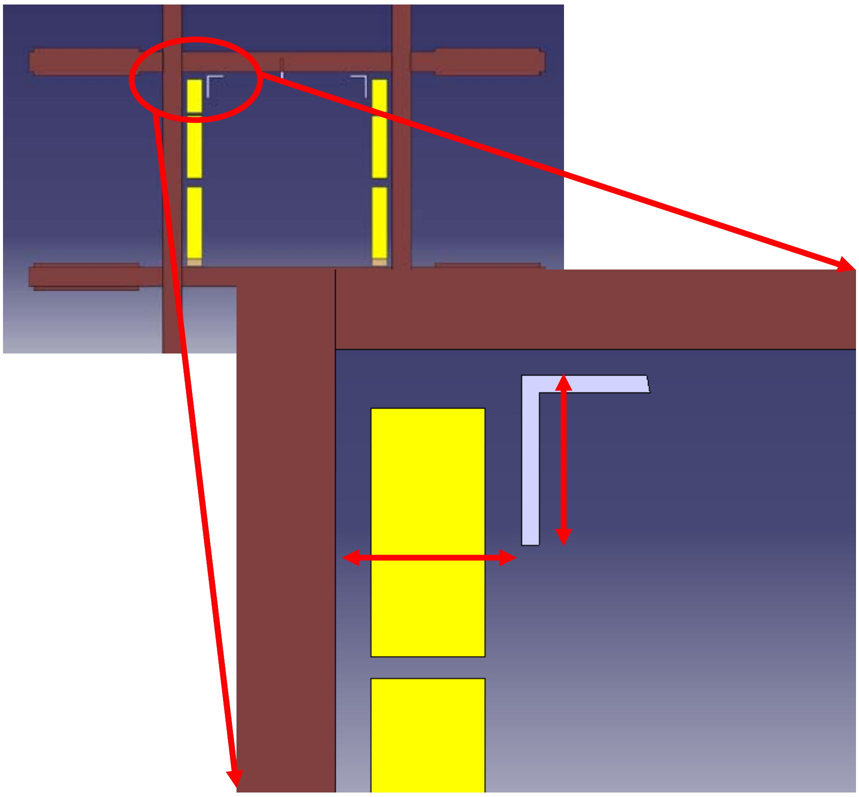

Figure 3.6: Inadequate design of the angle cleat dimensions

2. Inadequate headroom for operating the hammer. During the simulation of the construction process, the system alerted the team to a clash of the use of the hammer regarding the model of truss A (Figure 3.7). It was apparent that there was inadequate headroom for operating the hammer the truss

Figure 3.7: Inadequate working space within the truss

3. The need for on-site supervision. The simulation also assisted the safety management team in deciding the extent to which on-site supervision was needed. The DELMIA system allows the user to simulate processes from the viewpoint of the inserted virtual worker, as shown in Figure 3.8, and so, by simulating the construction process from the eye of the worker, the safety management team was able to understand the difficulties he faced. Several

signs of construction method failure during the construction process, were identified and which were hazardous from the worker's view point. This resulted in the recommendation of on-site supervision for this construction activity.

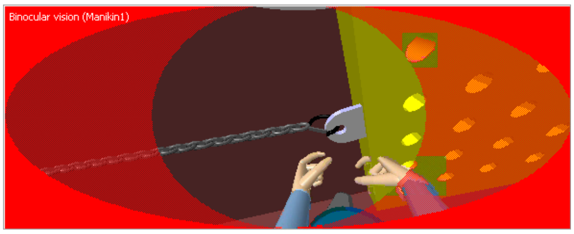

Figure 3.8: Eyesight of the worker simulated by CVP system

3.3.5 Simulation of Specific Scenario

Due to the problem of improper design of temporary support to the splice plates during installation, additional simulations were carried out to optimize the design of the angle cleat. Different dimensions and installation locations of the angle cleats were simulated by the CVP system, as shown in Figure 3.9. The CVP system was then used to conduct a spatial analysis to judge whether or not the splice plate would fail under different conditions. Based on the criteria provided by the safety management team, the design of the temporary support system was then radically changed in terms of the dimensions, installation location, material and number of installed cleats.

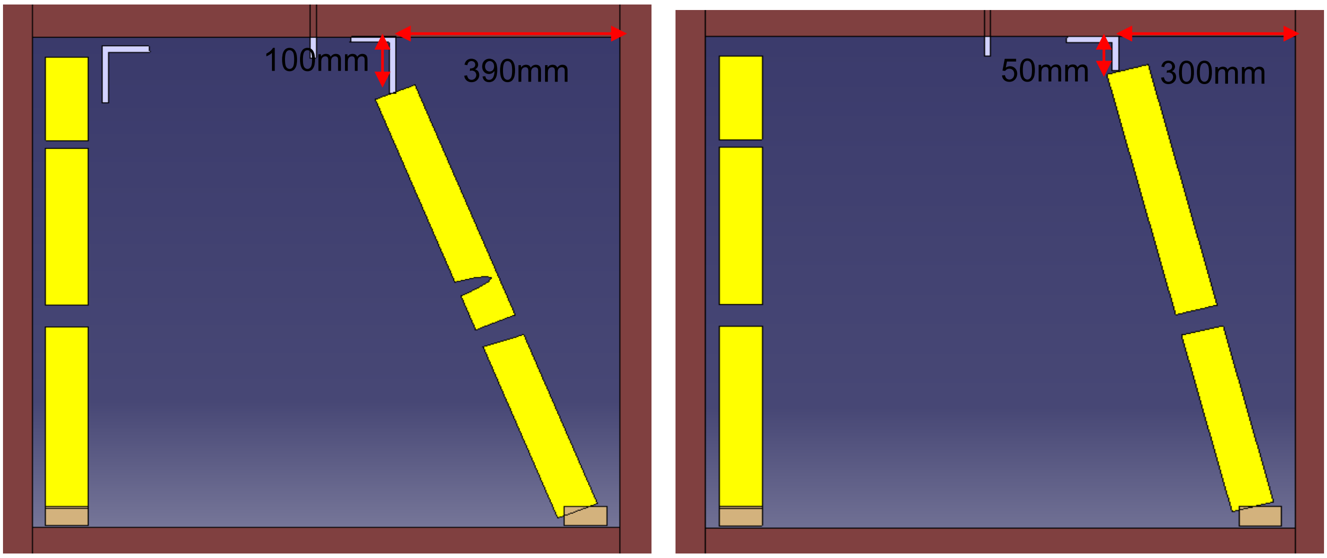

Figure 3.9: Dimensions and installation locations of the angle cleats

3.3.6 Feedback

Upon completion of the study, the CVP approach was evaluated through a number of interviews held on-site with ten members of the project, which includes one safety manager, three safety officers, two project managers and four project engineers. In this way valuable feedback was also provided regarding the utilization of virtual prototyping technology. The questions asked mainly concerned the functionality of the software and its benefits to the project. The average rating of the effectiveness of CVP in different areas is summarized in Table 3.1, where a rating of 5 r epresents ‘highly effective’ and a rating of 1 represents ‘not effective at all’.

Stage of Application	Average Score
3D environment for investigation	3.5
Construction Process for investigation	4.1
Simulation of specific scenario	3.8

Table 3.1: Effectiveness of CVP in safety management during the early construction stage

The average rating indicate that the safety management team members found: 1.their understanding of the working environment had been improved by the visualization of the engineering drawing in the first project stage and 2. the 3D environment assisted them in identifying inadequate safety designs. In addition, it was stated that the 3D environment allowed them to gauge the dimensions of the working environment more easily than by simple reference to the engineering drawings.

During the second stage, the safety management team members believed that the visualization of the construction process, including the simulation of worker behaviour, improved their understanding of the relationship between the working environment and the working procedure. The system provided a spatial check that identified such as, the use of a hammer was not suitable within the given working environment. The analysis conducted by the CVP system, in general, satisfied the safety management team, in that it enabled team members to reconsider the suitability of the working procedure, selection of hand tools and the design of the detail of the angle cleats at a relatively early stage and more easily.

Criticisms concerning the CVP approach, voiced by the safety management team focused on the length of time required for simulating the virtual worker. This problem is currently unavoidable as simulating human movement usually involves the comprehensive modelling of muscles and joints, a process that is currently very demanding on computer time.

Positive feedback concerned the identification of hazards. The safety management team recognized that a total of six potential threats were successfully identified by the use of CVP system during the early design stage (Table 3.2). Significantly, the team members believed that most of these hazards would not have been identified if the identification process had been carried out in the traditional way.

