Capturing Safety Knowledge Using Design-for-Safety-Process Tool

B. H. W. Hadikusumo[1] and Steve Rowlinson[2]

Abstract: An organization must strive to maintain its most valuable resource, knowledge, in order to be more productive and competitive. One of the steps to manage the knowledge is to capture contents of the knowledge. In construction site safety, success in capturing the tacit knowledge of safety officers is of paramount importance; however without a good mechanism, this process might be difficult due to time and hazard perception constraints. This paper discusses research in a design-for-safety-process tool, which aims at: (1) capturing safety knowledge from safety engineers about construction safety hazards and the safety measures required; (2) assisting a safety engineer to identify safety hazards in construction projects and determine the safety measures required; and (3) training students and inexperienced safety engineers in identifying safety hazards and the measures required. In this paper, the first objective is discussed.

DOI: 10.1061/(ASCE)0733-9364(2004)130:2(281)

CE Database subject headings: Accident prevention; Computer graphics; Computer aided simulation; Information management; Occupational safety; Safety factors.

Introduction

Construction site safety is of great importance to construction companies. Failure in managing construction safety results in worker injuries and impacts on financial losses, human conflicts, and civil penalties.

In order to provide a safe working environment for workers, governments set regulations. There are two kinds of safety regulations: prescribed safety regulations, where the government states minimal working conditions that must be provided in a construction site; and self-regulatory, where the government states general duties for an employer, thus allowing them to determine the best way of achieving the objectives of the legislation in an approach best suited to their organization.

For both systems, knowledge (i.e., experience) of a safety engineer is of great importance. In the prescribed system, it is a fact that governments could not state all of safety hazards that might be occurring at construction sites. In other words, the regulations do not reflect the dynamic nature of the construction processes; and therefore experience of safety engineers is very important. In the self-regulatory system, it is clear that an organization must develop its own approach to provide adequate working conditions and therefore the experience of safety engineers is equally of great importance.

[1]Assistant Professor, School of Civil Engineering, Asian Institute of Technology, Pathumthani 12120, Thailand ⟨http://www.sce.ait.ac.th⟩. E-mail: kusumo@ait.ac.th

[2]Professor, Dept. of Real Estate and Construction, The Univ. of Hong Kong, Hong Kong ⟨http://www.hku.hk⟩. E-mail: steverowlinson@hku.hk

Note. Discussion open until September 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on June 4, 2002; approved on February 26, 2003. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 130, No. 2, April 1, 2004. ©ASCE, ISSN 0733-9364/2004/2-281–289/$18.00.

This paper discusses an innovative method to capture the knowledge of safety engineers in terms of experience in safety hazards at construction sites and accident precautions by using a design-for-safety-process (DFSP) tool. First, knowledge management in construction site safety perspectives is discussed, and then the concept of DFSP tool and its function to capture the knowledge is presented. Finally, test cases to show the potential of the tool to capture the knowledge are reported.

Knowledge Management in Construction Site Safety Perspectives

Knowledge management (KM) has a lot of definitions; Hibbard (cited in Beckman 1999) defines it as ‘‘... the process of capturing a company's collective expertise wherever it resides—in databases, on paper, or in people's heads—and distributing it to wherever it can help produce the biggest payoff.''

Beckman (1999) noted, ‘‘In order to transform knowledge into a valuable organizational asset, knowledge, experience, and expertise must be formalized, distributed, shared, and applied.'' For this purpose, several authors proposed models for the KM process. Beckman (cited in Beckman 1999) proposes eight stages of the KM process: (1) identifying, determining core competencies, sourcing strategy, and knowledge domain; (2) capturing, formalizing existing knowledge; (3) selecting, assessing knowledge relevance, value, and accuracy; (4) storing, representing corporate memory in knowledge repository with various knowledge schema; (5) sharing, distributing knowledge automatically to users based on interest and work; (6) applying, retrieving and using knowledge in making decisions, solving problems, automating or supporting work, job aids, and training; (7) creating, discovering new knowledge through research, experimenting, and creative thinking; and (8) selling, developing, and marketing new knowledge-based products and services.

In order to capture knowledge, it is very important to know typologies of knowledge. Several writers, such as Nonaka and Takeuchi (cited in Beckham 1999), Von Krogh et al. (2000), and Alter (2002), identify two types of knowledge typologies: explicit

		Frequency		
		Often	Moderate	Seldom
Consequences	Major	I	I	II
	Moderate	I	II	III
	Minor	II	III	IV

Fig. 1. Frequency-consequences levels for categorizing safety hazards

and tacit knowledge. Explicit knowledge is defined as knowledge which is precisely and formally articulated and is often codified in databases of corporate procedures and best practices, whereas tacit knowledge is understood and applied unconsciously (Alter 2002). Nonaka and Takeuchi (cited in Beckman 1999) differentiate these two typologies of knowledge in terms of experience–rational and practice–theory aspects. Tacit knowledge is knowledge of experience and it is related to practical aspects, while explicit knowledge is a knowledge of rationality and it is related to theoretical aspects.

