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Application of 4D for dynamic site layout and management of construction projects

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Abstract

Construction schedules and site space arrangement are essential to project management, as they directly influence security, machine running, material deployment, power distribution as well as construction progress and cost. There has been a strong need for more effective planning and management of site space and facilities. This paper introduces a 4D Integrated Site Planning System (4D-ISPS) which integrates schedules, 3D models, resources and site spaces together with 4D CAD technology to provide 4D graphical visualization capability for construction site planning. The features of 4D-ISPS are described in detail. The implementation techniques of this system are also discussed and a real life case is presented.

Keywords: Site layout; 3D Model; 4D CAD; Construction management

1. Introduction

Visual 4D planning and scheduling technique that combines static 3D CAD models with construction schedules has proven to be beneficial over traditional tools such as bar charts or network analyses. The concept and development of 4D CAD in the construction field can be traced back to mid 1980s, when 3D CAD models were combined with the project timeline to form 4D models [1], and systems linking 3D CAD models with schedules started to be developed [2,3]. However, representative and influential applications do not appear until late nineties. In the 1990s, high-performance computer hardware, complex graphical software and object-oriented programming (OOP) made it possible to develop impressive 4D applications. 4D Annotator and 4D-Planner are two representative systems. 4D Annotator can visually explain to planners potential constructability problems or how a proposed construction sequence affects decision criteria such as cost, productivity and safety to commonly mentioned 4D components [4]. 4D-Planner is a visualization, simulation and

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communication tool that provides simultaneous access to design and schedule data [5]. It provides a graphical simulation of the work plan that allows early problem identification, including interference detection, and supports scenario analysis. Kamat and Martinez [6] designed a visualization methodology that allows developers of simulation models to verify and validate simulated construction operations. Recently, 4D technology has been further developed by professional software vendors. Typical products include Schedule Simulator by Bentley™ and Project Navigator 2000 by Virtual STEP™. The benefits of 4D CAD systems are apparent as they can display the assembling sequences of construction projects, simulate different scenarios before construction begins and/or help users conduct constructability analyses of the designs.

Another trend of investigation for construction management has targeted on the strategies or algorithms of locating site facilities on a set of predetermined sites and aims to develop 2D interactive management systems. The Critical Operations Planning Environment (COPE) [7] is an interactive plan management software package, used for planning critical construction operations involving large semi-stationary equipment such as cranes and concrete pumps. Similarly, various approaches for automatically locating site facilities have been presented [8–12]. It is common to see artificial neural networks, expert systems, genetic algorithms or hybrid intelligence utilized in the implementation of these approaches. The developed systems can help project managers make decisions and avoid inappropriate or incorrect layouts based on 2D drawings.

Nevertheless, for a large-scale construction project, site facilities generally are not limited to 2D static site layout. When some resources or facilities are put inside the buildings under construction, the above management systems can no longer meet the needs. Moreover, construction process itself is a very complicated production and generally contains three main phases: excavation–foundation–substructure work, superstructure work and fitting-out work [13]. Some projects may comprise of several buildings with the three phases having different durations and different starting time points. This adds to the complexity of construction layout. As shown in Fig. 1, a sample project contains two buildings A and B with A started earlier but the duration of its substructure is shorter than building B. The construction of the project is then divided into seven phases. In different phases, the site layout will change accordingly to meet the changing demands for materials. So site layout should never be static and two-dimensional, instead, it should be a dynamic activity across the whole 3D site.

Many researchers have already realized the importance of time to site layout. Tommelein and Zouein [14] developed MovePlan to support dynamic layout planning. Zouein [15] developed MoveSchedule, an extension to MovePlan, which can alleviate space conflicts by adjusting the construction schedule. A layout design system, called SEED-Layout was used to conduct dynamic site layout [16]. Temporary facilities ranging from material storage such as long-term lay-down areas to building structures such as temporary offices can be located with SEED-Layout. Guo [17] also takes time as an important part of site

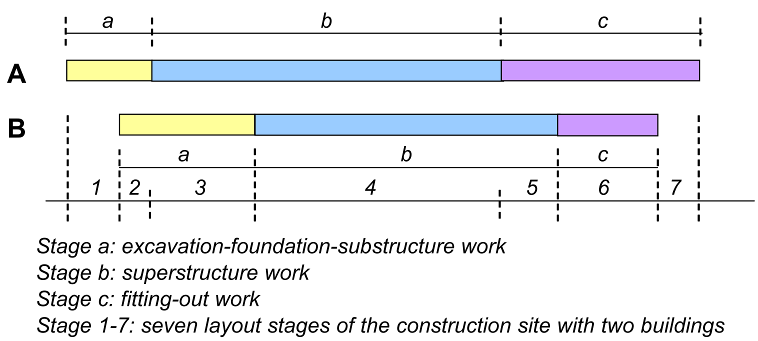

Fig. 1. Complex site layout periods.

planning. In his research, site spaces are organized according to time and scheduling.