Stage of application	**Hazards' reference number**	**Detail of the identified hazards**	**Issue may be missed without CVP**
3D environment for investigation	1	Inclined working environment with slippery metallic floor material	Will not be missed
Construction Process for investigation	1	Improper design of temporary support to the splice plates during installation, which could lead to fall of splice plates.	Will probably be missed
	2	Inadequate headroom for operating the hammer, which the working procedure should be reconsidered.	Must be missed
	3	The need of on-site supervision by safety officer was raised, which the officer can monitor the activity and stop the activity when signal of failure is noticed.	Will probably be missed
Simulation of specific scenario	1	The installation location, the dimension and number of angle cleats to be installed were modified according to the simulations conducted.	Will probably be missed
	2	The use of timber block was replaced by metal block, while the block was welded to the bottom of the splice plate instead of place below the splice plate.	Will probably be missed

Table 3.2: Number of potential hazard found in each stage

3.3.7 Cost-benefit Assessment

The benefits of new safety management approaches are always hard to measure as 'before' and 'after' comparisons are seldom available. In this research, the benefits of the proposed approach are summarized indirectly by the collection of users' opinions and comments (Table 2). The costs involved are divided into two parts: software and hardware, and human resources. The software and hardware are not discussed at length here, however it is clear that they are reusable, thus significantly lowering the longer term project costs involved. In terms of the human resources involved in the case study, some additional costs are involved. For example, the simulation of a ten-minute construction activity involved around a month's work, over which time several series of modifications were made including changes to the 3D models, construction methods and sequences The cost in this instance was approximately one-month's salary of the two to three safety managers involved. It is important to note, the identification of hazards likely to have been missed by the team, as given above. Without this identification, potential construction accidents, could have contributed significant financial and human costs to the project.

3.4 Discussion

Although the feedback received from the interviews suggest that the CVP approach effectively assists the traditional hazard identification process, in its current form, it is not recommended to be employed directly by safety management teams as the use of VP requires a suitable degree of professional knowledge in simulation. However, as the cost of simulation is quite low, at present the approach is viable through utilising specialist consultants.

In this study, the application of the CVP approach was demonstrated for a set of unique project circumstances and, in its current form, the approach acts simply as a cover for traditional practice as it relies heavily on the level of detail of the 3D environment and 4D simulation.

It must be noted that with inadequate construction information, the approach could miss potential threats. Another factor worthy of note is that, while the traditional approach cannot be employed until the design is completed. The CVP approach is used during the early design stage of a project, while the traditional approach cannot be employed until the design is completed.

3.5 Summary

This section presented the CVP approach for modelling and visualizing the construction process and allowing users to simulate construction processes and make investigations in a 3D environment prior to the commencement of actual construction. In the case of hazard identification, the simulation of worker posture substantially changes the traditional approach, which relies exclusively on drawings and method statements. As the case study illustrates, the CVP enables users to identify potential dangers that would otherwise be very difficult to identify without its assistance. As those involved pointed out, of the six potential hazards found with the assistance of the visualization technology, five would have been almost impossible to identify by conventional means. The approach, therefore, creates a new platform for the management team to discuss and inspect the validity of the safety measures needed during the detailed planning of construction work. By repeating the process, it is possible to identify optimal methods *during the design stage* for carrying out construction activities so as to fulfil both safety and scheduling requirements.

In its current form, the CVP system is unable identify construction hazards *automatically*. It is a platform for a proactive preventative approach, however, that assists the management team in planning very detailed aspects of particular construction activities and eliminating the potential hazards involved well in advance of on-site construction activities.

In section 2.5.4, it is mentioned the impossibility to identify all hazards before the start of construction. In case of missing any of the hazards before construction begins, the safety knowledge and attitude of workers is important as it is the last defence. In the next chapter, an improved safety training system is proposed. The safety training system aims to improve the safety performance of workers in order to further decrease the occurrence of construction accidents.

CHAPTER FOUR: MULTI-USERS VIRTUAL SAFETY TRAINING SYSTEM

4.1 Introduction

In this chapter, details of the Multi-user Virtual Safety Training System (MVSTS) are provided. The development of MVSTS is based on an existing game engine *3DVIA Virtools* - a development and deployment platform developed by Dassault Systems. This can facilitate prototyping and robust development and is an innovative approach to interactive 3D content creation. It has a wide range of applications, including widely used for design reviews, shopping experiences, simulation-based training, advergaming, sales configurators. Virtools is highly success in game industry and its ability to create network connection is the main reason for being selected in this study.

4.2 Framework of MVSTS

The implementation of MVSTS includes the definition of functions. The system should be capable of delivering the following functions in order to achieve training value:

1. Multi-user platform
2. Database
3. Knowledge and Rules

The combination of these functions forms the core of the system, which is shown in Figure 4.1. Trainees are connected to a shared virtual environment by the Multi-user platform. The Database stores the true values for all the pre-defined input of the trainees, while the Knowledge and Rules module validates the input of the trainees with the Database. The details of the functions are explained below:

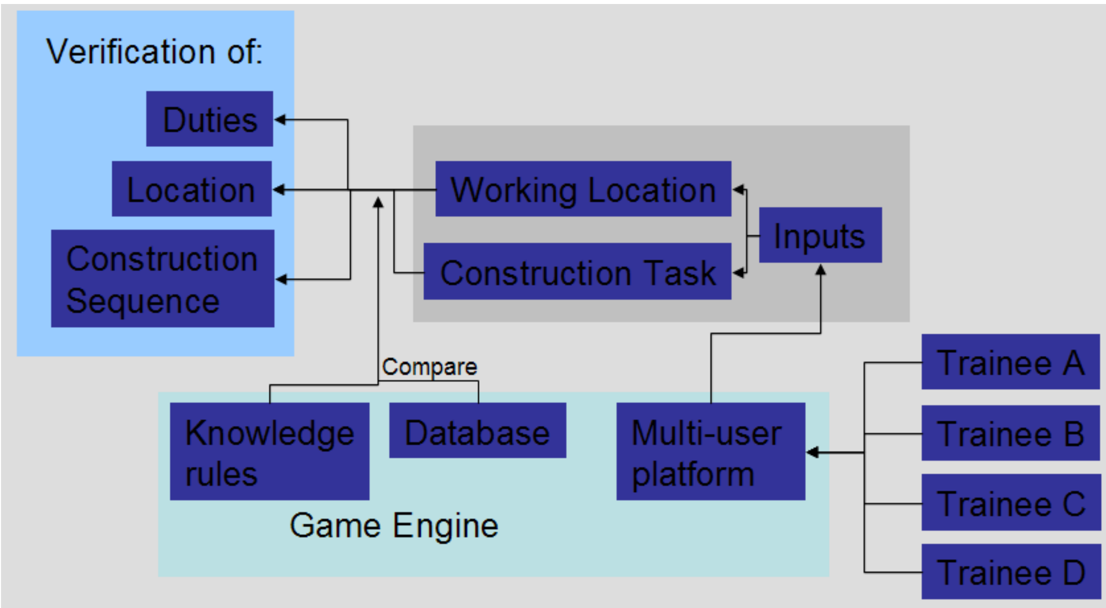

Figure 4.1. The system structure of MVSTS

4.2.1 Multi-user platform

In order to build a training system that can simulate the dynamic nature of construction site, it is necessary to allow more than one trainee to connect to the system simultaneously. The platform is developed by comprehensive computer programming work. The *3DVIA Virtools* development platform supports the use of the *C++* language used in the platform development.

4.2.1.1 Server Connection

Once the system is started on any computer, it automatically searches for the server. The trainees can also manually connect to the server by providing a suitable I.P. address. However, the platform is not only capable of connecting computer together, it is also capable of data synchronism between all connected computers. The detail of Synchronism is explained in next paragraph.

4.2.1.2 Assigning attribute

When the trainees sign in, MVSTS requires them to select their role during training, which can be labourers, safety officers, foremen or machine operatives. For each role, their responsibility during the training period is stored in a database system. The system gives an attribute to trainees, which indicates the role of the trainee within the process. Also, every construction activity within the system has another attribute. The attributes of construction activities are stored in the database system. This attribute is used for verifying the duty of the trainee. For example, labourers have an attribute “L” and all of their responsible construction activities are also given an attribute “L”. When the trainees who are not assigned as labourer initial a construction activity, the system checks the trainee’s role and compares it with the attribute of the construction activity.

4.2.1.3 Synchronism

The Platform also synchronizes all connected computers when any of the trainees provided an input, including workers’ movements, construction activity or machinery movement. This ensures that the virtual environments for all connected computers are always the same.

4.2.2 Database

It is necessary to explain the structure of the training tasks before describing the database. Within the training system, the complete construction process is divided into major construction tasks and these major tasks are further subdivided into minor tasks. Each of the minor tasks is an independent task, such as erecting of framework. The major tasks comprise the combination of numerous minor tasks. For example, the construction of a concrete wall includes formwork erecting, rebars fixing, concreting and formwork dismantling.

A small database is inserted into all minor tasks, which are pre-defined in the training system. The database is simple and it includes only three attributes:

1. Time Sequence

The correct construction sequence of all minor and major construction tasks are arranged and stored in the system.

2. Location

When the tasks require the trainee to work (or not to work) in a specific location, the data of the location is stored. It is usually represented by a 3D object.

