Automation in Construction 20 (2011) 167–180

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials

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ARTICLE INFO

Article history:
Accepted 16 July 2010
Available online 30 October 2010

Keywords:
Conflict analysis
Structural safety analysis
Construction management
System development
Site trial

ABSTRACT

In order to achieve the information-based integrated construction management, e.g., time-dependent structures analysis, schedule/resource/cost conflict analysis as well as dynamic collision detection amongst site facilities and main structure elements, an integrated archetypal system named 4D-GCPSU 2009 is developed. Through 3 project examples, it is verified that the integrated solution is able to assist construction managers or owners in the aspects of analysis and management for process conflict and structural safety problems during construction. The application outcome of the system is accepted and praised by users as they considered that the system functions and analysis results provide significant reference support to the approval and revision of construction proposals, increase efficiency and safety concerning building construction. They also point out some difficulties in practice. As for those difficulties mentioned, a series of solutions plus further development orientation are put forth.

1. Introduction

The accident rate of building industry and the numbers of accidents and deaths remain high. Researchers and construction managers have made efforts to improve workers' safety and health. Some related system are developed and applied to construction cases [1,2]. These researches mainly focused on quality of personnel, safety awareness, enforcement of safety regulations, and Environmental- and site-condition-related issues etc. [3]. However, it has become a consensus that more attentions should be paid to structural safety itself [4,5], and conflicts due to inappropriate construction management [6]. In this regard, Building Information Model (BIM) and four-dimensional (4D) technology can be accepted as implementation skills for research trials. For instance, with regard to BIM, existing literatures provided some new ideas, e.g., BIM was used as a link between manufacturing process and construction objects [7], a construction virtual prototyping to integrate design and construction [8], etc. As for 4D technology, a number of commercial systems were applied to construction projects. VTT [9] summarized that several 4D applications can manage analysis during construction such as work-flow, cost, resources, design, and collision and so on. Nevertheless, these researches limited applications in construction optimization rather than safety analysis and management.

In a companion paper [10], the BIM- and 4D-based theories and key technologies for the integration of dynamic safety analysis of time-dependent structures, conflict analysis and management of schedule/resource/cost, and dynamic collision detection of site facilities are studied, in order to provide a new rational analysis and management tool for process conflict and structural safety problems during construction. This paper firstly illustrates development of the system in detail, and then by three real project applications, the feasibility and effectiveness of the system are verified, and utilization experiences, as well as future directions and potentials are discussed.

2. Development of 4D-GCPSU 2009

This section primarily focuses on the entire design proposal of the integrated archetypal system named 4D-GCPSU 2009, including demand analysis of system design, function design, entire framework design, database and program design etc. in detail.

2.1. Design demand analysis

As for system design, the following 4 demands are taken into account:

1) Support multi-user operation, as well as information exchange and co-share through network. Being a network-based multi-user system, the system requires a data version control mechanism to avoid conflict caused by simultaneous modification.
2) Satisfy the demand claimed by several analysis and management functions for construction process conflicts and structural safety problems. Additionally, functions offered by the system are rather

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doi:10.1016/j.autcon.2010.09.014

professional and therefore a unified operation procedure is required for the purpose of making the functions easier to use.

3) Utilize historically accumulated data to the full extent. It usually takes quite a long time ranging from half a year to 3–4 years constructing a complex structure. Take the three projects to be mentioned as examples, the structural construction periods of the Nation Stadium project, the Guangzhou West Tower project, and the Qingdao Bay Bridge project last for 4 years, 2 years and 4 years, separately. Relevant information increases day after day over such a length of time. Those data in large quantities can be used to predict the following construction states and also provide reference supports for plan alteration.
4) The program codes should be in compliance with some widely-accepted "Coding Rules" and meanwhile, in order to reinforce its readability and expandability so as to lay an adamantine foundation for system hand-down, supplementation and perfection, it is strongly recommended to use a universal and sophisticated "Designing Mode" while designing and materializing program codes.

According to these design demands, function design, framework design, database design, and program design are carried out.

2.2. Function design

4D-GCPSU 2009 comprised of 5 function modules like system management, information modeling and management, 4D construction simulation, 4D construction management and 4D construction conflict and structural safety analysis as shown in Fig. 1. The system incorporated into the existing system 4D-GCPSU 2006 [11] as an expanded function model.

2.3. Framework design

2.3.1. Network and physical framework design

3D models are basic expressions in 4D-GCPSU 2009. It requires the client end to be more proficient when dealing with 3D figures. Moreover, 3D model data exist in large quantities, and model conversion as well as rendering involves enormous calculating work. As a result, Client–Server (CS) network mode is selected as network framework for the system.

