INTEGRATED 4D CAD AND CONSTRUCTION SAFETY PLANNING INFORMATION FOR A BETTER SAFETY MANAGEMENT

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Abstract. Safety is an important element of project successes. In the conventional project management, safety planning, as a function, is separated from other functions, such as planning/scheduling function. This separation creates difficulties for engineers to analyze what, when, why and where a safety measure is needed to prevent accidents in a construction activity. Another problem occurs due to the conventional practice of representing project designs using two-dimensional (2D) drawings. In this practice, a user (e.g. an engineer) has to convert the 2D drawings into three-dimensional (3D) mental pictures, and this is a tedious task. If only converting this 2D drawing is a tedious task, combining these 2D drawings with safety planning creates more difficult tasks. In order to address the problems, this paper discusses our research in integrating construction scheduling and safety planning in a 4D environment.

1. Introduction

Construction project covers a wide range of different activities performed by many organizations, i.e. contractor and its subcontractors. Each organization carries on activities which may have different potential hazards. These may cause accidents that affect on human, economic, and legal aspects. In order to prevent accidents, it is necessary to plan the safety aspect carefully. The plan, then, must be communicated to all organizations involved since they might interact directly or indirectly in order to perform their jobs.

In construction industry where an accident rate is so high, safety is already a crucial issue. BLS (2001) reported that construction employment contains around 6% of all employments but accounts for 20% of fatalities and 8% of injuries and illnesses. When an accident occurs, it impacts on human, economic, and legal issues (Barrie and Paulson, 1992). The human impact involves the pain of a worker as well as to his family. The economic impact concerns with the direct and indirect costs of an accident. Direct costs consist of medical expenses such as ambulance, hospital, and doctors' fees, medication, and rehabilitation, compensation payments, insurance premium increases and litigation costs, while the indirect costs of accidents are disrupted work schedules, lost productivity, clean-up and repair, hiring and training replacement workers, low worker morale, bad public relations, and time spent on accident investigation, claims management and litigation. These accident costs are subtracted from a contractor's bottom-line profit. These costs can't be depreciated, written off as business losses, or deducted as expenses. In addition, there is the legal impact that relates to a breach of safety regulations. Therefore, it is necessary to integrate safety and health factors into other project success factors, such as time of completion, project cost and quality.

This research studies an integration of 4D CAD and construction safety planning information as an aiding tool for communicating construction safety planning information. 4D CAD is as a result from integrating three-dimensional (3D) models as construction products and time planning represents construction processes. 4D CAD facilitates 3D construction products to be visualized along with construction processes. In other words, 4D CAD enables users to visualize construction products (i.e. design) as it would be actually built. Therefore, 4D CAD-Safety equipped with another construction information (i.e. safety planning information in this study) facilitates users to analyze the needs of implementing the safety plan in terms of what, when, where, and why a safety measure is needed.

This paper will discuss how a 4D CAD-Safety tool is designed, developed, and used for a better safety management in terms of communicating safety planning information. The paper begins with describing the concept of 4D CAD model and safety planning in construction. Then the integration of 4D CAD model and safety planning is discussed in the 4D CAD-Safety concept. Next the design and development of 4D CAD-Safety application is explained. Finally, the paper discusses utilizing the 4D CAD-Safety simulation and its benefits.

2. 4D CAD model concept

Koo and Fischer (2000) defined four dimensional computer aided design (4D CAD) model as a result form the integrating of three-dimensional (3D) models to the fourth dimension of time. The 3D and time integration allows the user to run a visualization of the planned construction process of the project. The first idea was conceived in 1986-87 when Bechtel collaborated with Hitachi Ltd. to develop the Construction CAE/4D Planner software (Cleveland, 1987, 1989; Simons et al., 1988 cited in Rischmoller, 2000). 4D model's aim is used to overcome deficiencies of the traditional planning and control, such as bar charts and network diagrams, that do not effectively represent and communicate the spatial, temporal, and non-precedence information.

Figure 1 illustrates that the traditional method to represent construction planning information abstracts the visual description i.e. drawings into a textual description of activities i.e. construction schedule (Fig. 1A). As a result planners must visually conceptualize the sequence of construction, and subcontractors must interpret and elaborate the construction plan because it lacks necessary details (Fig. 1B). 4D model explicitly represents the relationship between the description of a facility (3D model) and the construction schedule (Fig. 1C).