3. Responsibility

Since an attribute is given to trainees when they login, another attribute is given to the minor task to identify which trainees are responsible for the task.

4.2.3 Knowledge and Rules

The knowledge and rules are the functions that compare the input of the trainees with the database system. These comprise numerical and comparisons, the details of which are briefly discussed below.

4.2.3.1 Real-time construction sequence verification

As already mentioned, the system assigns attributes to all the minor construction tasks. An example is shown in Figure 4.2. Here, an integer is given to the minor construction task, such as “5”. The integer “5” indicates that it is the fifth minor construction tasks within the third major construction task. The flow of the construction sequence is shown in Figure 4.3.

0 : Major Construction Task	1 : Minor Construction Task	2 : Construction Location	3 : Restricted Location	4 : Responsible Trainee
3	5	Object 1	Object 2	Labourer

Figure 4.2. An example of the database of a minor construction task

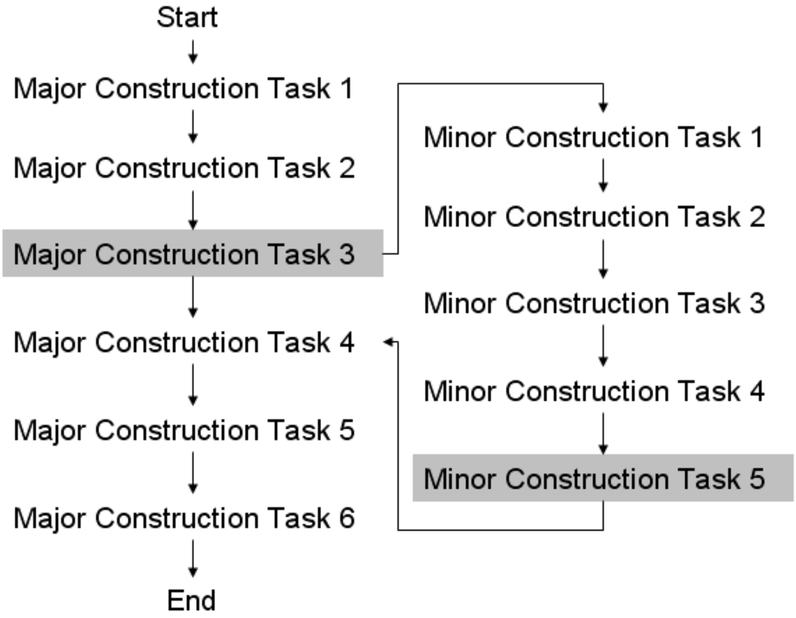

Figure 4.3. A typical construction sequence within the proposed system

When a trainee initiates a new construction task, the attribute of the new task is stored in the trainee database. The system compares the value of the original task with the new stored value as shown in Figure 4.4.

0 : Previous Major Construction Task	1 : Current Major Construction Task	2 : Previous Minor Construction Task	3 : Current Minor Construction Task	4 : Trainee's duty	5 : Trainee's identity
3	3	4	2	Labourer	1

Figure 4.4. An example of the database of the labourer

Typically, the value of current task should not be smaller than that of previous task. This should be the same for both major and minor tasks. The concept here is to check the value differences between these tasks. Logically, the program is similar to the following[1]:

[1] Full details of the computer program are not discussed here.

If “Previous Major Construction Task” – “Current Major Construction Task” <0,

or

“Previous Minor Construction Task” – “Current Minor Construction Task” <0,

V = “Current Major Construction Task”

N = “Current Minor Construction Task”

The program records the major and minor task numbers and put them into the database of the main system for scoring purpose. The system checks the status of all the trainees in real-time. When one of the trainees changes the value in his database, the system checks the database of all trainees. Once an error is found, the system records the error in a log book (see Scoring System below).

4.2.3.2 Real-time verification of the trainees’ working location

The verification of working location is carried out in two ways. The first is to check if the worker is working at the correct location. The second is to check if any other worker is present at this location. Real-time collision checks are used to do this. A 3D box is hidden and placed at the destination (correct location or restricted location). Once the trainees update their status, the system performs a real-time collision check. An example of a real-time collision check is shown in Figure 4.5. Here, the worker on the left hand side collides with the 3D object while the one on the right hand side is free from collision.

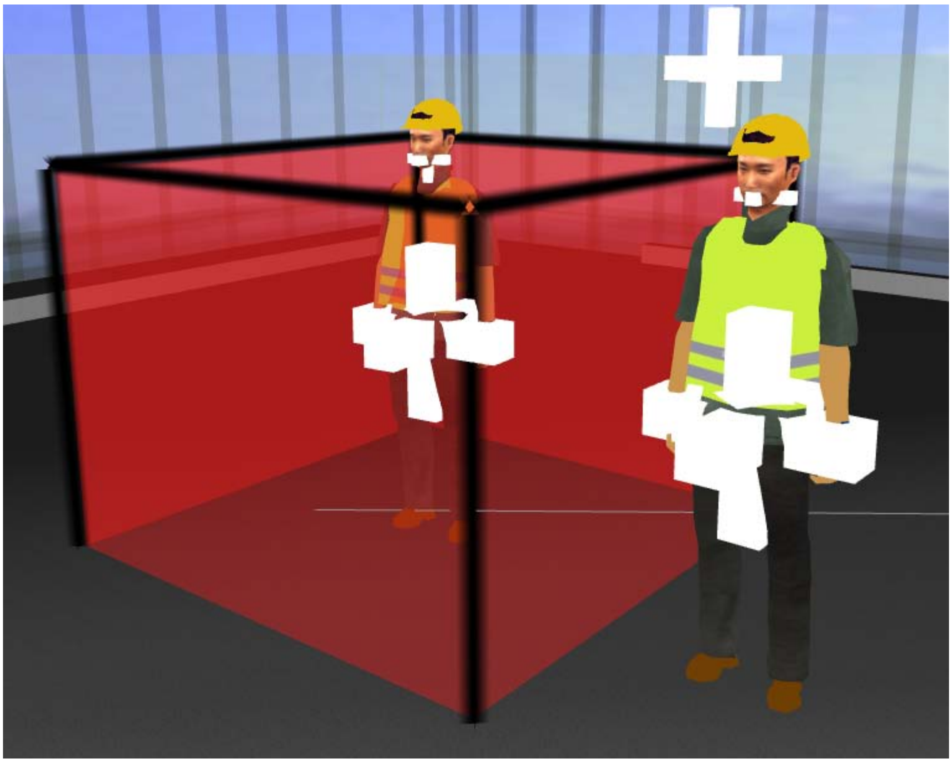

Figure 4.5. An example of a collided worker (left) and collision free worker

The system then records any errors in the system database. This includes the trainee's identity, the current major task, the current minor task and the construction location or restricted location (depending on the error).

4.2.3.3 Real-time verification of trainees' duties

Discipline is vital in the construction industry. It is important for operatives to work according to instructions together in order to complete tasks safely. In order to check if trainees have performed tasks within of their responsibilities, the system performs real-time verification of trainees' duties. This is done by comparing the database of performed tasks with the database of the trainee who initiates the tasks. As shown in Figure 4.2 and Figure 4.4, the data for "Responsible trainee" and "Trainee's duty" are compared. If the data are found to be different, this is reported to the scoring system.

4.2.3.4 Scoring system

The scoring system records the incidents caused by the trainees. There are three forms of incident involved, which are related to (1) the construction sequence, (2) construction location and (3) the duty of the trainees. Once an incident is recorded by Knowledge and Rules 1 to 3, its detail are recorded by the scoring system. Data are extracted from the database of both the construction activity and trainee and the system creates a new array for capturing the related information. An example is shown in Figure 4.6. Here the first two rows identify the trainees' incorrect construction sequencing. The next two rows records the tasks that trainees performed which should be the responsibility of other trainees. The last row shows that the errors in working location. In order to pass the training, the trainees should avoid making mistake during the training. The trainees get highest mark (32, as shown in figure 4.10) only if they complete the training without making mistake. There are two types of mistake, which are minor mistake and serious mistake. Minor mistakes are defined as the mistakes which may lead to minor injury or damage to equipment, while serious mistakes refer to mistakes that may lead to serious injury, fatality. Trainees have their training failed if they have made 2 minor mistakes or 1 serious mistake during their training.

0 : Major Task	1 : Minor Task	2 : Related Trainee Identity	3 : Related Trainee duty	4 : Task's responsibility	5 : Incident type
3	5	1	Labourer	Labourer	1
3	6	2	Labourer	Labourer	1
4	1	1	Labourer	Crane Operator	2
4	3	3	Crane Operator	Labourer	2
5	1	1	Labourer	Labourer	3

Figure 4.6. The database of the scoring system

4.2.4 Input devices

In computing, input devices refers to the communication between user and an information system. Keyboard and mouse are typical computer input devices. In this research, the Nintendo Wii remote and nun chuck is used as the input device. The reason for selecting Nintendo Wii remote and nun chuck can be explained by its function to connect to computer through Bluetooth and its accelerometers. The accelerometers allow the user to give motion input, such as swinging their arms. A program is built to link the Wii remote to computers through Bluetooth technology.