The consideration of 3D space as a factor of site layout has also emerged as a research focus. Riley and Sanvido [18] defined construction-space use patterns in multi-storey buildings. Further, a space planning method for construction of the buildings, based on a detailed model of construction space need and patterns of space use, is developed [19,20]. The use of this method yields information for planning decisions in the form of a defined work flow through the building, schedule of material delivery and assigned storage and work areas. Finally, a planning tool for such purposes was developed [21]. Akinci et al.[22] conducted similar research, which reduces non-value-adding activities due to time–space conflicts. A 4D production model was proposed, to describe and analyze these time–space conflicts [23]. Then, to automate the generation of work space requirements of activities, 4D WorkPlanner Space Generator (4D Space-Gen) was developed, based on user-defined generic space requirement knowledge and project-specific production model information [24].

Although many researchers have noticed the significance of time and 3D space in site layout, few studies have focused on the whole 4D construction site that should cover all space and facilities inside and outside the buildings. Moreover, existing software packages do not provide the automatic functions, and many tasks have to be conducted manually.

This paper presents a 4D integrated site planning system (4D-ISPS) that brings the state-of-the-art 4D technology into construction site management. The primary objective of this research is to develop an efficient 4D site management software package, which will solve the existing problems in this field. Besides, traditional 4D modeling and simulation processing of the buildings are also included. The 3D modeling methods, schedule establishment strategies and 4D linking mechanisms of the buildings and site facilities will be explained in the following sections. The technologies adopted to implement the proposed system are also introduced. The developed approach has been centered on creating an information and graphical model platform across the AutoCAD and MS project software interfaces using Visual C++ and ObjectARX. At last, a real-life project is used to illustrate the functions of 4D-ISPS.

2. Description of the system

The 4D site planning system integrates 4D building models and 4D site models. The 4D building models are designed to link 3D models of the building under construction with the schedule information through a Work Breakdown Structure (WBS), whereas the 4D site models integrate the schedule information with the 3D models of the facilities. This structure not only enables resource, schedule and manpower management of the project, but also provides convenience to 4D layout across the construction site. The 4D visualization and the 3D dynamic site layout is a major step forward towards achieving dynamic site layout and management of construction projects. The key features of this system will be described in detail in the following paragraphs.

2.1. Quick 3D building modeling

There are many software packages for 3D modeling such as AutoCAD, Microstation and 3D Studio. However, the lack of fast professional modeling tools forced us to develop a specific module for building modeling. Generally, a building comprises of a number of standard storeys and units, which in turn comprise of a series of standard elements such as beams, walls, floors and columns. The fast modeling method stems from copying or repeating these standard components. In 4D-ISPS, standard objects are defined and drawn only once. If one standard object is constructed, all objects with the same properties can be generated automatically. On the other hand, the procedure of creating standard objects is also simplified. Manual work initially done in AutoCAD can be reduced with only a little project information needed. Most information like storey height, storey elevation and size of elements' section are available in databases. Users only need to set the current storey, select the current standard component and input few locating points. In 4D-ISPS, the involved information is transformed into geometrical data recognizable by AutoCAD automatically. Fig. 2 illustrates the process of drawing a wall of 370 mm width.