Explicit Knowledge

The explicit knowledge of construction site safety exists in accident records, and safety regulations as well as safety guidelines. The accident records represent the knowledge of actual accidents reported on construction sites. This record is useful for the purpose of risk assessment for categorizing the safety hazards in terms of ''frequency–consequence'' level (see Fig. 1). By categorizing the hazards in terms of this frequency–consequence relationship, an organization can have better information regarding hazards which must be prioritized since it is not possible to allocate all of the organizational resources to respond to all the hazards which can occur. For example, in Fig. 1, hazards categorized as Type I must be prioritized while Type IV can be least considered. Type-I hazards may be hazards which may cause major consequences and often occur, such as falling objects from an unprotected opening in a slab in building construction projects. Type-II hazards may be hazards which may cause major consequences but seldom occur, such as a person falls from the upper floor of a building construction project, or minor consequences but often occur, such as a person gets caught by protruding rebars. Type-III hazards may be hazards which may cause moderate consequences and seldom occur, such as a person is struck by a tower crane. This categorization of hazards varies in different organizations since the frequency and consequences of accidents occurrence depend on several factors such as: (1) nature of the construction works, (2) quality and quantity of existing accident precautions used, and (3) safety culture.

Another type of explicit knowledge in site safety is safety regulations, such as Occupational Safety and Health Acts from the U.S. and Construction Site Safety Regulations (CSSR) of Hong Kong. The regulations state the minimum required conditions that must be met in a construction project; however these conditions are not enough to provide a safe working condition. This is especially true for contractors working in countries encouraging self-regulation through the implementation of a safety management system. This system provides general duties for an employer, thus allowing them to determine the best way of achieving the objectives of the legislation in an approach best suited to their organizational culture (Phillips 1998). In the self-regulatory system, tacit knowledge of construction site safety is of paramount importance for organizations since the knowledge of safety engineers and managers (i.e., experience knowledge) determines the quality of safe working conditions acceptable, and therefore their knowledge must be captured.

Tacit Knowledge

Von Krogh et al. (2000) noted that tacit knowledge is tied to the senses, skills in bodily movement, individual perception, physical experiences, rules of thumb, and intuition. In construction site safety, safety hazard recognition is an important actualization of tacit knowledge. Safety hazard recognition is considered a tacit knowledge because it relies on the safety engineer's experience. A hazard is ''a condition with the 'potential' of (causing) an accident or ill health'' (King and Hudson 1985). This definition of a 'hazard' must be noted to avoid confusion with the definition of risk, which is the likelihood of an occurrence of a hazard (Phillips 1998).

Ramsey (cited in Furnham 1998) noted an important theory of hazard recognition, which in itself is an important element in the occurrence of an accident. If management does not recognize the hazards that may occur on a site, then management cannot provide relevant training or procedures to handle the uncertain conditions. The importance of this theory is shown in a study of behavior-based safety management conducted by Lingard and Rowlinson (1997). The results of their study showed that behavior-based safety management successfully improved the safety performance with respect to personal protective equipment and housekeeping, but not bamboo scaffolding and access to heights. One reason for this was attributed to the failure of workers to recognize hazards.

In knowledge management, which is usually manifested in the form of a business system that is enabled by an array of technologies (Auditore 2002), both the explicit and tacit knowledge of construction site safety personnel must be captured to gain advantages including:

1. Establishment of an effective safety program which recognizes the actual safety hazards. Different persons might have different perceptions toward a condition; one might perceive the condition as a safety hazard, while the other might not. This ambiguity can be eliminated by capturing the knowledge and studying and discussing whether a certain construction condition and process would be considered to be an actual safety hazard. Once the knowledge is captured, an organization can ensure that the safety engineers and operational units have the same perception of the actual hazards. This can be used to develop a safety program containing a working procedure to solve the actual hazards.
2. Establishment of an effective training program which improve workers' skill related to the actual safety hazards identified. Once the knowledge is captured by the safety management team, they can provide an effective training program to improve workers' skill in coping with the actual hazard identified.

Problems with Capturing Knowledge in Construction Site Safety

Explicit knowledge is easier to capture than tacit knowledge. Explicit knowledge related to construction site safety can be captured from existing theories and axioms written in books, regula-

J. Constr. Eng. Manage., 2004, 130(2): 281-289

tions, company records, and guidelines. However, tacit knowledge exists from the experience of an individual (i.e., safety engineer or manager); therefore it is difficult to capture since the knowledge is stored in an unstructured manner in an individual's mind.

There are two conventional mechanisms to capture the knowledge of safety engineers or managers. First, it can be undertaken by conducting discussions. For the purpose of representing cases for the discussion, several tools are required, such as engineering drawings, and method statements. The problems with these tools are the drawings and method statements are represented as texts and two-dimensional (2D) drawings which may be difficult to understand (Collier 1994), and the drawings only represent construction components, such as walls, beams, and columns; but they do not represent construction processes which also have inherent safety hazards (Young 1996). Second, it can also be undertaken by observing the actual site. This mechanism can provide better safety information related to the actual construction components and processes which may have safety hazards. An obvious advantage is that the actual representation of the components and processes can stimulate safety engineers or managers to recall the experience they have. However, this mechanism has some limitations: (1) it is unsafe to them since they are exposed to the construction operations; (2) it obstructs the workers in carrying out their works; and (3) it can only be undertaken during the construction stage.