4.2.4.1 Move around the site

By controlling the nun chuck as figure 4.7, the user can control the movement of the virtual worker to location by controlling the direction of the highlighted button.

Figure 4.7. The control of movement

4.2.4.2 Change of virtual worker's view point

To change the view point of the worker, it is similar with the procedure to move the worker around the site. The only different is that the user is required to press an addition button, which is show at figure 4.8.

Figure 4.8. the control of view angle

4.2.4.3 The use of action keys

Another remote is used for carrying out different actions. For example, when the users are required to install or remove a bolt, they users should move the workers next to the bolt, as show in figure 4.9, and hold the highlighted button of the controller and swing it as shown in figure 4.10.

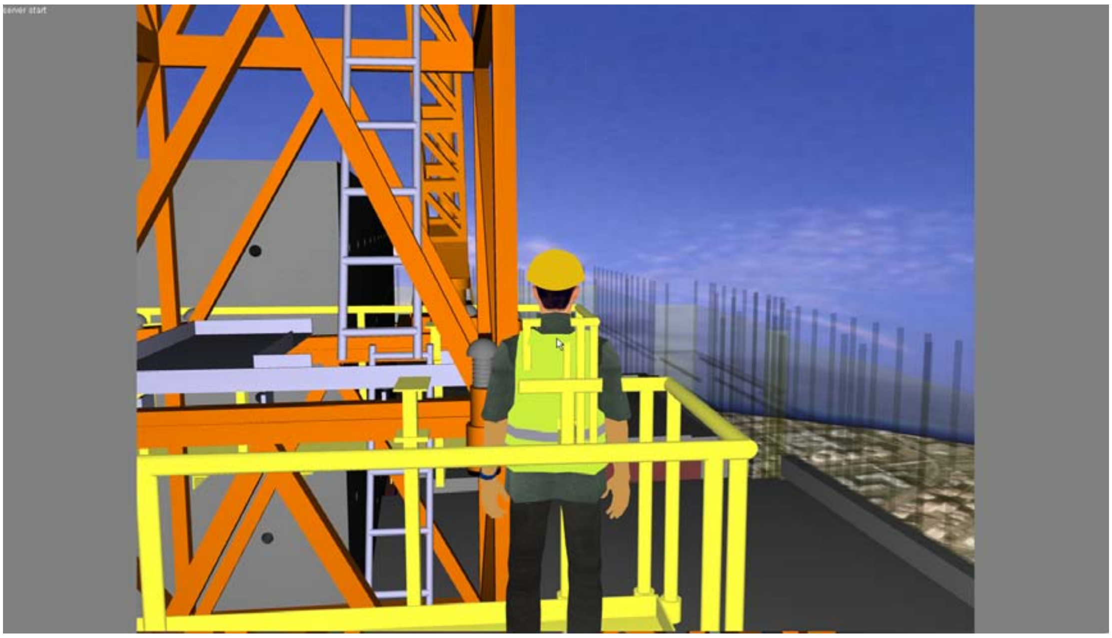

Figure 4.9. The worker stands next to the bolt before installing or removing the bolt

Figure 4.10. the control of bolt installing or removing process

4.2.4.4 Manufacturing of equipment

During the construction process, it requires different construction equipment. In this research, as the manufacturing of heavy machinery is not the main focus, the manufacturing of construction equipment is simplified. For example, the user is only allowed to perform slewing, trolley travelling and hoisting up and down for a tower crane. Similar with moving around the site, the use of Wii remote and nun chuck is used for controlling the equipment.

4.3 Case Study

In order to evaluate the proposed approach, the method of case study was selected to demonstrate the application and interviews were followed to provide qualitative data for the evaluation. Before conducting the case study, the area of safety training had to be defined in advance. The training for dismantling tower crane was selected. The detail is explained in the following paragraphs with literature review.

4.3.1 Selection of case study

A case study was conducted for tower crane dismantling. Tower cranes are widely used in the construction industries of all developed countries. In Hong Kong for example, the Deputy for Labour of the Hong Kong Labour Department, Ting (2007), summarised an inspection conducted in July 2007 which recorded a total of 215 tower cranes being used on 113 construction sites in Hong Kong - nearly two tower cranes for every construction site. Immediately after, a total of 123 warning letters were issued to construction sites concerning the use unsafe working practices involving tower crane operations, suggesting that much improvement is needed. In fact, the use of tower cranes, which includes erecting, dismantling and operation, is one of the major causes of fatalities on construction sites (Beavers et al. 2006). In Hong Kong, a total of 12 tower crane accidents occurred during the period 1998 to 2005, causing 14 fatalities (Occupational Safety and Health Council 2006), with approximately 50 workers dying in the past 40 years as a result of unsafe use of tower cranes and related operations (Lee 2006). More recently, there have been five fatal accidents related to tower crane use during 2002 to 2006, with three workers being killed in July 2007 alone (Ting 2007). The tower crane accident caused in July 2007 was an example of serious construction accident which caused two fatalities and five serious injuries. The accident happened during the dismantling process, which workers were found working on the tower crane when the tower crane was climbing down. The investigation team reported the possibility that the workers were unfamiliar with the dismantling process and they were working at the location which should be restricted during the climb down process. It is believed that the number of fatalities and injures could have been reduced in this accident if the workers were probably trained.

4.3.1.1 The need of safety training for tower crane operation

The Construction Industry Research and Information Association (CIRIA) (2006) has examined the major causes of tower crane accidents on construction sites and classified their causes into three groups:

1. Failure of the tower crane structure
2. Installation errors
3. Improper operation, such as overloading

Some of these causes are obviously related to human errors, which could have been avoided if the operatives had been probably trained before working with the cranes.

In general, it is well known that the lack of structured training for providing skills and safety training to new workers is a hindrance to safety (eg., Goldenhar et al 2001). For tower cranes, this is even more important as, lack of education and regular training of workers in the crane environment is one of the main causes of tower crane accidents (Hakkenin 1993). Likewise, Beavers et al. (2006) agree that crane operators and riggers do not receive enough training and suggest that they all should be qualified before they work, and that requalification should take place every three years. They also suggest that special trade crafts should attend crane safety training *before* they are allowed to work for crane related operations instead of just through on-the-job experience as is the traditional and current approach.

4.3.1.2 The current practice of crane operation

In the USA, Beavers et al. (2006) found that approximately 40 p ercent of employers were rated as having “inadequate” or “nonexistent” training programs during fatality investigations in 2005. In Hong Kong, the situation is similar. There are two types of training for tower crane operation, which are on-the-job training and training courses. Lee (2006) pointed out that there are no safety training courses in tower crane dismantling provided by any of the local training institutions. The reason is that, although the importance of tower crane training is acknowledged in the industry, off-the-job training opportunities for tower crane related workers are limited for, in term of cost alone, it is usually impracticable to erect a tower crane and derrick boom merely for practice purposes. Therefore, the only way for trainees to practice is to work on site on real projects

In Hong Kong, on-the-job training is carried out by training under a mentorship programme. The mentor passes his experience and skill to the mentee, which usually starts with the provision of guidelines to the mentee during the work. Of course, as the success of this system relies highly on the quality of the mentors, a poor mentor could easily pass improper attitudes to the mentee. Unlikely the new regulations of OSHA, the trainers are not required to have any form of certification process. There is also no regulation for the training contents. Thus, there is no assurance of good practice. Also, even after the mentees have received tuition during the work, they still have occasional difficulties in applying their skills and knowledge due to lack of sufficient practice. This situation has particularly hindered the development of mentees. In other industries, where safety is paramount, operatives are required to undergo regular training to ensure their competence. Airline pilots are an example.

A further issue concerns the shortage of information on tower crane use. This is a particular problem in the disassembly or dismantling phase, where construction operatives can only rely on the erecting-dismantling manuals produced by crane manufacturers (Lee 2006). Putting such information into practice is not a simple task and mistakes are bound to happen. Clearly, what is needed is some facility for operatives to develop the necessary skills in a non-hazardous situation. O ne means of doing this is in a virtual environment.

4.3.1.3 Previous study in crane operation

Crane accidents and their prevention were studied by researchers as early as 1970s (Hakkinen, 1978). Shepherd et al. (2000) conducted a taxonomic analysis in crane fatalities happened in the US. The report divided more than 500 recorded crane related accidents in the US into different types. Neitzel et al (2001) reviewed the crane safety in the US and has given related suggestion to the industry. Others have suggested to control the safety performance of cranes' related construction project by measuring and analyzing factors affecting the site safety by different approaches (Shapira and Lyachin, 2009; Shapira and Simcha 2009a; Shapira and Simcha 2009b). Shapira et al (2008) suggested using vision system to assist the use of tower crane, which could eventually improve the safety performance. Meanwhile, Kang et al (2009) suggested that the use of 3D simulation and visualization for simulating the erecting process of steel structure. They believe that the use of 3D simulation to rehearsal the construction process in virtual environment can help the crane operator to better understand the operation process. The previous effort in crane study is huge, however there is so far no research focus on training, which is one of the most important issue.