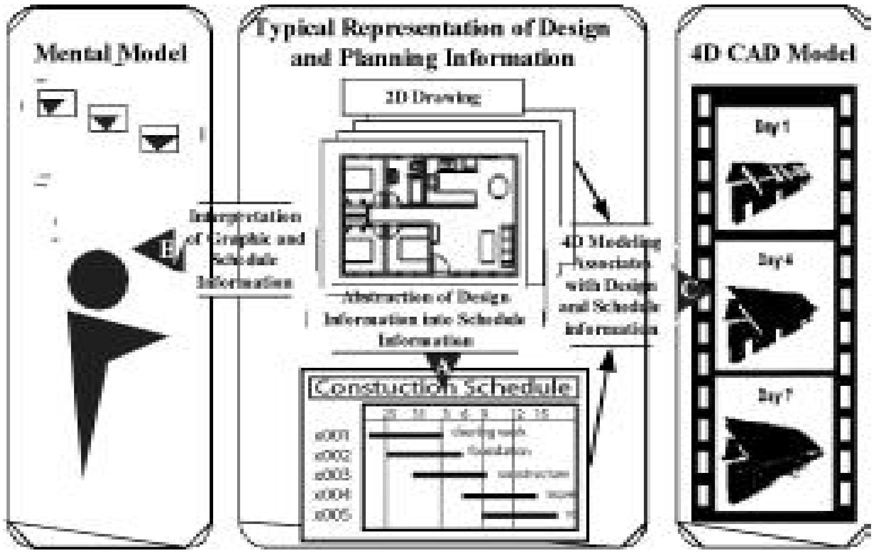

Figure 1. Comparison of Traditional Representation of Construction Information and 4D model (Source: Modified from McKinney, 1998)

3. Construction Safety Planning Information

Normally in construction project, a general contractor has several sub-contractors performing some specific tasks. Each sub-contractor has to plan safety measures, equipments, tools, and precautions himself following the general safety guidelines provided by the general contractor.

In this conventional method, safety planning has two main limitations: 1) it is communicated separately from other project planning functions, construction schedules and drawings; and 2) it is not integrated with safety planning from other organizations.

In the first problem, a construction schedule represents activities; and safety plan must be coordinated with this schedule because safety engineer must know when safety measures on the safety plan will be used. In another case, safety plan has to be coordinated with construction drawings as well because these drawings have the information related to why and where safety measures of the safety plan are chosen. Therefore, if a safety plan is not integrated with construction drawings and schedules information, project participants might have difficulties to analyze when, where and why safety measures are needed. Another problem related with object representation, in conventional construction project, most of the objects are represented using 2D drawings. Collier (1994) noted that this 2D representation is a bottleneck since engineers has to convert this drawing into 3D mental picture which is not an easy job. If only creating this 3D mental picture is a tedious task, then combining the 2D drawing with safety planning is more difficult. Therefore, the importance of integrating these project planning functions and safety plans using 4D CAD is a rationale of our study. In relation to integrating project planning functions, Kartam (1997) has developed Integrated Knowledge Intensive System for Construction Safety and Health Performance Control (IKIS-Safety System) that integrates safety and health requirement (i.e. safety plan) into a CPM-based project schedule. This integration provides a way to manage safety and health performance proactively rather than reactively, and alert construction manager and involved parties when reviewing the CPM schedule (MacCollum, 1995: 130; Kartam, 1997). IKIS-Safety system facilitates users to know when a safety measure is used since it is integrated with project scheduling; however, this system does not provide the visual view of construction products which is important for users to analyze when, where, and why a safety measure is needed.

In the second problem, when a contractor delegates some specific tasks to its subcontractors, one subcontractor might plan its safety plan separately from others. This separation makes safety planning information difficult to be communicated to all projects participants, such as to other subcontractors. Therefore, a mechanism must be provided to integrate all safety plans from different organizations for a better of communicating the plans.

4. 4D CAD-Safety Concept

Preliminary, the concept of 4D CAD-Safety is an integration of 3D CAD objects, tasks (or activities), and safety plans. The 4DCAD-Safety tool consists of two important components (see Figure 2): 4DCAD model and Safety plan.

The first component applied in this research is the 4D CAD model. 4D CAD facilitates 3D construction products to be visualized along with construction processes on a computer screen therefore users need not to interpret construction products and processes in their minds. In other words, users can visualize the construction processes as they would be actually built in reality.