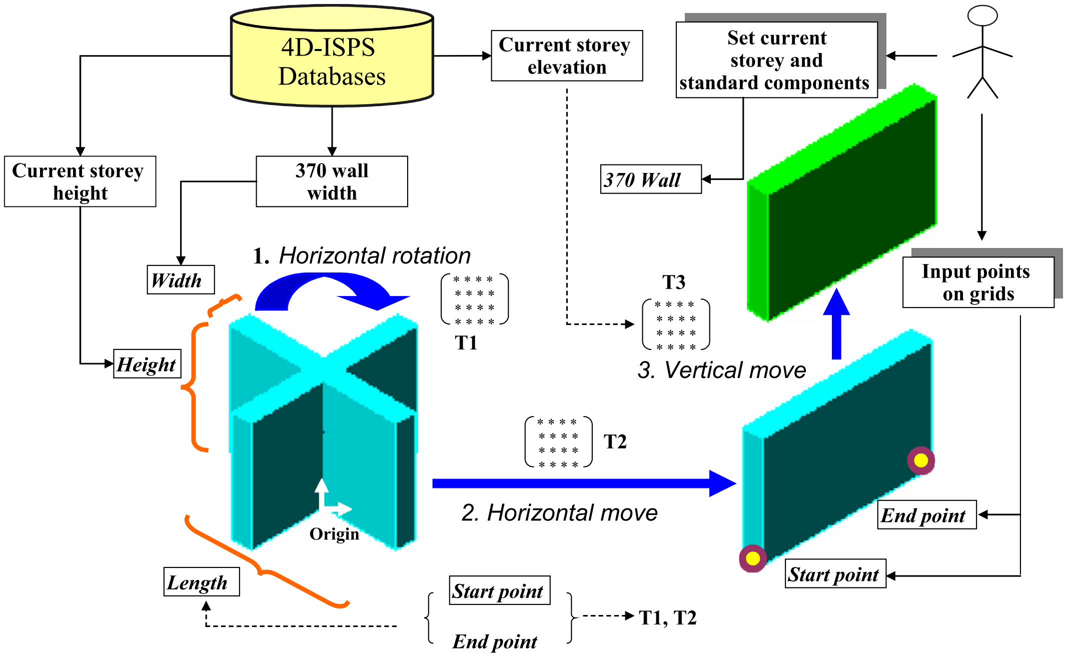

Fig. 2. The process of creating a wall of 370 mm width in 4D-ISPS.

Using object-oriented programming method, we can characterize a real component as a graphical object which possesses project information of the real component. Each object belongs to a specific group. In AutoCAD, the properties of a number of objects can be changed by modifying common properties of their group. In this way, 4D-ISPS changes the color of objects within one group to represent different activities. The group name follows the rule of: "project ID"–"storey ID"–"segment ID"–"element ID". For example, if a beam resides in building 2, the 4th storey, the 1st segment, then its group name is "2–4–1–2" (for beam, the element number is 2).

The fast modeling method is only applicable for regular buildings with duplicable storeys and units. Nevertheless, very few buildings are of irregular shapes that do not have standard storeys. This method is not appropriate for buildings that contain atypical structures (such as a dome roof) and do not have standard and repeated elements. However, 4D-ISPS is still able to create 4D models for them. The 3D models are constructed manually in AutoCAD or other professional 3D modeling packages. Then 4D-ISPS imports and assigns these 3D models to their corresponding groups, according to the above rules of group names. Thus, the 3D models can also be linked with schedules through WBS codes, which will be discussed later. Both applicability and speed are enhanced in comparison with traditional modeling tools.

2.2. Work Breakdown Structure

In project management, WBS is a method for analyzing a project's activities served as a basis for project scheduling, reporting, staffing and budgeting. A WBS is a top-down structure that defines the desired end result of a project and is made up of related elements often called tasks and subtasks. The WBS code is an alphanumeric code that represents the task position within the hierarchical structure of the project. WBS codes are unique and each task has and only has one WBS code.

In this study, the buildings under construction act as the main tasks and the WBS structure is organized in the form of "project section"–"phase section"–"building section"–"storey section"–"construction segment section"–"component type section"–"activity section". The chunks in sequence mean which project, what kind of work (structure or fitting work), which building, which storey, which segment, which kind of element (beam or column, etc.) and what activity (false work, steel work or form work, etc.). We use capital letters followed by numbers to represent different sections of WBS codes. Thus WBS codes for tasks and their subtasks from top to down are in the form of "XM##", "XM##–DX##", "XM##–DX##–DW##", "XM##–DX##–DW##–FC##", "XM##–DX##–DW##–FC##–FD##", "XM##–DX##–DW##–FC##–FD##–FB##", "XM##–DX##–DW##–FC##–FD##–FB##–GX##"(## means arbitrary natural number that indicates the ID of that task node). Each task in 4D-ISPS uniquely relates to a WBS code. Table 1 describes the WBS tree structure.

Through WBS codes, relations between schedules and 3D models can be linked without difficulty. It is also convenient for 4D models to acquire information from other modules or databases. In one word, WBS codes act as a bridge to link 3D models, schedules and other project information together.

2.3. Formation of schedules

A series of standard activities are predefined in one activity database. Each activity is annotated with its resource requirements including material, plant, labor, workspace, cost and, most significantly, time. As mentioned above, activities locate at the lowest level of the WBS tree so that a task's progress time is available if all activities under that task are assured.

Table 1
WBS tree structure

Description	WBS
Information technology school	*XM1*
Structure work	*XM1–DX1*
Main building	*XM1–DX1–DW1*
Storey 1	*XM1–DX1–DW1–FC1*
Segment 1	*XM1–DX1–DW1–FC1–FD1*
Column	*XM1–DX1–DW1–FC1–FD1–FB4*
False work	*XM1–DX1–DW1–FC1–FD1–FB4–GX1*
Steel work	*XM1–DX1–DW1–FC1–FD1–FB4–GX2*
Form work	*XM1–DX1–DW1–FC1–FD1–FB4–GX3*
Concrete work	*XM1–DX1–DW1–FC1–FD1–FB4–GX4*
Solidifying work	*XM1–DX1–DW1–FC1–FD1–FB4–GX5*
Form removal	*XM1–DX1–DW1–FC1–FD1–FB4–GX6*
Storey 2	*XM1–DX1–DW1–FC2*
Storey 3	*XM1–DX1–DW1–FC3*
Fitting work	*XM1–DX2*

Old activities can be edited and new activities can be added for a range of schedule management requirements. Many previous 4D applications need to establish schedules manually, which is a kind of arduous work. In 4D-ISPS, these operations are reduced by utilizing the standard activities that are created for different types of elements. When a type of element is assigned to a segment, the activities belonging to it are automatically generated and located at the right positions of the WBS tree. The schedule information of each activity is accessible from the activity database. Thus, after the WBS tree is established, the initial schedule for each task is available. 4D-ISPS employs a PRJ file (MS Project file format) to store schedule information. The initial schedules are preserved in this PRJ file.