In accordance with CS network mode, the physical framework consists of a server end and several client ends. The server end is configured with routers, firewall and a SQL-Server, responsible for data access and service management. At every client end, there is an XML-formatted configuration file in which system configuration specifications and project details are contained for users to set up the application environment. In order to improve data access efficiency, each project contains several binary-formatted files as mapped local PC copies of the latest data in the remote database. The data control mechanism ensures users to obtain the latest data by simply opening a project even without thinking about whether the local data is in the latest version, thus facilitating user's operations significantly.

2.3.2. Logical framework design

The 7-layer logical framework diagram as shown in Fig. 2 is designed for the system in accordance with the chosen network mode.

1) *Data Source Layer:* The origin of all data.
2) *Connector Layer:* Imports data source into the data layer through interface programs. The 3D model interface is able to create 3D models by importing IFC model files or AutoCAD entities, and the progress interface communicates with Microsoft Project in a bidirectional way.
3) *Data Layer:* Stores relevant data in accordance with data structures in the system. Inside this layer, there is a data access control mechanism, which improves the system's operation efficiency.
4) *Model Layer:* Organizes data in the data layer through categorization according to different modules and then built up the 4D structural information model.
5) *Platform Layer:* Forms an integrated environment and several application modules with a series of arithmetic and functions on

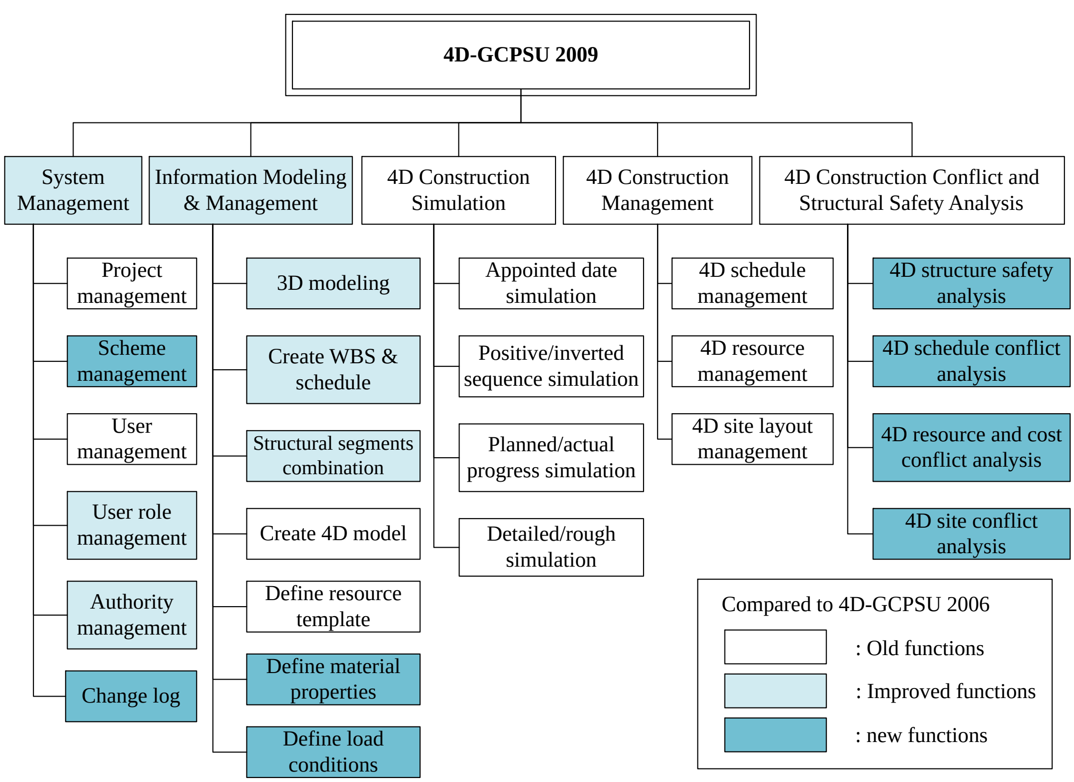

Fig. 1. Function model of 4D-GCPSU 2009.