The second component is construction safety planning which is used to plan and communicate a safe work procedure. In general, safety planning consists of many activities need to be done, such as safety analysis, training and education (CSA, 1999), this research, however, focuses on providing a safe work procedure planning because it is used as a direct guidance for workers to perform a safe work.

4D CAD-Safety tool is designed to contain several important features. In order to simulate whole construction processes in the 4D CAD simulation, all sub-schedules from sub-contractors are needed to be combined into one main schedule. Hence, the first feature provided is combination of sub-schedules with a main schedule. The second feature is to generate 4D CAD models by linking the existing 3D CAD models and combined schedules. The third feature is to integrate the safety plan with the 4D CAD model. The fourth feature is to enable users to visualize the safety plan within 4D environment. In other words, the tool is able to integrate safety plans from different organizations, and communicate the safety plan information along with construction processes and products to all project participants. Consequently, they can have a better understanding about how, what, when, where, and why safety measures in a safety plan are need as well as how they should be used to support safe works.

For example, the roof truss installation task needs some safety plans such as equipping a safety helmet, and providing a safety belt. When the 4D simulation reaches roof objects (construction products) and roof truss installation tasks (construction processes), these safety plans will be displayed. Therefore, project participants will know that a safety helmet and belt are needed for undertaking the roof truss installation task. Moreover they also know when, where, and how safety helmets and belts will be provided as well as in term of why, they will understand because of height of work area safety belts and helmets need to be provided.

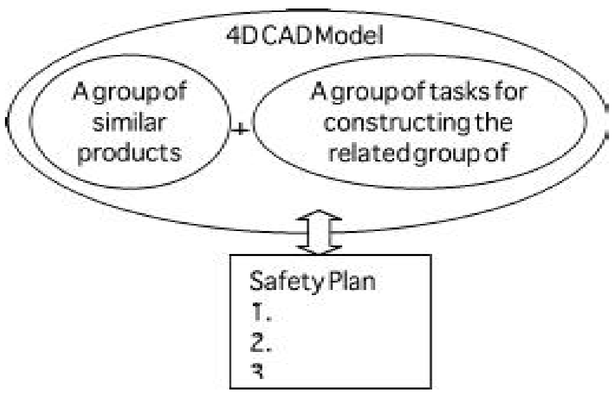

Figure 2. Concept of 4D CAD-Safety

5. 4D CAD-Safety Design and Development

5.1 SYSTEM ARCHITECTURE

In this section, the design of 4D CAD-Safety system is explained. Figure 3 illustrates the 4D CAD-Safety system architecture which consists of three parts: a) MS Project TM, b) AutoCAD TM or AutoDesk Architecture Desktop TM, and c) the 4D CAD-Safety tool (i.e. interface application developed in this research). The construction project scheduling are created using MS Project TM software. The advantage of using MS Project TM is its ability to export a schedule file to a database file using an ODBC (Open Database Connectivity) function; and therefore the construction schedule developed using MS Project can be easily converted into a MS Access database. For visualizing construction products, AutoCAD TM software is used for developing the 3D objects as well as displaying them for 4D simulation purpose. It provides group function to permanently contain all objects including 3D objects in a group. Therefore, 3D objects under a group can be made visible and invisible by turning on or turning off the visibility of the group. The last part, 4D CAD-Safety tool, is an interface application consisting of 4D CAD-Safety interface and its system database. 4D CAD-Safety interface has been developed using Visual Basic programming language. It aims to integrate the system database and AutoCAD TM or AutoDesk TM that is elaborated in the interface and function design section. The system database is designed to store three categories of data: 1) safety planning information, 2) imported construction schedules, and 3) 3D objects group information. In order to manipulate the system database, 4D CAD-Safety interface is designed.

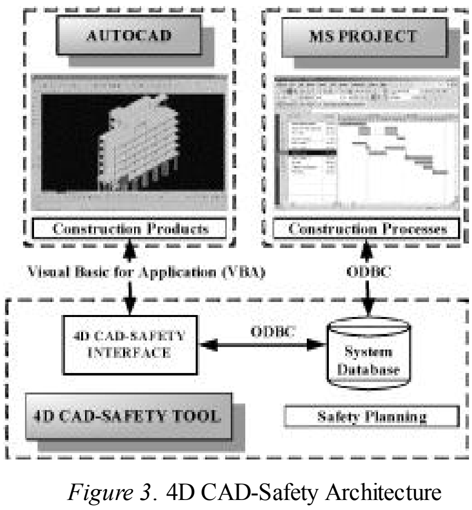

Figure 3. 4D CAD-Safety Architecture

5.2 DATABASE DESIGN

The 4D CAD-Safety system database was developed using a relational database by using MS Access application. Its data can be mainly categorized into three groups: products, processes, and safety plan. Figure 4 illustrates the database structure of 4D CAD-Safety system that consists of 8 tables (i.e. entities): "ObjHandle", "Group", "4DLink", "Task", "SafetyLink", "SafetyLib", "Safety&Keyword", and "Keyword".