MS Project is a powerful scheduling software package, which is currently used in the construction project management domain. It involves the estimation and specification of the duration of each task in a designed project based on resource usage, including the logical relationships among tasks and their effects on the total time duration of the project to be delivered. In MS Project, schedules can be represented by Gantt charts. The bar charts displayed for the initial schedules only denotes time span for each task. But it is convenient for project managers to establish task dependencies such as Start-to-Start dependencies and Finish-to-Start dependencies. The managers are also able to make analysis to solve resource conflicts or reduce project duration using CPM or PERT methods. As such, 4D-ISPS enables project managers to establish complex schedules in a professional way. In addition, the system may share other benefits of MS Project. Fig. 3 illustrates the possible functions MS Project may bring to 4D-ISPS.

2.4. Mechanism of linking 3D building models with schedules

As we have mentioned before, when 3D models are created, they are attached to AutoCAD groups. These groups correspond uniquely with WBS codes. Further, schedule information is available by exploring the PRJ file according to these codes. There is no need to link each activity to its associated 3D element because 4D-ISPS will search the proper activities

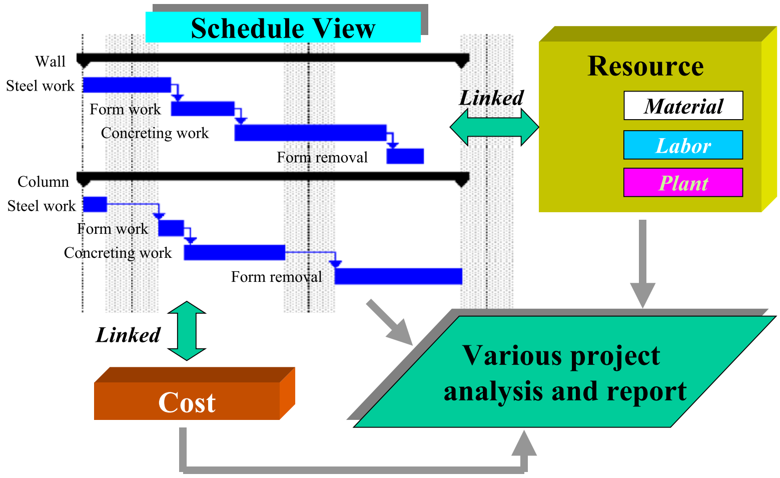

Fig. 3. Functions of the selected schedule management software.

automatically for each element through WBS codes when performing 4D simulation. Group names map uniquely with the nodes of the 6th level of the WBS tree. The code mask of these nodes is "XM##–DX##–DW##–FC##–FD##–FB##". The group names eliminate the first two chunks. Then, the leading letters are also removed and only the task node IDs are reserved. As such, the group names are in the form of "##–##–##–##". In 4D-ISPS, task nodes are numbered increasingly, in each level of the WBS tree. No two IDs are identical in the same level. Hence, the reverse conversion from group names to WBS codes is also unique. There is an exception for the numbering of the task nodes. Task IDs of the sixth chunk are assured according to the element type: 1 for wall, 2 for beam, 3 for floor, 4 for column and so on. Nevertheless, this will not influence the uniqueness of the whole mapping relationship.

In addition to the one–one mapping relationship, a notable feature of 4D-ISPS is the two-way data exchange mechanism between 3D models and the schedule information. This ability is very desirable because it assures consistencies between 3D models and schedules. When any modification of 4D models is conducted through picking a 3D element and modifying its schedule property, 4D-ISPS will immediately evaluate whether or not the modification is acceptable. If so, the 4D models will be changed and the schedules in the progress file are revised accordingly. On the other hand, if there is any modification to the schedules in the PRJ file, the 4D models will be regenerated automatically by the computer.

2.5. 3D Site facilities modeling and scheduling

In 4D-ISPS, site facilities are organized into a two-level tree structure. The top level contains nine main categories: buildings, roads, fences, storages, linear facilities, cranes, mixers, other plants and sites. Sites are defined here to denote planes of different elevations for us to place facilities and storages. These categories own a few attributes but have no graphical representations. Further, these categories are sub-divided into sub-types. The sub-types have graphical representations and own their private attributes. The attributes of each category are shared by all sub-types under it. Each site facility resides in 4D-ISPS as an entity. These entities are created as instances of the sub-types, and correspondingly have their graphical representations. Attributes of site facilities include geometrical properties, project information and mechanical parameters. The schedules are embodied by two attributes of the entities: start time and finish time. As such, there is no need to link schedules and 3D models together, for they are bounded in one entity.