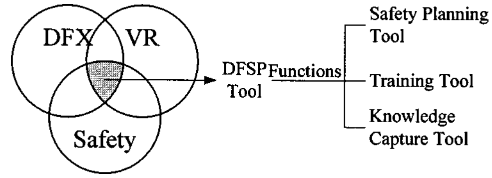


Fig. 2. Design-for-safety-process tool: core components and functions

Design-for-Safety-Process Tool for Capturing Construction Safety Knowledge

Due to the problems stated in the last section, a DFSP tool is proposed. In this research, this tool is designed for capturing safety knowledge in the Harmony Block of the Hong Kong Housing Authority (HKHA). This block design is built repetitively; and therefore, knowledge captured by using the DFSP tool can be reused in Harmony Block projects or in other similar construction projects.

The DFSP tool is developed based on three components (see Fig. 2): design for X-ability (DFX), virtual reality (VR), and construction site safety, as well as the safety hazard identification method. The advantage of using VR as a visualization tool is that it can enhance knowledge discovery (Auditore 2002). This is related to the nature of the human brain where it can process real-

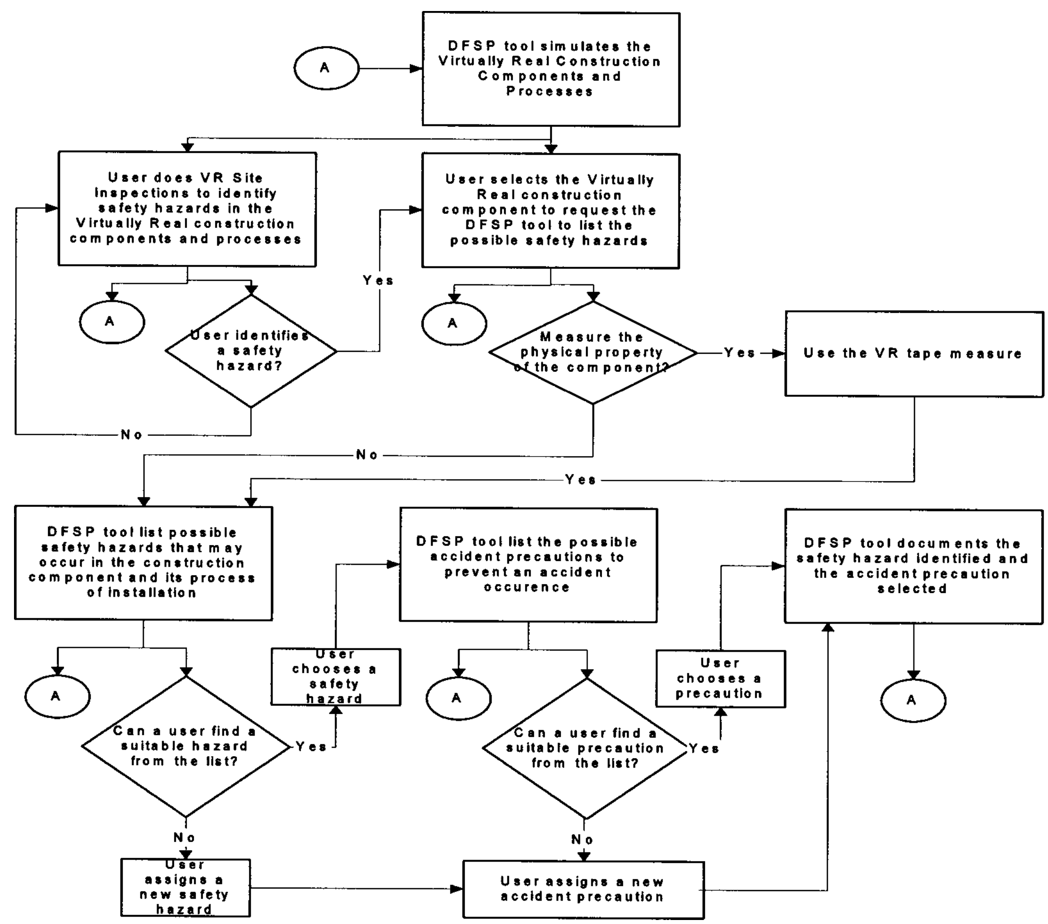


Fig. 3. Mechanism to use design-for-safety-process tool

J. Constr. Eng. Manage., 2004, 130(2): 281-289