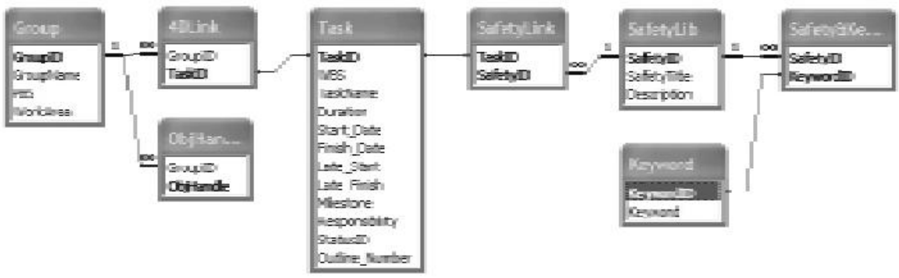

Figure 4. Database Structure of 4DCAD - Safety

Task table is needed to store scheduling information from the MS project. This table contains several information (i.e. TaskID, WBS, Task Name, Start Date, and Finish Date, etc.). All activities in the MS project schedule must be exported to MS Access database files, combined with other MS project schedules and stored in this "Task" table. All construction activities from the system database (exported from MS Project) must be assigned into a group. For example, a detailed of column construction is usually elaborated into four activities: installing rebar, installing formwork, concreting, and stripping off the formwork; and this four activities can be grouped together. In order to group tasks from the "Task" table and assign them to relate with a group of 3D objects, a composite entity so called 4Dlink table is created. In this 4Dlink, the relationship between "Group" and "Task" table is set as "a group can contain many tasks, but one task can be a part of a group only."

The "Group" table stores data of 3D object group such as group name, WBS, and work area. One group might contain one or more 3D objects that are similar and must be built at the same time, for example, a group of 2nd floor column which represent the column products in 2nd floor contains all columns that are in 2nd floor. In order to avoid duplication -where an object that has already assigned into a group is selected again for another group-, the "ObjHandle" table is created. This "ObjHandle" is needed to store a unique ID of each object. This restricts users to select an object that is already assigned into a group.

In relation to safety planning, the "SafetyLib" table is created as the library of safety plan. It stores several records of pre-defined safety measures collected from regulatory standard and safety engineers' experience. For example, install a guardrail to protect workers to fall from an open slab. These safety libraries are used to create a safety plan stored in a composite entity, "SafetyPlan" table. The "SafetyPlan" table connects several safety libraries as a safety plan with a task from "Task" table. This enables safety measures in a safety plan to be displayed along with construction products and construction processes being simulated in the 4D simulation. For example, the roof truss installation task needs some safety plans such as equipping a safety helmet, and providing a safety belt. When the 4D simulation reaches roof objects (construction products) and roof truss installation tasks (construction processes), these safety plans will be displayed.

The last two t ables, "Safety&Keyword" and "Keyword", are optional tables. They help users to list the specific records of safety library using keywords such as list all records of safety library related to excavation work.

5.2 INTERFACE AND FUNCTION DESIGN

The interface and function of the 4D CAD-Safety tool are developed using Visual Basic programming language. The interface is designed integrating system database and AutoCAD TM or AutoDesk TM. It can be mainly divided into three parts: 1) 4D CAD interface (see area 1 in Figure 5), 2) Safety interface (see area 2 in Figure 5), 3) viewing part (see area 3 in Figure 5), and 4) Schedule Combination interface (see Figure 6).

Firstly, the 4D CAD interface is designed for controlling the 4D components consisting of object groups, related tasks, and lists of tasks as well as providing the 4D generating function and the simulation function. The 4D generating function aims to generate the relationship between the object group and related tasks and the simulation function are intent on simulating 4D CAD-Safety simulation. These two functions are the main objective of this tool.