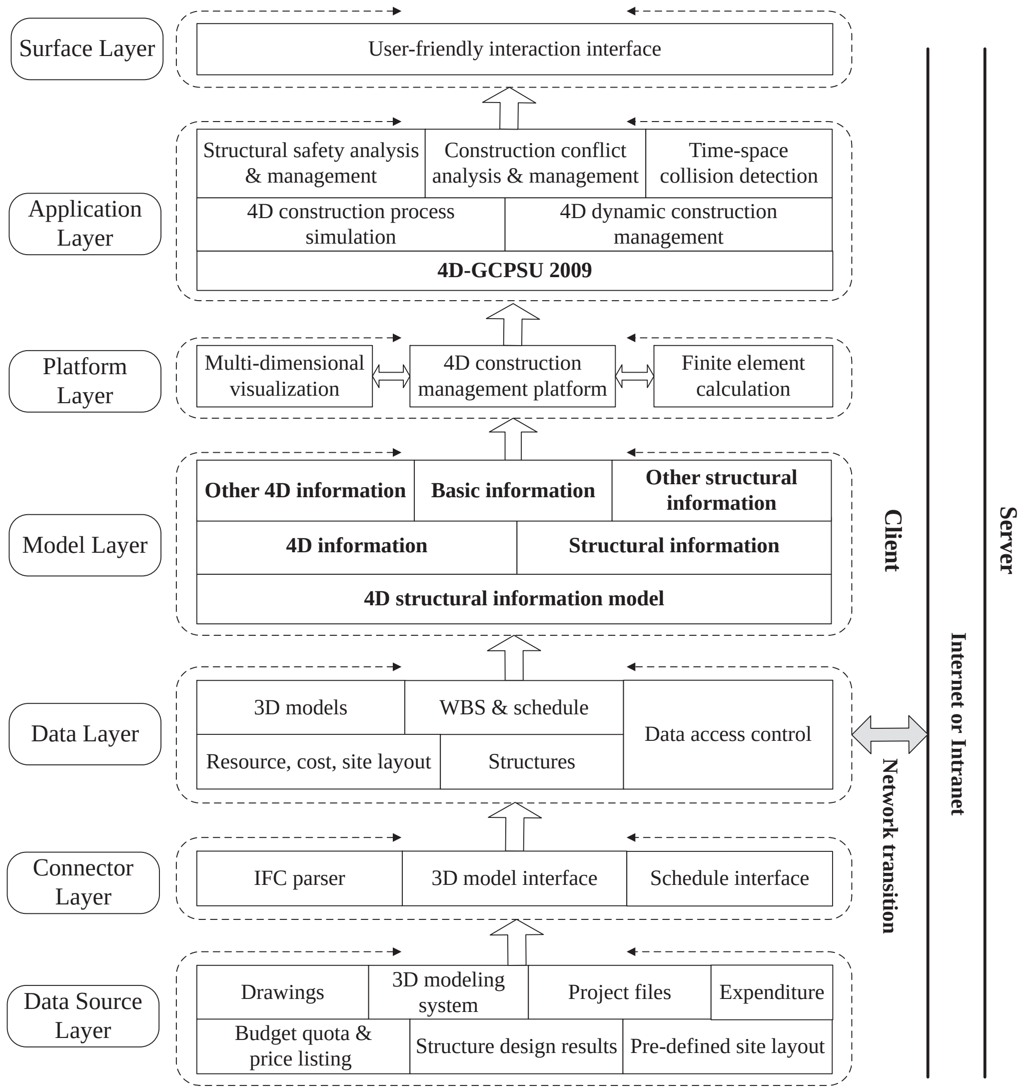

Fig. 2. Logical framework of 4D-GCPSU 2009.

the basis of the model layer. The multi-dimensional visualization platform offers a dynamic 3D visualization environment. The 4D-GCPSU 2006 is chosen as the 4D construction management platform, providing 4D simulation and original construction management functions. The sophisticated commercial software ANSYS is selected as the finite element calculation platform.

6) *Application Layer:* Refers to the specific applications of the system.
7) *Surface Layer:* Provides user-friendly human-machine interaction interface for various functions.

2.4. Database design

4D-GCPSU 2009 adopts relational database and distinguishes objects from relationships, making the information definition of the database clearer and the database more manageable. The project database consists of 89 data tables that can be divided into 12 modules such as schedule management, 3D model storage, 3D model management, material attribute, extended attribute, resource attribute, site layout information, scaffold system, load, project environment, version and log, and linkage information. As for relations among modules, please refer to Fig. 3.

This paper takes the "Task" in the schedule module and the "Building Element" in the 3D model data module to exemplify the design principles of data tables.

2.4.1. Conceptual design

The "Task" describes specific information of a Work Breakdown Structure (WBS) node, e.g., time, time difference, float time, milestone, priority and inter-layer relation etc. and is also a table extracted as an isolated object. Depending upon the inter-layer relation of WBS node, the "Task" is able to form a tree-shaped structure. The "BuildingElement" which is also an independent object, describes geometrical information about building elements, e.g., geometrical performance, transformation matrix, cross-section and axes etc. In the system, a construction segment node, which is a specific type of "Task" node, is connected to several building elements. All the building elements that belong to the same segment node share a series of same construction activities and schedules. That means a one-to-several relationship should be built up between "Task" and "BuildingElement". Such correlation is materialized through a "Rel_BuildingElement_To_Task" table in the database. Figs. 4 and 5 are the Entity-Relation (E-R) diagram and conceptual model of these tables.