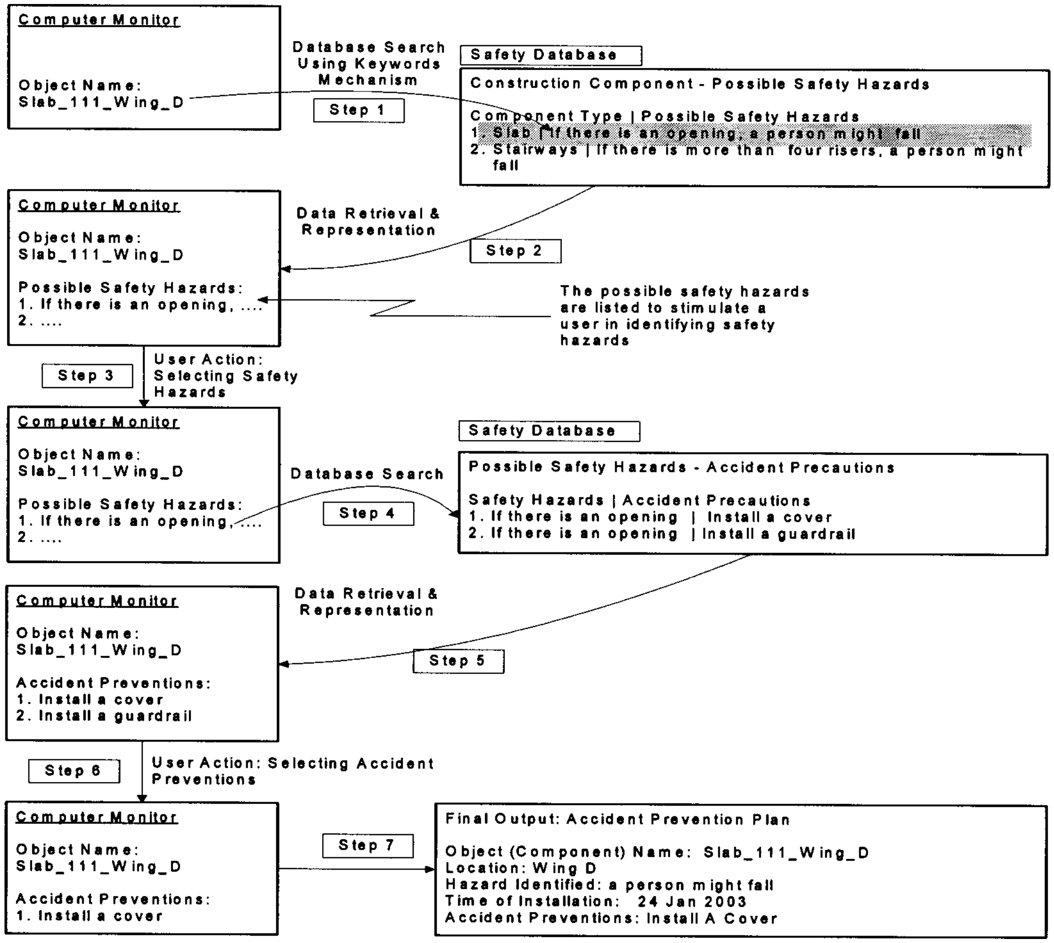


Fig. 4. Use of design-for-safety-process tool safety database

time, multidimensional data much more efficiently and faster than 2D data (Thierauf 1995). In the particular case of construction site safety, after design stage has been completed, construction components and processes of the Harmony Block construction project are represented in VR, called the virtually real construction project. By using this representation, safety engineers can observe the virtually real project and share their experience to identify safety hazards inherent within the virtually real project. In addition, they can also use their experience to propose suitable measures for the identified hazards.

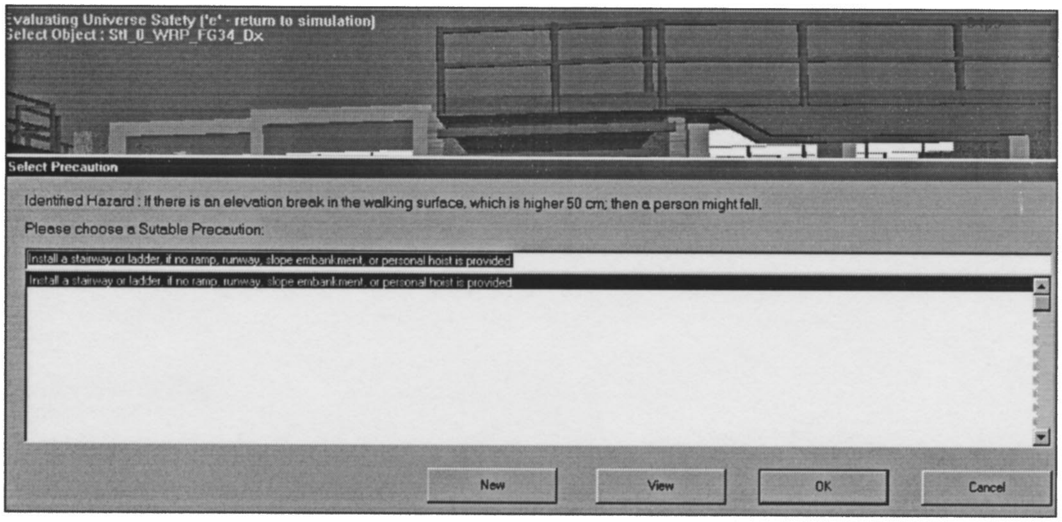
Design for X-Ability

The fundamental concept of DFX is the ability to design a product from several viewpoints or characteristics (Gutwald cited in Prasad 1996). For example, one of the design-for-assembly approaches might be to investigate how a product design can be improved in terms of its assembly time as a performance measurement.