Secondly, the safety interface is designed to report a safety plan to a user when its related 4D CAD model is being simulated (i.e. being constructed in real world). Moreover it also enables a user to develop a new or modify an existing safety library as well as integrate safety plans with 4D CAD model.

The third part is AutoCAD TM or AutoDesk TM application. The main purpose of using them is to display 3D objects and 4D simulation.

Each interface is designed to work consistently with others. For example when a user specifies an object group in the 4D interface, whole 3D objects in that group will be highlighted and safety plans related with that group will be reported as well.

Due to the separation of sub-schedules form different sub-contractors, the last interface named schedule combination interface, is also provided for combining a master schedule with sub-schedules. This function is one of main objectives of the tool as shown in Figure 6.

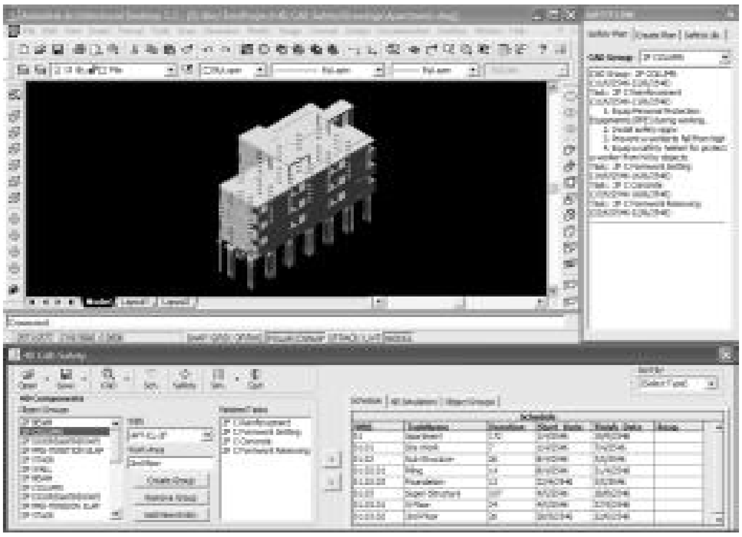

Figure 5. The Interface of 4D CAD-Safety tool: (1) 4D Interface, (2) Safety Interface, and (3) Viewing Interface

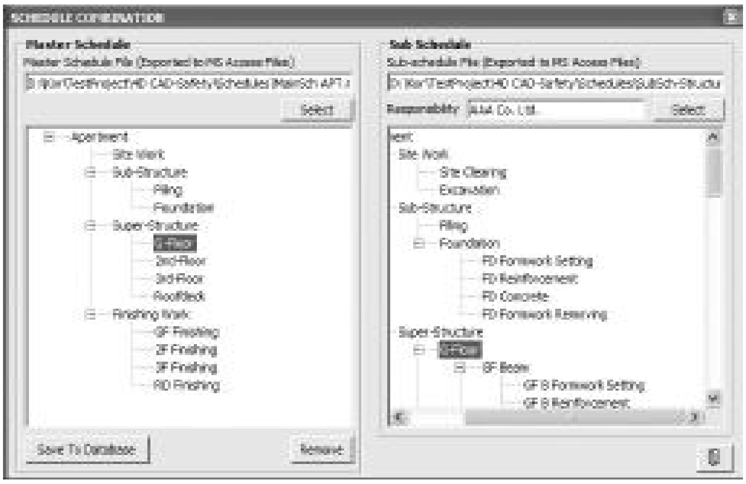

Figure 6. The Schedule Combination Function

5.4 UTILIZING THE 4D CAD-SAFETY SIMULATION

This section discusses how to use the 4D-Safety simulation. Incorporating with a systematic flowchart as shown in Fig. 9 and an example of application, the utilizing of the 4D CAD-Safety simulation is elaborated as follows:

1. For representing the products and processes, the 3D CAD objects and schedules are generated using AutoCAD TM and MS Project TM respectively. The 4D CAD-Safety tool is not intended to generate these data, a general contractor an sub-contractors have to take these responsibilities.
2. The 3D entities that are classified in the same work breakdown structure (WBS) code are grouped such as all concrete columns located in the 2nd floor need to be grouped together. There is a function provided in an application to group the 3D CAD entities as shown in Figure 7(A). The users can assign name, WBS code, and work area of each group of products. For instance a group of columns in the 2nd floor names 2F COLUMN is represented by code APT-CL-2F. Moreover for helping a user to select 3D objects, there is a useful function to turn on/off a CAD layer as shown in Fig. 7(B).