In order to create vivid 3D site models, different kinds of facilities are represented by different shapes, colors and body materials. Moreover, a graphical block library of plants, which contains a series of

DWG files, is employed to create equipment. The block library is organized in a tree structure. All site plants are classified into several main categories and a category may be further divided into different types of equipment with each type having an AutoCAD 3D block file. Fig. 4 shows the structure of the block library and two sample blocks from the library.

2.6. 4D Simulation and site layout

A kind of relationship is established between 3D models and schedule information both in 4D site models and 4D building models. All site facilities contain schedule information themselves, whereas building components are linked with schedule information through WBS codes. 4D-ISPS employs the relationships between 3D models and schedule information and forms one seamless 4D interface for site management.

As mentioned before, all building elements are organized in groups, and the schedule information of them is stored in one PRJ file. These elements first analyze their group names to find their WBS codes, through the unique mapping relationship between them. Then tasks and activities related to the calculated WBS codes are filtered out in the PRJ file. These tasks and activities contain the required schedule information of the building elements. For site facilities, the schedule information is obtained directly. When a progress time point is designated, the construction states of all elements and facilities can be ascertained by comparing their schedule information according to the given time. Different colors are employed to represent different construction states. At different given time points, 3D models of the building elements and the site facilities in the drawing are redrew in the corresponding colors to embody different construction states. Fig. 5 illustrates how 4D-ISPS implements 4D application.

If the given time points continuously change with the construction progress, the 3D models in the drawing will vividly demonstrate the construction process. This is the way 4D-ISPS employs to make construction simulation. As for site layout, a period must be provided first so as to ascertain the 3D space environment. As such, the problem of 4D site layout

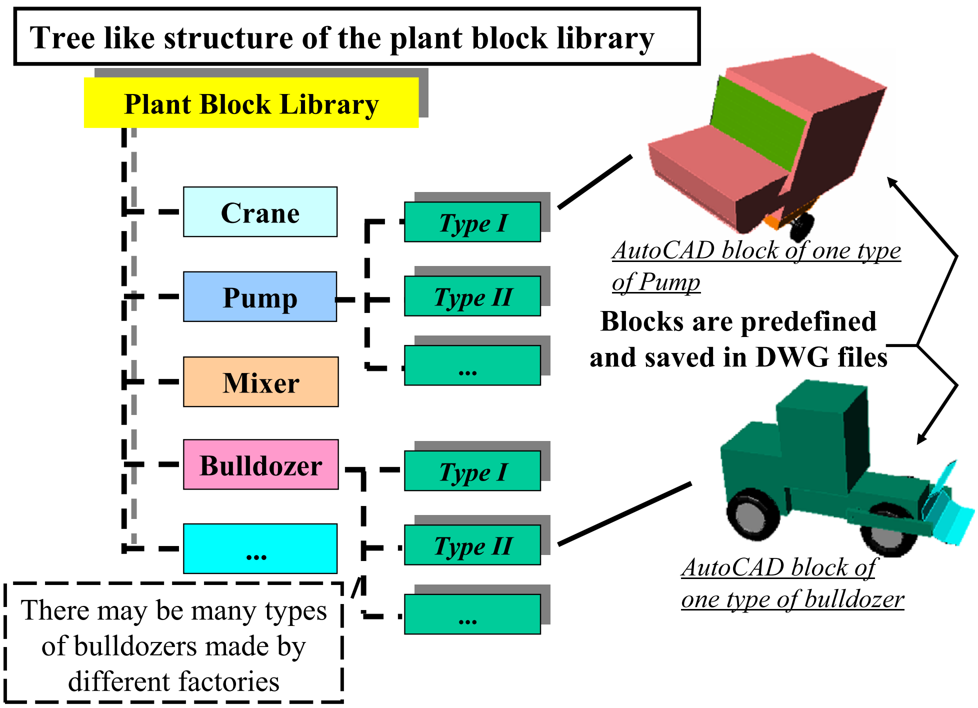

Fig. 4. Blocks of site plants.