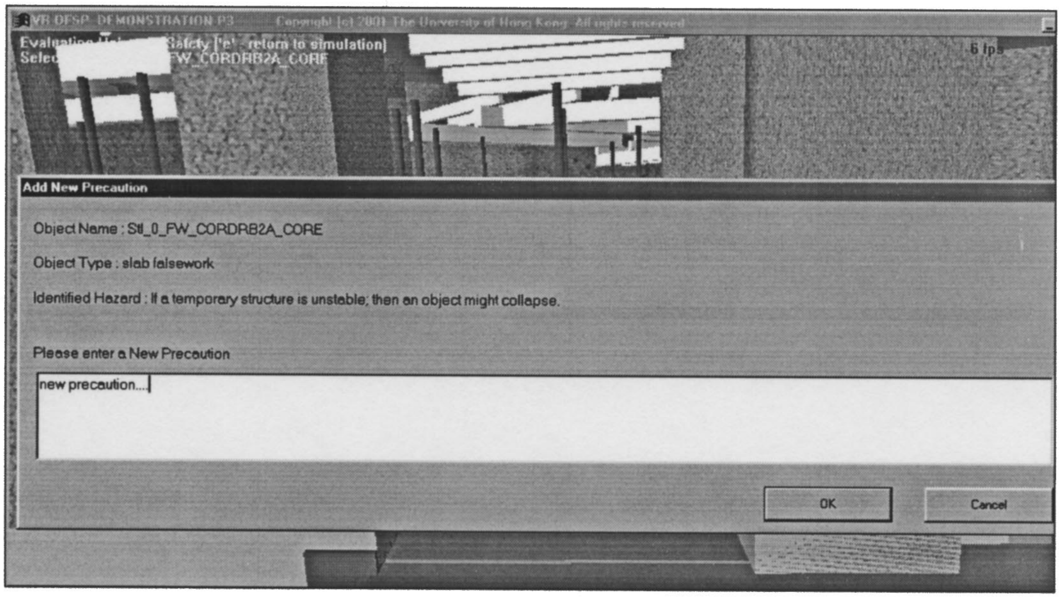
In order to develop a useful DFX tool, Huang (1996) noted five basic functionality requirements of a DFX tool. The five requirements are used as a DFX shell to develop the DFSP tool as follows:

1. Gather and present facts. The DFSP tool developed aims to gather and present facts about virtually real construction components and processes, to assist a user in identifying safety hazard(s), to assist a user in developing accident precaution planning, and to assist a user in assessing the current existing accident precaution components.
2. Measure performance. Since one goal of the DFSP tool is to identify the safety hazard(s) inherent within the construction components and processes, there are two elements to measure the DFSP tool performance: (1) to count how many and (2) to determine what kinds of safety hazards, such as hazards related to fall accident, fire accident, collapse of a construction accident, etc., can be identified using this tool.
3. Evaluate whether or not a product/process design is good enough. In this study, the DFSP tool functions to assisting a user in evaluating an installed accident precaution in the virtual world. The user can use the accident precaution database of the DFSP tool and compare it with the installed accident precaution. Based on this comparison, the user can give a score to the product (the installed accident precaution). This scoring can be based on his qualitative judgment. For example, he is observing a virtually real working platform that has been installed in the virtually real construction project. By comparing the installed virtually real working platform with the recommended working platform in the possible accident precaution database, he can decide whether the virtually installed working platform should be scored as very bad=0, bad=0.25, fair=0.5, good=0.75, or very good=1.0.
4. Compare design alternative. The DFSP tool is equipped with an accident precaution database that provides several accident precaution methods to prevent the occurrence of acci-

J. Constr. Eng. Manage., 2004, 130(2): 281-289



(a) Selecting an Accident Precaution From DFSP Tool Safety Database



(b) Assigning a New Accident Precaution Based on Users' Experience

Fig. 5. Design-for-safety-process tool: selecting and assigning accident precautions

dents due to safety hazards. Using this database, a user can compare several accident precaution alternatives in order to decide which would be the most suitable in terms of effectiveness to avoid accident occurrence and cost. The cost consideration, however, is not addressed in our research.

5. Highlight strengths and weaknesses. A DFX tool should have a function that can highlight the strengths and weaknesses of a design. In the DFSP tool, the function of highlighting strengths and weaknesses can be achieved by reading the results of the accident precaution evaluation/assessment. If an accident precaution component is scored less than 0.5 (the range of scoring is from 0 to 1.00, see the third requirement above), it means that the accident precaution component used is weak and further improvement must be considered.

In addition to the functionality requirements, Huang added another element: that the tool must stimulate creativity. Having this additional element, the DFX tool should encourage innovation and creativity, rather than impose restrictions. In the DFSP tool, there are sets of standards in the safety regulations that must be observed; for example, the minimum width of the working platform must be at least 400 mm if the working platform is not used to transport material. However, it does not restrict a user to creatively develop the best safety design solution. A user is provided with choices for establishing which accident precautions would be the most suitable, or to create a new design solution if it is considered better than the data available in the accident precautions. This is the main reason why the DFSP tool, which is derived from DFX, can be used to capture construction site safety knowledge. The mechanism to use the DFSP tool is illustrated in Fig. 3.

J. Constr. Eng. Manage., 2004, 130(2): 281-289

Virtual Reality

Aukstakalnis and Blatner (1992) define "VR as a way for humans to visualize, manipulate, and interact with computers and extremely complex data." Burdea and Coiffet (1994) define VR in terms of its three important features that make it widely used by several industries which are: interaction, immersion, and imagination.

Interactive

The interactive feature enables a user to provide input and modify a virtual world instantaneously. In the DFSP tool, it enables a user to do a virtual site investigation and observation at any location in the virtually real construction project.

In order to execute the virtual site investigation and observation as effectively as the safety hazards identification task, VR functions are needed to be incorporated in the DFSP tool. There are four main VR functions developed in the DFSP tool: collision detection, terrain following, geometry picking, and VR tape measure. Hadikusumo and Rowlinson (2001) discussed further details of these VR functions, design, and development. Fig. 3 illustrates the mechanism of safety hazard identification using the DFSP tool.

First, a user performs a walk-through to see the virtually real construction site, navigating by means of a mouse. In VR software there are different types of viewpoint movements, such as pitch, roll, rotate, and yaw, each controlled by pressing a left and/or right button and dragging the mouse. This complex viewpoint movement creates difficulties when doing a walk-through since a user might have difficulty in maintaining the walking plane. A terrain following mechanism for the walk-through addresses this difficulty.