Figure 7. Grouping Function (A) and Turning On/Off Layer Function (B)

3. To access the schedule data easily, users have to export the schedule from MS Project to MS Access files using Open Database Connectivity (ODBC) function provided in MS Project application as shown in Figure 8.
4. One of important functions of this tool is that all sub-schedules from involved organized such as a general contractor or sub-contractors need to be combined into the main schedule produced by the general contractor. Fig. 6(4) shows the function to combine the main schedule (left side) and sub-schedules (right side), and then saves them the 4D-Safety database.

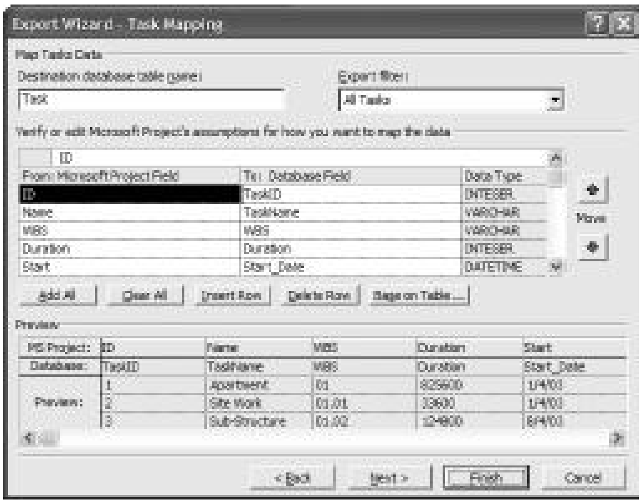

Figure 8. Exporting Schedule Data form MS Project Files to MS Access Files

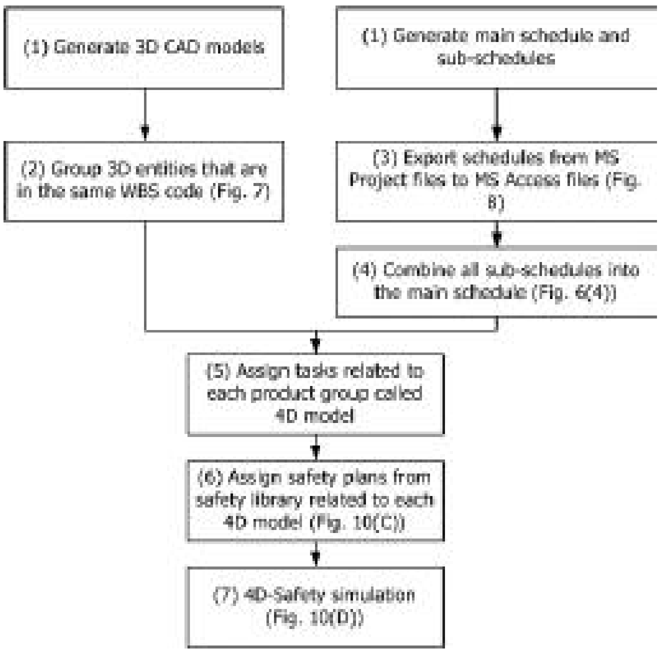

Figure 9. Flowchart for Generating of 4D-Safety Simulation

5. After grouping 3D objects and combining all schedules, the links between a group of 3D objects and a task or a group of tasks form the main schedule in the 4D-Safety database are assigned. For instance, a group of tasks consists of form work setting, reinforcement, concrete, and formwork removing, is assigned to the group of column (e.g. APT-CL-2F).