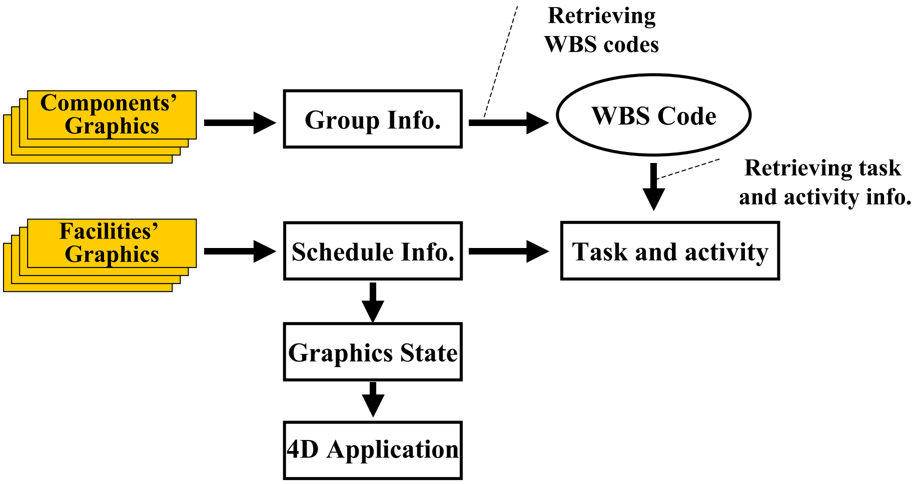

Fig. 5. Procedure of 4D application.

is simplified to a 3D static one. In 4D-ISPS, facilities can be placed at any elevation underground or above the ground, inside the buildings or on the storeys under construction. 4D-ISPS provides convenience to implement 3D site layout. One reason is that all site facilities have one property of elevation and it is straightforward to move them vertically by modifying this property. In addition, the elevation and storey height of any storey can be obtained easily.

3. Implementation and application of 4D-ISPS

3.1. Development technologies

The 4D-ISPS is developed with an objective of integrating 4D construction models with site facilities layout, which is developed as a series of ARX/DBX files in AutoCAD 2000 and interacts with several databases through DLL modules. The product aims to achieve commercializing and has substituted the original user interface of AutoCAD, which will then run underground instead. This is realized by the most advanced programming technology: subclass. Subclass is a technique that allows an application to intercept and process messages sent or posted to a particular window before the window has a chance to process them. This is typically done by replacing the window procedure for a window with application-defined procedure. Through subclass, the developed system can take the functionality of a control of AutoCAD and modify it. In 4D-ISPS, AutoCAD's main window is sub-classed and replaced with a new window applicable to our research. The end users no longer need to interact with AutoCAD directly.

As mentioned before, object-oriented programming method is used in this system. There are many plants in a construction site, such as cranes, mixers and concrete pumps, all of them have their own specific attributes. For example, the attributes of cranes include model, height, arm length, position and so on. Through abstracting them as classes, and using data members to identify their attributes, module dependencies can be decreased significantly. This advantage is enhanced when ObjectARX is used to develop the software system. Because each entity class can be encapsulated in a DBX file, thus each construction site entity has a corresponding DBX file. Each DBX file is generated with an absolute Visual C++ project. There are almost no dependencies among different modules. In addition, class hierarchy relationships are established through inheritance to reduce source codes and we also benefit from the modularity.

4D-ISPS system stores project information in databases, with which each subsystem need to exchange information frequently. It is therefore very important to adopt an appropriate database client access technology. Database client technologies for the Windows platform have rapidly evolved during the past few years. Technologies for doing database client development include Open Database Connectivity (ODBC), Microsoft Foundation Class (MFC) ODBC classes, Data Access Objects (DAO), Remote Data Objects (RDO), Object Linking and Embedding Database (OLE DB) and ActiveX Data Objects (ADO). Of all these technologies, OLE DB and ADO have the most promising future. ADO is built on top of OLE DB. ADO's primary benefits are high speed, ease of use, low memory overhead and a small disk footprint. It supports stored procedures with in/out parameters and return values, limits on number of returned rows, other query goals for performance tuning and multiple record sets returned from stored procedures or batch statements. Furthermore, it has different cursor types, including the potential for support of back-end-specific cursors. In view of all these benefits, 4D-ISPS uses ADO as its database client technology.

3.2. Key modules and running environments

In summary, 4D-ISPS has been developed with the state-of-the-art programming technologies to form a seamless integrated system with high speed and compatibility. It comprises three main modules that exchange data among themselves through databases or dynamic data exchange. The configuration module deals with basic information of the project, creates the WBS tree and stores the information into databases. The 3D building modeling module manipulates 3D models of the buildings and links the 3D models with schedules. The 4D site management module will construct 4D site models, incorporate 3D building models and is responsible for 4D applications. The system runs in the following environments:

Required hardware environment:

(1) CPU: Pentium II or above
(2) 128 MB RAM
(3) 1 G free disk space
(4) 8 MB graphics card

Required software environment:

(1) Microsoft Windows 2000
(2) Microsoft Access 98/2000
(3) Microsoft Project 98/2000
(4) AutoCAD 2000

3.3. Test in real-life cases

4D-ISPS has been applied in several real-life projects. In this section, application in collaboration with industrial partners, i.e., contractors is to be discussed with a real case. The sample project is composed of seven storeys with one storey underground. Two to four storeys are standard storeys. In addition, many units are the same in each storey. The total cost is about 0.13 billion dollars. The construction period for the structural works is from July 2002 to January 2003. In order to assess the appropriateness of the extent of the involved data, the entire structural construction was traced in detail by using 4D-ISPS.