During the walk-through, a user might be able to walk through a solid object, such as a wall. This condition should be avoided in order to mimic the real world site inspection where humans cannot walk through solid objects. A collision detection mechanism is also featured to block users from walking through solid objects.

During the safety hazard identification task, a user selects a virtually real construction component that might be considered a safety hazard. To perform this function, a user chooses the virtually real construction component by clicking the mouse pointer on the virtually real construction component. This initiates the geometry picking function mechanism, which allows users to perform the safety hazard identification task.

For the purpose of safety hazard identification, it is very important to understand the nature of the safety hazard. Most of the safety regulations note dimensions of an object as a safety requirement. For example, the CSSR of Hong Kong Schedule 3 notes that the minimum width of a working platform is 400 mm. In addition, if the working platform is used for material transportation, the minimum width is 650 mm. This indicates that a VR tape measure is needed to measure the dimension in the virtually real project for the purposes of safety assessment.

Immersive

The immersive feature facilitates a user to see a realistic looking world as well as to touch and feel it. This feature is used to represent and gather facts, which is representing virtually real construction components and processes (i.e., virtually real construction project), as defined in the functional requirements of the DFX shell of Huang.

The virtually real construction components represent construction products which are to be built on a construction project, e.g., walls, columns, and beams. The virtually real construction processes represent sequences of construction activities to install a construction component. The virtually real construction project is developed using VR software, *World Up*™. Details of the development of the virtually real project are discussed in Hadikusumo and Rowlinson (2001).

Imagination

The imagination feature enables a developer of VR to create an application that is able to solve a particular problem, such as representing the terrain of an area for flight simulation training to solve the problem of controlling a VR aircraft. In this study, this feature is used to solve the problem of safety hazards inherent within the virtually real construction project. Details of this feature are discussed in the next section.

Safety Hazard Identification and Accident Precaution

The DFSP tool is used for knowledge capture, safety planning, and a training tool. As a planning tool, the DFSP tool can assist a user in identifying safety hazards and determining accident precaution to avoid the occurrence of accidents in the hazards identified. For this purpose, the DFSP tool is equipped with a safety database. This database is designed based on "construction components–possible safety hazards–accident precautions" relationships (see Fig. 4). One construction component can have many possible safety hazards, and one possible safety hazard can have many accident precautions. An advantage of using this relationship is that safety hazard information related to a construction component and its process of installation can be attributed to a construction component. In the construction process simulation, an installation process of an object can be identified from the component itself. If a user is seeing a precast facade being transported using a tower crane, it can be interpreted that he is seeing the installation process of a precast façade.

In the DFSP tool, the mechanism to retrieve the possible safety hazards from the DFSP tool safety database is based on keywords which are types of virtually real construction components, e.g., cast-in situ slab, and precast slab. For this, each virtually real construction component has a component type property. When a user selects a virtually real construction component, the DFSP tool retrieves and lists the possible safety hazards, which are related to the virtually real construction component, from the safety database. The user then can select, from the list, safety hazards occurring according to the conditions observed in the virtually real construction project. When the user selects a safety hazard, the DFSP tool retrieves and lists possible accident precautions. The user then can select, from the list, accident precautions to prevent accidents related to the safety hazard identified. Finally, this information—component name, component type, safety hazards identified, accident precaution, and time of installing the precaution—are documented in a safety plan.

For the purpose of a training tool, users can do a walk-through in a virtually real construction project and study possible safety hazards inherent within the project by using a DFSP tool safety database.

Capturing Construction Site Safety Knowledge from Engineers

The capturing of knowledge starts when safety engineers (i.e., users) observe the virtually real project and check possible safety hazards in conditions suggested by the DFSP tool safety database. The users can then recall their experience to check whether other

J. Constr. Eng. Manage., 2004, 130(2): 281-289

possible safety hazards, which are not yet compiled in the database, exist. If other possible hazards may occur, the users can add new possible hazards by pressing the ‘‘New’’ button [see Figs. 3 and 5(a)]. Once safety hazards are identified, users can also consider safety accident precautions suitable to prevent accidents. For this, the DFSP tool lists accident precaution data related to the safety hazard identified and the user can choose accident precautions recommended by the database. Before deciding on an accident precaution, the users recall their experience to check whether other accident precautions, which are not yet compiled in the database, are also possible. If other accident precautions are also possible, users can create new accident precautions [see Fig. 5(b)]. These new safety hazards and new accident precautions will be printed in the safety plan discussed in ‘‘Safety Hazard Identification and Accident Precaution’’. In addition, if management consider that the new safety hazards and new precautions are effective for avoiding safety accidents, this new tacit knowledge can be stored by adding them permanently in the DFSP tool safety database [i.e., safety database: possible safety hazards–accident precautions, in Figs. 4 and 5(a)]. This illustrates that the DFSP tool provides a mechanism to capture the tacit contents of engineers’ safety knowledge.