The complete dismantling process was divided into major tasks and minor tasks as shown in Figure 4.11. The database of the construction activities was set after the completion of related 3D models and construction process simulation. The virtual workers, roles and its database for the training were then defined.

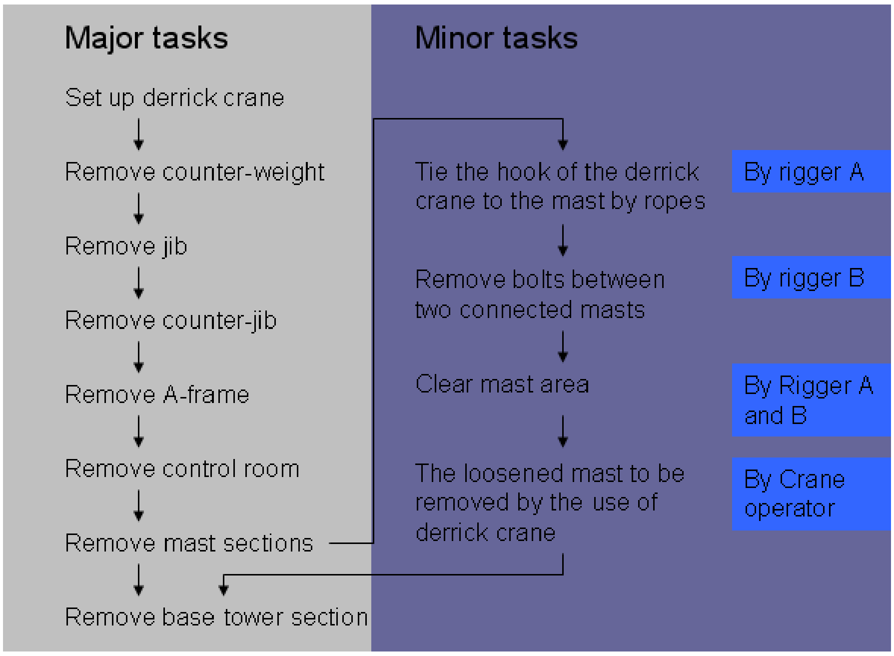

Figure 4.11. Classification of major and minor tasks

4.3.2 The detail of the case study

After explaining the reason for selecting dismantling tower crane as the studied case, the following paragraph explains the flow of the framework.

4.3.2.1 Real-time construction sequence verification

The construction sequence for the training process was pre-defined as shown in Figure 4.11. The major and minor tasks were also arranged accordingly. The construction sequence was set according to an erecting-dismantling manual produced by one of the major crane manufacturers and a method statement for crane dismantling from one of the major main construction contractors in Hong Kong. Attributes are given to individual activity, by comparing these attributes, the system can verify the users input. When the trainees failed to follow the pre-defined working sequence, the system recorded the mistake.

4.3.2.2 Real-time verification of the trainees' working location

This involves two situations:

1. The trainees must work in certain area in order to avoid accident
2. The trainees must avoid working in certain area in order to avoid accident

An example is shown in Figure 4.12. The working area to be *avoided* is highlighted. Two cubic boxes are placed and hidden at the temporary working platform. Before the crane operator starts the next task, all other trainees have to leave the highlighted area to avoid detection by the real-time collision check.

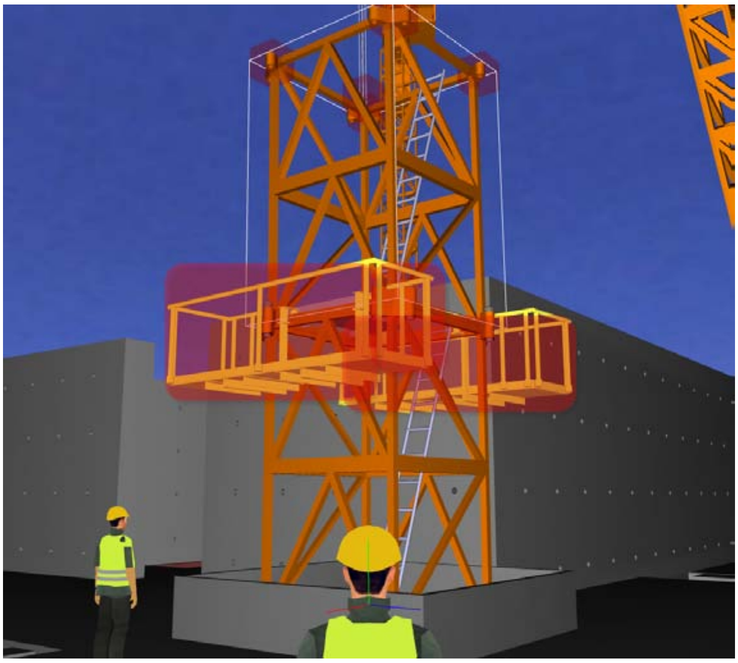

Figure 4.12. The avoided working area

4.3.2.3 Real-time verification of the trainees' duties

The minor tasks were assigned to rigger A and B respectively. If rigger A accidentally completed the minor task "remove bolts between two connected masts" (which is the duty of rigger B), the system recorded and reported the situation to the scoring system.

4.3.2.4 Scoring system

The scoring system collected information from all the different databases within the MVSTS. The information was stored within the system and printed in table form at the end of the training session. Each of the trainees receives a report containing all mistakes made by the trainee. An example of the report is shown in Figure 13.

4.3.3 Feedback

In order to evaluate the effectiveness of the system, thirty construction operatives working as riggers during a tower crane dismantling process were invited to participate. The participants have different working experience, whose has worked for tower crane erecting and dismantling from approximately three years to no experience. All riggers were then divided into three groups, named group A, B and C. Group A included 10 construction workers whose have no experience in tower crane related operation and have not been trained by any tower crane related course. Group B and C respectively included 10 construction workers whose are experienced in tower crane related operation and have recently trained by traditional tower crane dismantling course. Both group A and B were trained by the proposed system. Afterward, all groups were invited to take a short quiz, which consists of twenty multiple choices questions about tower crane dismantling process. The maximum score for the quiz is 20, w hich means the interviewees have given correct answers to all questions. The results for different groups are compared in Table 4.1. It indicates that group B's performance is slightly better than group C. The performance different can be the result of the additional use of the proposed training system. The result of group A and C are similar. Base on the different in experience and previous training, It can be explained that the proposed system is an effective training platform and the trainees have gained valuable experience and knowledge from the platform.

	Average of Group A	Average of Group B	Average of Group C
Scoring & Result Max = 30	24.2 *(2.441)	26.1 *(2.427)	24.3 *(2.283)
Working Location related Max =10	8.1 *(0.830)	8.8 *(0.980)	8.0 *(0.894)
Working Sequence related Max =10	7.8 *(0.872)	8.7 *(0.781)	8.2 *(0.872)
Working duty reltated Max =10	8.3 *(0.900)	8.6 *(1.02)	8.1 *(0.943)

*(Standard Deviation)

Table 4.1. Result of the MVSTS case study

Interviews were arranged separately for group A and B to collect their opinions regarding the proposed training system. Four questions were asked during the interview to rate the traditional training method against the MVSTS. The average ratings are presented in Table 4.2. A rating of 5 represents ‘highly effective and a rating of 1 represent ‘not effective at all’. The results indicate the MVSTS to be satisfactory. The workers generally acknowledged that the system assisted them in learning the correct construction process. Compared with traditional training, the workers thought that the use of visualization improved their interest in training. They also stated that the use of visualization has made the training content easier to understand. Moreover, they also agreed that the system’s final report helped them to find out their own weaknesses – a major concern in traditional training is that they cannot identify their own weaknesses and areas in which they are short of training.

MVSTS as a training tool for:	Rating
Learning construction sequence	4.1
Learning working location and restriction	3.8
Learning working cooperatively	3.5
Learning own weaknesses	4

Table 4.2. The average rating for the MVSTS

4.4 Summary

The research described in this project marks a major step toward the use of visualization skills in safety training. A new system of training for dismantling tower crane is described by utilising an existing game engine approach. The integration of game engine and safety training provides a close-to-reality 3D environment for the trainee to learn and practice their knowledge. This system, termed the Multi-user Virtual Safety Training System (MVSTS) comprises four developed functions to allow trainees to learn the comprehensive construction processes in a virtual environment, which is risk-free. A live case study is also described in which operatives undergo off-the-job training for the dismantling process of a tower crane, which follow-up interviews indicated to be a successful improvement on t he traditional approach to skill development in this context. Feedback showed one of the main benefits to be the identification of the trainee's weaknesses and opportunity to develop skills through off-the-job practice. T he ability to allow the trainees to work corporately in a dynamic 3D environment clearly creates a chance for the worker to practice before the start of actual construction. As the virtual environment of the system is not critical to the platform and could be changed in a short period of time, the system can be used for training users in different virtual environment, such as a small construction site with limited space or a large construction site with numerous of cranes erected.