It takes 8 man-hours for a trained technician to construct the WBS tree and create the 3D models of the target building from the construction drawings. The 3D building models are created storey by storey. The first step is to draw the axis and define a series of standard components like concrete walls of 370 mm width, for the whole building. Then the technician needs to select the current storey and the current standard component in turn. The screen will only show elements in that storey and the axis. He inputs a series of points as locations of the elements to be constructed. As a result, 4D-ISPS automatically generates the 3D models based on the elevation and height of that storey, and attributes of the current standard component. The constructed elements can be copied in one storey or across different storeys. For the standard storeys, the technician only needs to construct the 3D models for one storey. Fig. 6 shows the created 3D models of the building. The 3D models demonstrate visually what the structure will be like after construction.

The initial schedules are automatically generated after the WBS tree is constructed. The technician can view and edit the PRJ file in MS Project. What he does here is to turn the initial schedules to formal ones. After the schedules are confirmed, 4D simulation of the construction process can be conducted. In 4D-ISPS's main interface, the project managers can vividly view the construction process. The upper left of Fig. 7 is the graphical representation of the construction of the project's ground floor. The virtue of this representation is that the overall plan is visible and it is easy for all stakeholders to understand how the project progresses at a designated time. After

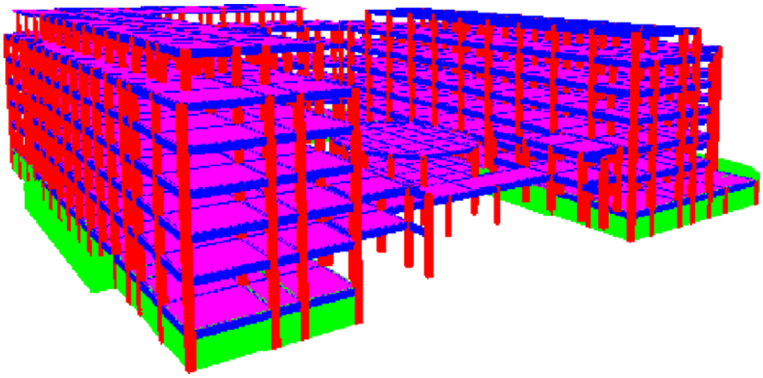

Fig. 6. 3D Models of the target building.

several weeks of work, the progress is newly depicted in the down right picture. Through comparing with the upper one, the project managers become very clear with the whole construction progress.

Then the technician comes to arrange facilities of the construction site. The layout process is much like arranging Lego. Attributes of plants can be adjusted dynamically. For example, when he selects a crane and inputs a new arm length through the main interface, the crane in the drawing will be changed synchronously. He can push and drag the crane to a new place as he wants. As such, any of the designer's new ideas can be reflected in the 3D drawing immediately. It is very convenient for verification and validation of different layout schemes. Moreover, new ideas are easy to be inspired through changing angle of views of the construction site. Fig. 8 illustrates the 3D site layout at a given period of the sample project. In 4D-ISPS, the users can lay temporary storages on any storey. In this case, the technician attempts three storages inside the building as Fig. 8 shows. This function improves usable site space considerably and may bring about more rational layout methods that can facilitate material circulation of the construction site. Besides, the storages and all site facilities contain schedule information, so site layout evolvement can also be simulated.

The industrial partners of this project have expressed their interests in 4D-ISPS after viewing our application. They believe that this kind of tool can

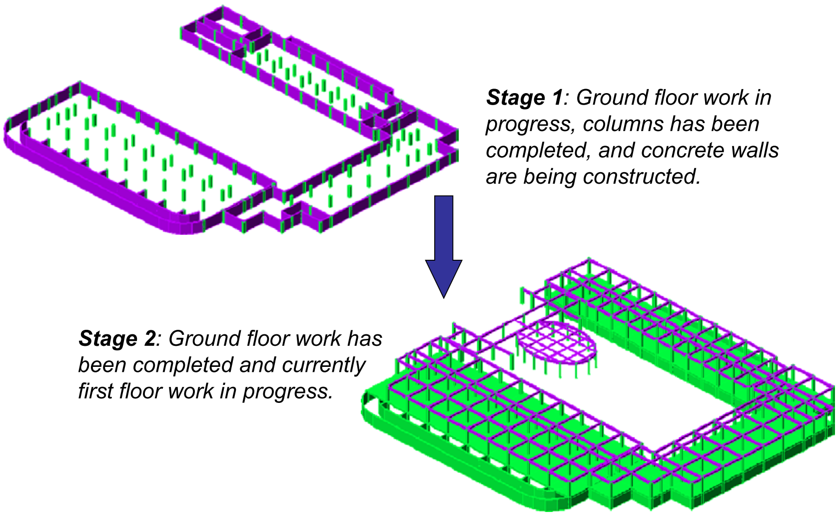

Fig. 7. 4D Simulation of construction process.