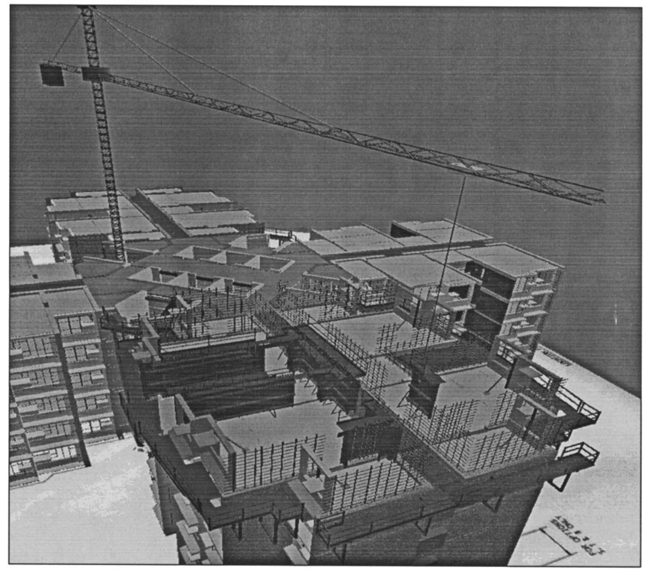


Fig. 6. Virtually real construction project of Hong Kong Housing Authority harmony block

Test Case Study

In order to test the capability of the DFSP tool to capture safety knowledge, test case studies were conducted. A typical floor of the Harmony Block of the HKHA public housing project is used as a virtually real construction project. The reason for using this project as a model is because this project type is the most commonly built HKHA public housing project; and therefore the tool and the knowledge captured can be reused in several projects. The virtually real project of this model is shown in Fig. 6.

The tests case were conducted by asking the safety officers and safety managers from seven construction companies and one government institution in Hong Kong to use the DFSP tool for an approximately 60 min test duration. Some tests were done in groups that consisted of two to four safety officers and/or safety managers from an organization, and some tests were done individually. The participants were asked to undertake the following:

1. Observe the virtually real construction components and processes;
2. Select safety hazards occurring from the DFSP tool safety database, or assign a new safety hazard; and
3. Select accident precautions from the DFSP tool safety database, or assign a new accident precaution.

Several examples of the participants’ knowledge captured using the DFSP tool related to possible safety hazards occurring and accident precautions are as follows:

1. At lifting concrete wall formwork using a tower crane activities (see Fig. 6), two safety hazards were identified. In first hazard, the participants considered that concrete debris might fall down and hit workers. An accident precaution recommended was to clean the formwork of concrete debris before lifting. The second hazard was also identified: tools and equipment left in the working platform of the formwork might fall down. For this, they recommended that before

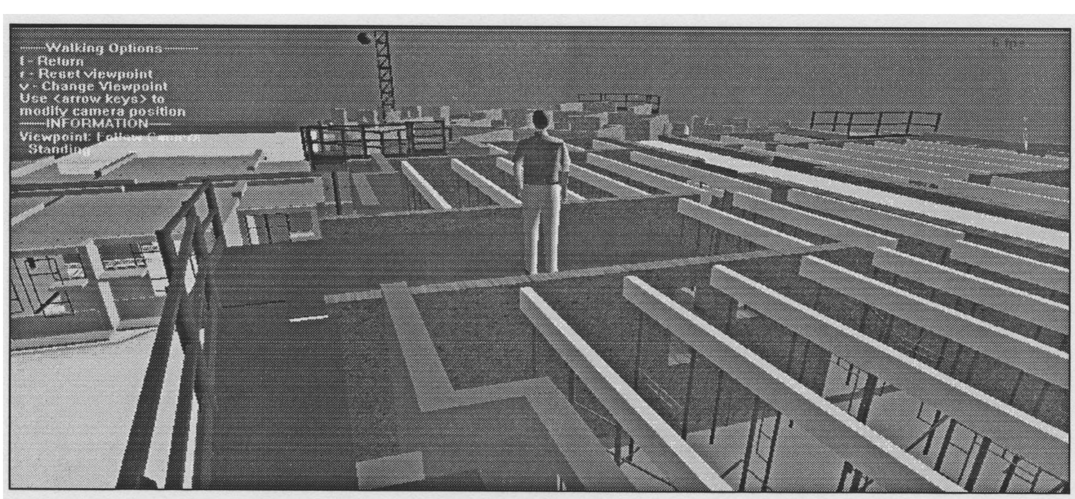


Fig. 7. Floor slab concrete forming using ledger beams and steel shoring frames

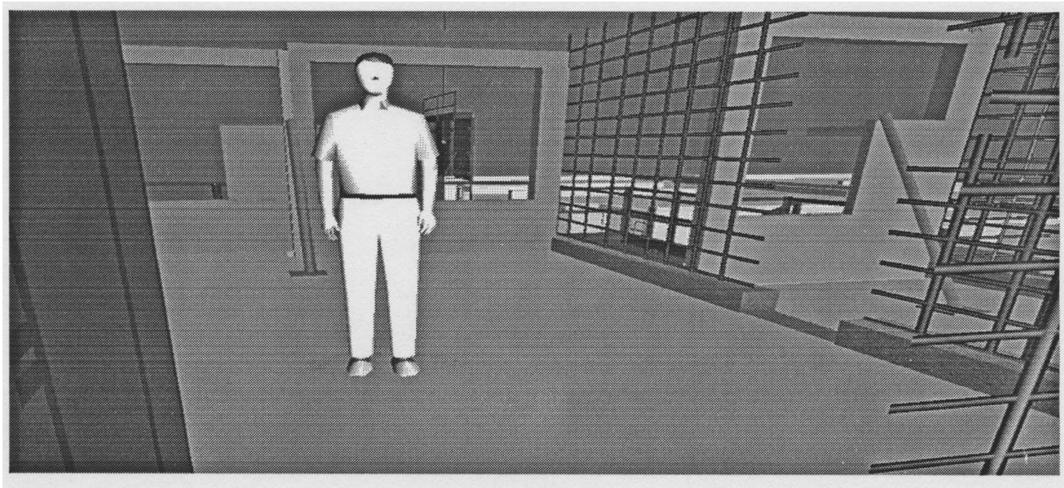


Fig. 8. Protruding rebars

lifting the formwork, workers should check whether tools and equipment are left in the formwork.