As far as future studies are concerned, further investigations on the use of existing game engines for safety training are suggested. This would involve the use of different game engines and explore new functions for conducting safety training in a more effective way. As different game engines have different strengths and weaknesses, the use of other game engines may achieve an improved result both in terms of cost and effectiveness. The change may also bring about a new training approach to the construction industry. In addition, by expanding the case study, the system has the potential to provide a complete platform for manufacturing machinery training. In this study, the manufacturing of tower crane is studied and simulated within the game environment. The movement of the tower crane control is simplified by the authors in order to make the programming process more efficient. However, it provides a success story for simulating the basic manufacturing for a heavy construction machine and more effort should be placed in studying the process for simulating the comprehensive operation of other heavy construction machinery.

CHAPTER FIVE: VIRTUAL SAFETY ASSESSMENT SYSTEM (VSAS)

5.1 Introduction

The weaknesses of the current hazard identification practice are pinpointed by the literature review. The effectiveness of construction safety training and assessment is also questioned by different researchers. At a result, it is important to precisely assess the workers before they are eligible to work on site. In the last chapter, a new training system, which allows the trainees to practice different skills virtually, was proposed and evaluated. The use of new technology to improve only safety training, however, is inadequate. The improved safety training approach may only help the trainees to learn in a virtual environment, but there is still no guarantee in the quality of the workers if the current certificate practice is not changed. Hence, a new assessment system is needed order to improve the quality of individual construction workers.

In this chapter, a new safety assessment approach Virtual Safety Assessment

System (VSAS) is proposed. Base on the success in other industries, the VSAS approach aims to visualize the assessment process by using existing game engine. The value of the approach is presented at the end of the chapter.

A game engine "Unity 3D", which is developed by Unity Technologies, is employed in this research. Unity 3D is a game development environment allows users to create game easily and it is one of the most powerful game engines which could perform close-to-reality real-time rendering, which is essential for the development of the proposed platform.

5.2 The framework of VSAS

Typical causes of construction accidents are reviewed in previous chapter. The development of VSAS aims to visualize the reviewed causes for safety assessment. The visualization processes are the combination of virtual environments and 3D simulations. The logic framework of VSAS is shown in figure 5.1. The detail of the visualization procedure is discussed respectively.

5.2.1 Visualizing unsafe site condition

Before visualizing unsafe site condition, a complete virtual site environment is needed. The virtual environment contains all available detail, which includes both temporary and permanent structure, building services, construction material storage, wastes, construction equipments and tools. A close-to-reality virtual environment is the basic requirement in order to provide a 3D experience to the examinees. The use of material and texture can easily improve the rendering performance especially for real time rendering. The use of material and texture is demonstrated in figure 5.2. A close-to-reality engine is built by applying suitable material and texture. By repeating the process on different model, the system can form a virtual environment which is close to the reality. Different hazards are then inserted into the virtual environment, such as building edge without proper fencing. The system allows examinees to observe within the environment and the examinees can make their own decision regarding safety based on their knowledge and experience. An example of virtual environment is shown in figure 5.3.

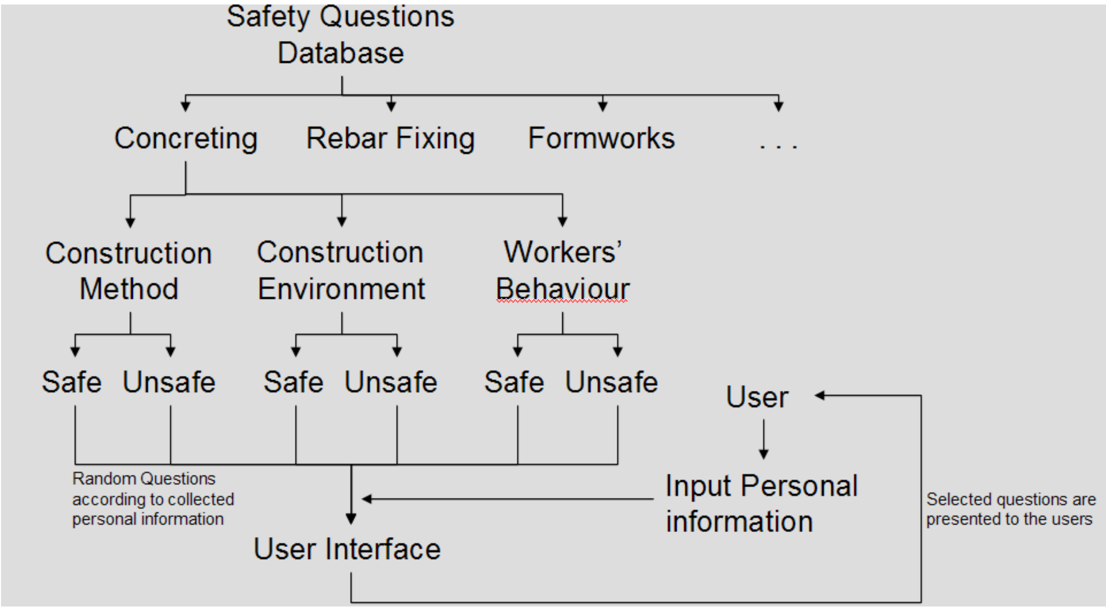

Figure 5.1. Logic framework of VSAS

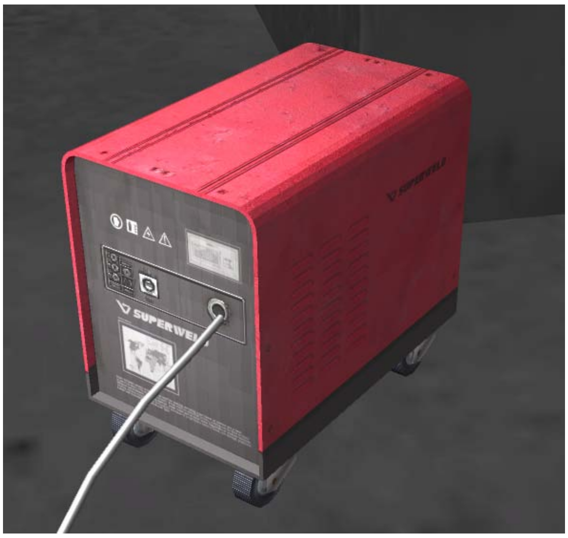

Figure 5.2. The welding machine with texture

Figure 5.3. An example of virtual environment within VSAS

5.2.2 Visualizing unsafe working behaviour

The presentation of hazardous working behaviour is achieved by integrating the use of virtual workers and the virtual working environment. The Working behaviour is presented in 3D or 3D animation. Virtual workers are inserted into the environment and they are assigned to different construction activities. For example, Figure 5.4 shows a typical hazardous working behaviour which a virtual worker is welding without wearing suitable gloves. Improper working behaviour can also be access of prohibited items, such as smoke and alcoholic during working hours. An example is given in figure 5.5.

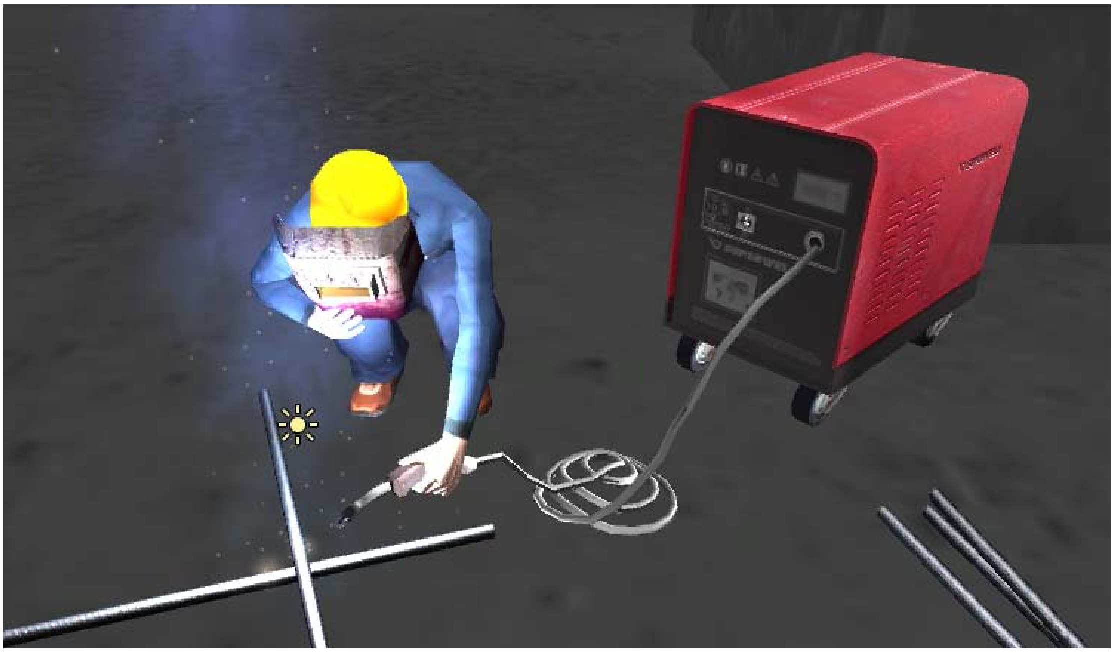

Figure 5.4. The simulation of the use of welding machine

Figure 5.5.Example of unsafe working behaviour

5.2.3 Visualizing unsafe construction methods or sequencing

The visualization of unsafe construction methods is also based on t he use of virtual environment, workers and equipments. It is presented in 3D animation. Virtual workers perform construction activity accordingly within the virtual environment. For example, dismantling of tower crane is started before all workers have left.