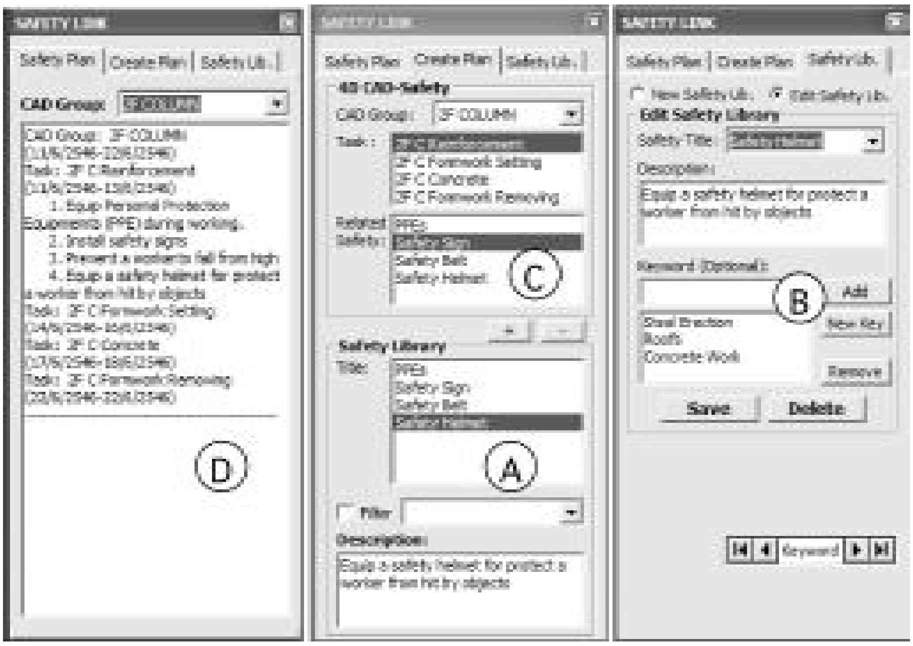

Figure 10. Communicating (D), Generating Safety Plans (C) and Modifying a Safety Library (B)

6. The 4D CAD-Safety tool provides the pre-defined safety library that contains several records of safety plan as shown in Fig. 10(A) and also provides function for creating a new or modifying an existing safety library as shown in Fig. 10(B). In order to generate the relationship between a task and a safety plan for performing the task, the users must select a safety library by clicking safety measures (see area A in Figure 10) and assign it to the group of products by selecting the task related (see area C in Figure 10) and then clicking the "+" (i.e. add) button.
7. Finally this safety plan will be communicated to users along with construction products and processes when simulation called the 4D CAD-Safety simulation is running as shown in Figure 9(D). Can you make a new picture showing that when a different object is simulated, the safety plan information is also changed.

6. Benefits of the 4DCAD-Safety

The benefits of 4D CAD-Safety application are discussed in two categories: general benefits, and specific benefits. The first category is the benefit that has been proposed by other researchers. The second category is the benefit that is found in this study.

6.1 GENERAL BENEFITS

As the 4D model displays the actual project being built, the disparity in participants' experience or knowledge that lead to vary interpretation is less significant and communication among participants can improve (Koo and Fischer, 2000). The 4D CAD-Safety tool can be applied to visualize and interpret construction sequence on a computer display rather than in their mind. This allows users to better understand construction sequence and detect potential problems in construction drawings as well as schedules prior construction starts (McKinney, 1998; Kang et al, 2002).

6.2 SPECIFIC BENEFITS

There are three specific benefits related to the 4DCAD-Safety tool developed. Firstly, the 4D CAD-Safety tool can be used to combine sub-contractors' schedules and a contractor's schedule as well as their safety plans. This combination allows all safety plans from one organization to be communicated to other organizations since they might interact directly or indirectly in order to perform their jobs. Secondly, in relation to safety planning information, when construction activities are progressing as the project calendar is changing in simulation, the safety plan that is required to do current works is also changing. In other words, the safety plans displayed are safety measures related to construction activities being constructed. Thirdly, since the safety plan displayed is related to the construction activities represented in 3D model, the tool facilitates safety engineers to visualize spatial and physical information of construction activities and their products. This facilitates safety engineers to know and analyze when and what safety measures are needed to be installed, prepared, or provided for current activities as well as how to install or prepare those safety measures.

7. Conclusion

4D CAD is an emerging powerful technology to manage construction project. Several researchers have identified its advantages in terms of betterment of a) project representation which reduces design interpretation among project members, and b) understanding of construction sequences.

This 4DCAD technology can also be utilized to manage construction site safety. For this, 4DCAD must be designed to be able to support schedule combination functions and safety planning representation.

The schedule combination function of the 4D CAD-Safety tool helps users to combine sub-schedules from all sub-contractors with the main schedule of the main contractor. This combined schedule is important to develop a 4D CAD-Safety simulation, otherwise some of the 3D models are not simulated because of incomplete schedule information. This integration of subcontractors' and contractor's schedules is important for developing, integrating and communicating safety plan for the whole project.

The 4D CAD-Safety tool can be used to integrate safety planning with construction processes and products. This allows users to visualize and analyze what safety measures (i.e. tools, equipments and Personal Protective Equipment (PPE)) are needed; when they are needed; where they are needed; and why they are needed as well as how to use them.

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