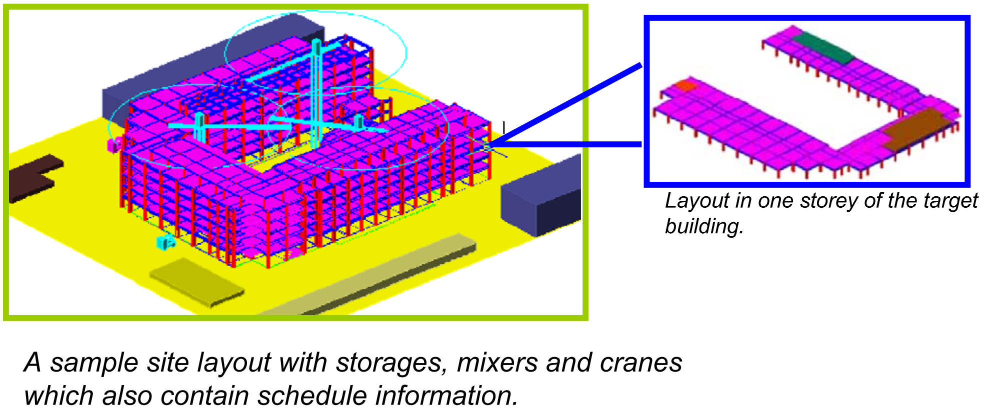

Fig. 8. 3D Site layout at a given period.

enhance efficiency and effectiveness of construction management. Meanwhile, their confidence of successfully accomplishing the projects is improved, as is based on predictable and visible models. In other testified projects, the project managers have given similar comments.

4. Discussions

Through the sample project, we discovered several virtues of 4D models and current 4D tools. In the first part of this section, the key virtues of this system are outlined as follows:

(1) Layout inside the multi-storey buildings and implementation of 4D site layout are the chief virtue of this system. 3D Site drawings have better visual effect than traditional 2D site layout drafts. When 3D site models are linked with schedules, the site layout evolution procedure during the whole construction life cycle can be vividly simulated. Moreover, usable space is expanded by planning site facilities inside buildings. The whole material circulation path in the site can be traced.
(2) Efficient schedule data preparation and acceleration of 3D CAD model generation are the second aspect that improves over other 4D CAD applications. Koo and Fischer [25] have emphasized two major limitations of 4D models and 4D tools are the low speeds of schedule data preparation and 3D CAD model generation. In 4D-ISPS, the schedule data generation is automated through a set of activity templates and the WBS tree. The generated data can be viewed and edited in MS Project for professional analysis. The creation of 3D CAD models can be expedited through repetitive steps across standard storeys and units. 3D CAD models and schedules are linked automatically through the unique mapping relationship between group names and WBS codes.
(3) Consistencies between schedules and 3D models are another advantage 4D-ISPS has achieved. There are no direct linkages between schedules and 3D models. So if schedules are modified or the properties of 3D models are changed, 4D models need not to be reconstructed. In addition, the data exchange between MS Project and our system is bidirectional. The schedules can be revised by modifying the 4D models.

Despite these benefits, there are two limitations in the system that will be investigated further in subsequent studies:

(1) In 4D site models of the proposed system, positions of site plants are not recorded. Position alteration of one site plant is implemented by laying two same plants in different periods. It is difficult to calculate the number of plants used during the whole construction period. 4D site

models should be extended to keep track of the positions of site plants.

(2) 4D-ISPS has used its own product and process modeling methods. This approach, however, inhibits data sharing with other 4D systems. Although there have been such initiatives like Industry Foundation Classes (IFC) by International alliance of Interoperability (IAI) and Standard for the Exchange of Product Model Data (STEP), it is difficult to employ them in our system. It is noted that several researchers are utilizing IFC standards as product modeling references [26,27]. Yet, IFC standards are currently lacking needed functionality, and they do not support all types of structures [28].

5. Conclusions

With an impetus to achieve efficient construction site planning, this paper has introduced a system 4D-ISPS which can deal with both 4D building models and 4D site models. By utilizing innovative technologies such as ObjectARX and DLL and a series of common software packages like MS Project and AutoCAD, an integrated site layout system with management, visualization, schedule and facility layout across the dynamic 3D site has been developed. The system was verified in real projects through contractors' assessment and field tests. It is envisaged that successful implementation of the system for site layout will assist project planners to produce more reliable plans, which will, in turn, promote effective management across site spaces at the construction phase. Despite these benefits, it should be noted that the system presented in this paper does not have the function of position tracking of plants and common data standards that serve as the foundation for information sharing. These two aspects will be addressed in our future research.

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