5.2.4 Database of VSAS

After visualization, it is important to systematically store the data. A database is required in this development. In order to enhance the current assessment practice, the questions (unsafe site condition, behaviour, construction method or sequencing) are classified with related attributes. The classification of the questions and its attributes are used for choosing questions to different examinees according to their work trade and personal qualification. All the visualizations are stored in 3D graphical or 3D animation format. Information of the activity, which contains different attributes, is then stored in the 3D or 4D model. An example is demonstrated in figure 5.6.

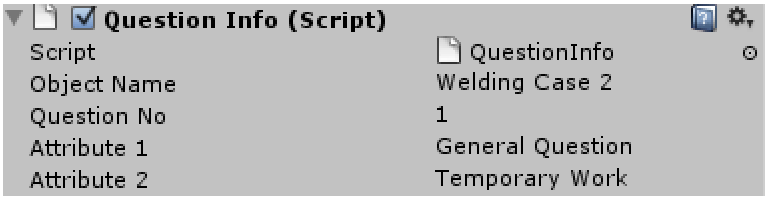

Figure 5.6. The database of a construction activity

The object name identifies the name of the construction activity. The question number means the number of questions consisted by the activity. Sometimes, there can be more than one question stored in a construction activity. The two attributes show the category of the activity and its related target examinees. It helps the system to select suitable questions for different examinees.

5.2.5 Virtual experience in VSAS

In order to select the correct answer, examinee is required to study the questions carefully. Although the questions are presented in texts format, examinee should study the entire virtual environment carefully in order to select the right answer. Within the virtual environment, examinee can walk thorough the virtual environment and talk with any virtual workers to obtain information. Examinee can also observe the environment from different view angle, which is similar to reality. This virtual experience allows examinee to perform a v irtual hazard identification process in virtual environment which is not risky.

5.2.6 Real-time interactive answering function

VSAS system allows the examinee to answer at anytime after login. It allows time for the examinee to clearly analyze the situation and to select the correct answer. In VSAS, dialog boxes are used to solve this problem. An example is shown in figure 5.7.

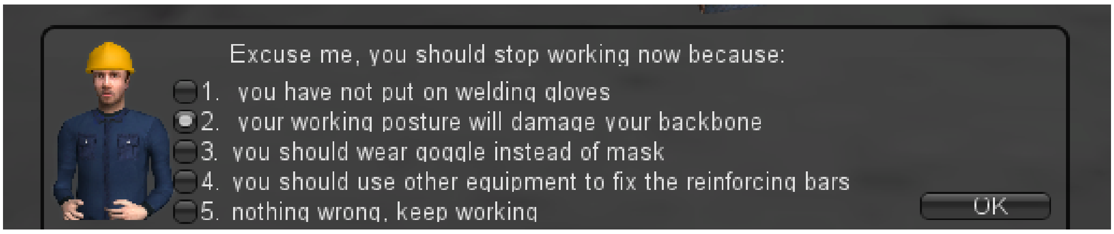

Figure 5.7. An example of dialog box for users to answer

After the examinee has selected their answer, the answer is stored in the previously discussed database. As VSAS offers only multiple-choice test, the examinee is only required to answer by clicking related answer box. The examinee can change the answers anytime before the end of the test. The examinee is required to complete all questions within limited time. When all answers are answered, the examinee can submit the test. The system checks the answers of the examinee by comparing the result with the database. An attribute is given to the activity to highlight the importance of the activity. Higher factors mean the caused accidents are more fatal than those of lower factors. The factors affect the final report of the test.

Questions are randomly selected base on the examinees' information, however the sum of the weighting factor for all examinees are the same. The system has three different weighting factors, which are 1, 2 and 3. Factor 1 means the accident may cause minor injury to the examinee, while factor 2 means more serious injury. Fatal accidents are always referred by factor 3. For each test, the sum of all questions' weighting factor should be equalled to 30.

The scoring in this system is totally different with the traditional safety test in Hong Kong. Examinees are required to complete the test and to give all correct answer for questions which have weighting factor 3. The examinees should also not to have 2 mistakes in factor 2 questions and the sum of factors for all incorrect answer should not be more than 8. The high requirement of the VSAS assures the level of safety performance in construction site which prevents serious accidents.

5.3 Case study

In order to evaluate the value of the VSAS, a case study is conducted. The VSAS is a system consists of huge database which consists of numerous of different construction activities. In this case study, the database of Personal Protective Equipment (P.P.E) is demonstrated.

The database of the case study focus mainly on the proper use of P.P.E.. More than 20 cases which include all three different weighting factors are stored in the database. The cases are typical causes of construction accidents in Hong Kong. One of the typical examples is the invalid use of safety belt. In order to create an environment for the examinee to spot such crisis, an external temporary platform, which is next to the edge of the floor, is built and surrounded by scaffolding and safety net. It is important for the examinees to know that where they are required to wear suitable P.P.E. Examples of visualization of different accidents causes are summarized in the table 5.1.

Accident causes	Examples of visualization	Question format
Unsafe site condition	Working at height without safety belt (figure 5.9)	3D model
Unsafe working behaviour	Welding without welding gloves (figure 5.4)	3D Animation
Unsafe construction methods or sequencing	Improper weight lifting method (figure 5.10)	3D Animation

Table 5.1. Form of visualization in the case study

Answer validation starts automatically after the test submission. After validation of the answers, the system reports the performance of the examinees. A screenshot of the report is shown in figure 5.8. The background of the incident and the correct answer is also reported to the examinee, which explains the importance of the incident to the examinee.

	Average number of incorrect answer which causes		
	Minor injury	Serious injury	Fatality
Construction workers	1.41	0.5	0.33
Engineers	0.4	0.2	0
Safety officers	0.33	0	0
Construction managers	0.5	0	0

Table 5.2. The result of the use of VSAS

(1 referring to ineffective, 3 referring to normal 5 referring to highly effective)	Average rating for the VSAS in term of:		
	Close-to-reality 3D environment for hazard identification	3D representation instead of texts to improve understanding to the questions	Demonstrate the safety consideration in real-life construction case
Construction workers	3.67	3.58	3.75
Engineers	3.6	4	4.2
Safety officers	3.67	4	4.3
Construction managers	3.5	4	4

Table 5.3. Effectiveness of the VSAS

Report on USER1 safety performance
Test contents: Proper use of Personal Protective Equipment (P.P.E.)

Incident: 1

Background:
Working at height is the working nature in construction industry. Ladder is available for construction use which is below 2 meters. Working on higher level requires the use of temporary working platform.

Suitable answer:
You should erect temporary working platform instead of ladder

Possible result:
Serious injury

Figure 5.8. A screenshot of the report generated by the VSAS

Figure 5.9. Working at height without safety belt

Figure 5.10. Improper weight lifting method

A group of construction workers and professionals were invited to try the VSAS. A group of fourteen construction workers, five engineers, three safety officers and two construction managers were assessed by the VSAS on the topic "proper use of P.P.E." which is demonstrated in the case study. They were required to complete the test within thirty minutes. All of the participants are currently the holder of construction industry safety training certificate and are eligible to work in the construction industry. The result of the test is shown in table 5.2. It is found that construction workers could still easily suffer from fatal construction accidents while the professionals performed relatively better. It also reports the possibility that the traditional safety assessment method may be incapable to assess the examinees' safety knowledge.

In order to evaluate the use of the VSAS system, group interviews were arranged to obtain individual opinions regarding the use of VSAS. The interviews were divided into four groups according to their jobs. The questions are mainly focus on the usefulness and effectiveness of the use of the VSAS. The result of the interviews is shown in table 5.3.