2. When constructing falsework for installing precast slabs activities (see Fig. 7), the participants identified a possible hazard: collapse of a temporary structure (i.e., scaffold as a shoring structure). As an accident precaution, they recommended that the scaffolds' legs be footed on stable ground or on a stable support or structure.
3. At protruding rebars (see Fig. 8), especially if the rebars are at an inadequately lit location, the participants considered the protruding rebars to be a safety hazard. They recommended that outer sides of rebars be covered with a protective wooden board.

The examples above indicate that the DFSP tool can be used to capture the knowledge of safety engineers. The reasons are as follow:

1. Virtual reality can represent the virtually real project in three-dimensional image [i.e., what-you-see-is-what-you-get (WYSIWYG)]. This enables a user to understand the virtually real construction components easier than if they are represented in 2D drawings.
2. Virtual reality can be used to represent virtually real construction processes which may also have inherent safety hazards. The virtually real construction processes are much easier to be understood compared to the conventional method statement represented in a text or written description of work installation.
3. The DFSP tool is equipped with a DFSP safety database containing possible safety hazards for each construction component, and possible accident precautions for each safety hazard. This database, together with the virtually real project, can stimulate safety engineers to recall their experience about safety hazards occurring and the accident precautions.

Conclusion

Typically, safety engineers' knowledge related to safety hazard identification and accident precaution is captured by discussions using 2D construction drawings and text data, such as method statements, and discussions on-site as case study tools. Both of the methods, however, have limitations. Therefore, in this research an innovative method is proposed to capture the knowledge by using the DFSP tool.

The DFSP tool is developed by using three major components: DFX, VR, and safety hazard identification and accident precaution database. One of its potential advantages is that it can be used to capture tacit knowledge (e.g., experience) residing in engineers' minds, which is stored in an unstructured manner. The DFSP tool can be used to capture the tacit knowledge because: (1) VR can represent data in a WYSIWYG model which enables an engineer to understand a virtual object easier than if they are represented in 2D drawings; (2) VR can represent virtually real construction processes which also have safety hazards; and (3) the tool is equipped with a possible safety hazard database and accident precaution database which can stimulate the engineers to recall their experience.

Acknowledgment

This research is funded by Hong Kong Research Grants Council, CERG Project Ref. No. HKU409/96H.

References

Alter, S. (2002). *Information systems: Foundation of E-business*, 4th Ed., Pearson Education, Upper Saddle River, N.J.

Auditore, P. (2002). ''Enabling knowledge management in today's knowledge economy.'' *KMWorld*, 11(1).

Aukstakalnis, S., and Blatner, D. (1992). *Silicon mirage: The art and science of virtual reality*, Peachpit Press, Berkeley, Calif.

Beckman, T. J. (1999). ''The current state of knowledge management.'' *Knowledge management handbook*, J. Liebowitz, ed., CRC Press, Boca Raton, Fla.

Burdea, G., and Coiffet, P. (1994). *Virtual reality technology*, Wiley, New York.

Collier, E. B. (1994). ''Four-dimensional modelling in design and construction.'' thesis, Stanford Univ., Stanford, Calif.

Furnham, A. (1998). *Personality and social behaviour*, Arnold, New York.

Hadikusumo, B. H. W., and Rowlinson, S. (2001). ''Development of a

J. Constr. Eng. Manage., 2004, 130(2): 281-289

virtually real construction site—design for safety.'' *Int. J. Comp. Integrated Design Construction (CIDAC)*, 3(2), 55–60.
Huang, G. Q. (1996). ''Developing design for X tools.'' *Design for X concurrent engineering imperatives*, G. Q. Huang, ed., Chapman & Hall, London, 107–129.
King, R. W., and Hudson, R. (1985). *Construction hazard and safety handbook*, Butterworths, London.
Lingard, H., and Rowlinson, S. (1997). ''Behavior-based safety management in Hong Kong's construction industry.'' *J. Safety Res.*, 28(4), 243–256.
Phillips, R. (1998). *Health and safety in construction*, The Univ. of Bath Press, Bath, U.K.
Prasad, B. (1996). *Concurrent engineering fundamentals*, Vol. 1, Prentice-Hall, Englewood Cliffs, N.J.
Thierauf, R. J. (1995). *Virtual reality systems for business*, Quorum Books, Conn.
Von Krogh, G., Ichijo, K., and Nonaka, I. (2000). *Enabling knowledge creation: How to unlock the mystery of tacit knowledge and release the power of innovation*, Oxford University Press, Oxford, U.K.
Young, S. (1996). ''Construction safety: A vision for the future.'' *J. Manage. Eng.*, 12(4), 33–36.

J. Constr. Eng. Manage., 2004, 130(2): 281-289