The result of the interview is encouraging as most of the interviewees believe the system enhances the current practice. Generally, all users believe the visualization of safety rules and knowledge is effective for assessing their level of knowledge and its application. The visualization of questions also improves the users' understanding to the questions. The users also believe that the virtual environment is reasonably realistic and it is possible to simulate most of the unsafe working environment.

In conclusion, the users generally believe that the use of the VSAS can assess their current knowledge and the generated report can pinpoint their weaknesses. The visualization allows the examinees to carry out hazard identification in a virtual environment which is not risky. The visualization (3D and 3D animation) improves the examinees' understanding of the questions. It also tests the examinees if they can find the problem in real construction scene, but not only texts format. However, some of the users also express the opinion that the control of 3D navigation within the system is complex and find it difficult to control the viewpoint.

5.4 Summary

The successes in identifying hazard and training in 3D/4D environment provide reinforced the foundation of this research. The use of new computer technology to enhance specific performance is not a new idea. The use of game technology and to reuse game engine in other industries are proven successful. Game technology is used in high risk activities, such as pilots and car drivers training and assessing purposes. For construction industry, there is an obvious need of a comprehensive and well organised safety training system. The use of game engine is also seems as a suitable platform for visualization, which is also proven to be beneficial for training and assessment in other industries. In this chapter, the authors demonstrate the reuse of existing game engine for visualizing the safety assessment. The development of VSAS system does not only visualize the current use of text into 3D and 4D simulation, but it also starts classifying the current safety consideration according to different factors. The classification of questions is important for the assessment system to select suitable questions for assessing individual users in deep. The report helps the users to understand their own area of weaknesses and the users can then reinforce their knowledge in specific area. All in all, this chapter has successfully developed a new assessing platform for the industry which it does not only assess the users when they are required to, but it also provides a platform for the user to assess themselves when they need.

CHAPTER SIX: CONCLUSIONS

6.1 Summary of the research

From available statistics, it was found that construction accidents accounted for the majority of industrial fatalities in Hong Kong. This statistic naturally raises the questions about construction safety management, such as what were the management problems regarding the assurance of construction safety? Why was the accident rate so high?

From the literature the following three causes of construction accidents were identified: 1 unsafe site conditions; 2 unsafe worker behaviour; 3 unsafe working method / procedure. The task of this study was thus to find the means to improve the above. After reviewing the weaknesses of current management practice, advanced information technology (I.T.) for the visualization of information in different industries, including the construction industry, two advanced I.T. applications were selected for this study. The two applications selected were the

Construction Virtual Prototyping (CVP) and Game Engine Technology and 3 new approaches were developed to improve levels of site safety. The case studies used to validate the application of these methods fall into two categories: 1.to find ways to reduce hazardous working conditions; 2 to find ways to improve worker safety attitudes. The proposed new applications developed are based on modifications to existing technologies and provide new methods for the industry to manage safety. The contribution made by the developed approach and the findings are presented section 6.2 below.

6.2 Contributions and Findings

Three new approaches based on the use of two advanced information technology (I.T.) applications have been developed. The three approaches are: (1) the use of Construction Virtual Prototyping (CVP) for hazard identification before construction; (2) the use of game engine technology for developing a multi-users virtual safety training system; (3) the use of game engine technology for developing a virtual safety assessment system.

The three new approaches tested on case studies, proved to be practical and nothing similar is currently available in the construction industry

- The weakness of traditional construction projects hazard identification was tackled using the newly developed approach. Construction Virtual Prototyping (CVP), a framework for carrying out hazard identification through visualization was successfully used. This framework enabled simulation of the working procedure of construction workers. No such tool is currently available in the construction industry. The newly developed approach enables hazard identification before specific construction procedures takes place. Such potential hazards could be overlooked using traditional practices. Hence, with CVP, working conditions and the selection of safer construction sequences/methods is more likely.

- A new safety training method has been developed, by modifying an existing game engine, “Virtools”. Visualization technique (by using game engine) has successfully been used to more effectively present construction training materials and as a new means to handle safety queries. The developed system, using game engine technology, has also provided a new training platform for the construction industry. The new system enables the training of workers in different roles, and maybe unfamiliar operations, by simulating necessary specific individual movements. This is particularly useful when new procedures are adopted and can help ensure that physical behaviour patterns will not negatively affect safety. The system proved to be better than traditional training methods. The clear difference was demonstrated in a comparison of the performance of construction workers after undergoing the two types of training. The safety knowledge of the workers appeared to be improved by the use of this training system.

- A new safety assessment system was developed by modifying the existing game engine “Unity 3D”. A new structure for the database of questions and a new method to rate the performance of the workers was implemented. The new database structure improves current assessment practice by assessing the user’s safety knowledge and skills more precisely. The developed system also provides a new platform for users to assess their own performance, when or if they feel the need. The safety attitude and knowledge of the construction workers is able to be assessed and ensured by this system.

The result of this research study has: (a) confirmed the need for new safety management tools; (b) confirmed the importance of better safety performance; (c) proved that the use of CVP to visualize hazard identification is feasible; (d) proved the feasibility of the use of game engine technology for safety training and assessment.

Some elaboration of the above is offered as follows:

a. Confirmation of the need for new safety management tools

Currently, a limited number of effective tools is available for carrying out construction safety management. A difficult task for the safety management team is the identification of construction hazards by traditional 2D drawings. Although numerous research studies have investigated the cause of accidents and factors that affect safety management, no t ools have been developed to rectify negative situations and performance.

b. Confirmation of the importance of and need for a better safety performance

The cost of construction accidents shows the importance of construction safety. However, the safety performance of the construction industry is far from satisfactory and several weaknesses in current safety practice have been pointed out above. The identified weaknesses provided a foundation for considering future research in construction safety.

c. Proof that the use of CVP to visualize hazard identification is feasible

The proposed CVP approach, based on 3D and 4D simulation, illustrates safety hazards by visualization. The approach proved to be practical in the case studies, and was also confirmed by interviews responses. The differences in hazard identification between the traditional and proposed approach demonstrate the benefits of the new technique.

d. Proof of the feasibility of the use of a game engine for safety training

The use of a game engine for safety training and assessment enables the visualization of construction safety information, knowledge, skill and questions. Using case studies to test the new approach, revealed that, the differences between the new and traditional approaches to be substantial, proving the approach to have practical benefit. The differences were further verified during interviews.

6.3 Objectives of the research

The objectives of the research are listed in Section 1.3. The objectives are revisited individually in this section.

Objective 1 to objective 5 are successfully achieved through comprehensive literature review. The causes are identified in section 2.3. The factors are summerised as *1. unsafe site conditions; 2. unsafe working behaviour; 3. unsafe working methods or sequencing.* The safety practice in Hong Kong construction industry is reviewed in section 2.4 while the problems for safety management are reviewed in section 2.4.3. In section 2.6, the use of VR technology that has been successfully implemented in construction industry and other industries are reviewed.

For objective 6 and 7, they are achieved by the three developed approaches in this research. The three developed approach are *1. The use of Construction Virtual Prototyping in hazard identification; 2. Multi-users virtual safety training system;*

3. Virtual Safety Assessment System (VSAS); The three developed approaches are briefly discussed and evaluated by case study in chapter 3, chapter 4 and chapter 5 respectively.

6.4 Limitations of the research

Although the objectives of the research were achieved, several limitations were encountered during the study.

1. Incompleteness of the training and assessment database

The author had limited time and resources. As a result, only a part of the training and assessment platform was developed in the study. The development of the training and assessment database will require huge effort to complete due to the comprehensive nature of the construction industry. Modification of the content is required before these systems could be applied to other countries due to the differences in safety regulations.

2. Limited number of case studies

Due to the limitation in case studies available, only one case study was used for both the training aspects and the assessment aspects.

6.5 Suggestions for future research

During the course of the research, several limitations were found and highlighted as potential areas for further study.

1. The use of Game engine technology to develop new training systems

   In this research, the training content for tower crane dismantlement was developed. During the development, the results indicated the huge potential of the simulation of heavy construction equipment as a training tool. The ability to simulate equipment in an interactive environment developed by a game engine means a suitable virtual environment could be provided for developing a heavy equipment training platform.

2. Visualizing safety information

   The result in this research has also proved that the identification and visualization of hazards can enhance the understanding of safety information and the need for enhancing safety behaviour. The author recommends further investigation of such as visualizing Safe operation procedures (SOPs), to study the effects.

3. Customization of the CVP approach

The simulation of human ergonomics using the Construction Virtual Prototyping (CVP) approach is time consuming. The users have to input every detail of the working posture in order to achieve a detailed simulation. It is recommended that some standard working postures of construction workers on site are captured and used for training. The simulation of construction workers' working posture could be available within the CVP platform enabling faster study of related workplace injuries, workplace illness and the causes. Because of the ability to simulate human movements, the author suggests using the CVP approach to simulate the standard working posture of construction workers and thus investigate the effect on occupational injuries and diseases.

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