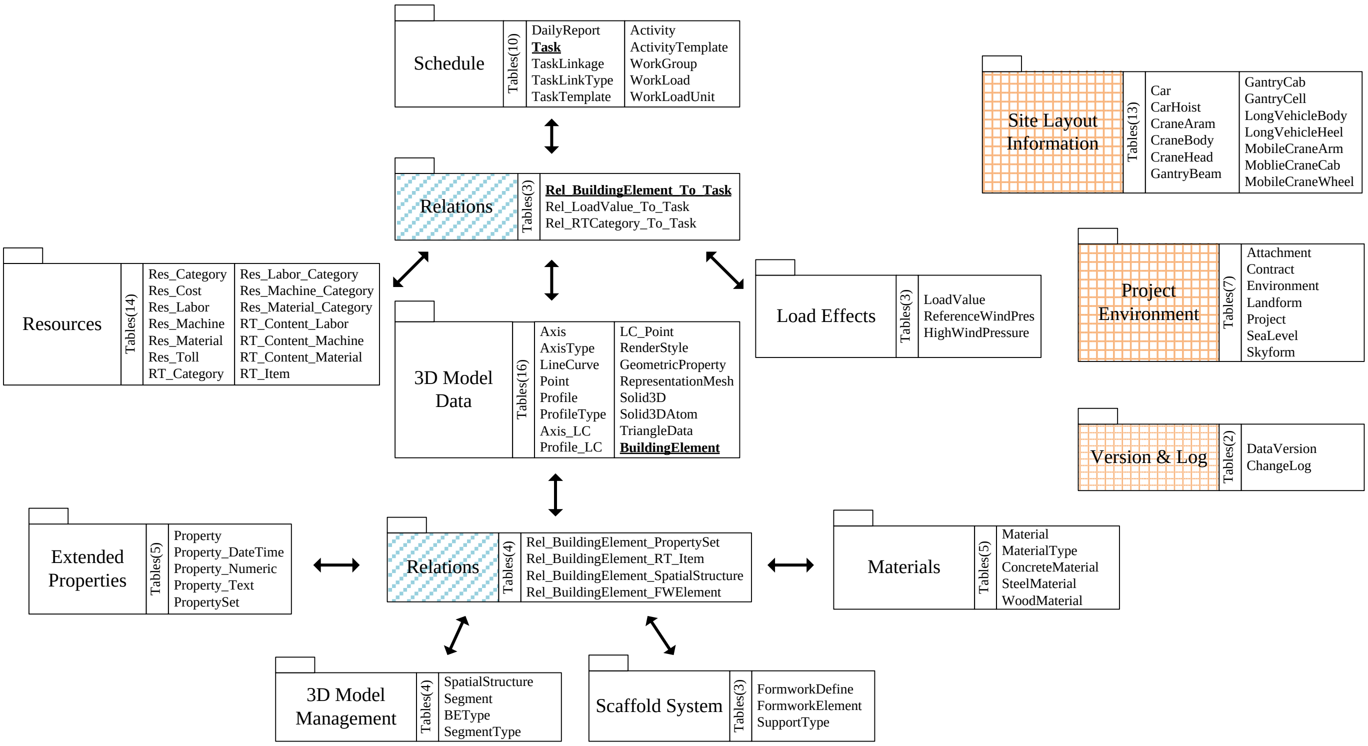

Fig. 3. Module relationships of database tables in 4D-GCPSU 2009.

2.4.2. Logical model

Fig. 6 illustrates the logical model that correlates the "Task" with the "BuildingElement" according to the abovementioned conceptual design.

It is revealed that both Task record and BuildingElement record take "ID" which is configured to Primary Key (PK) as their unique identification, and use "GlobalId" that exists independently to a single application as supplementary ID. The relationship inside the "Task" forms a tree-shaped WBS structure that is linked via "OutlineNumber" or "ParentID". On the other hand, in the "Rel_BuildingElement_To_-Task" table, "BuildingElementID" and "TaskID" are adopted as Foreign Key (FK) for both abovementioned tables and two of them are also used in combination as combined PK. This relation table is able to express data relationship of one-to-one, one-to-several and several-to-several, thus making it applicable to every situation. These 3 forgoing tables can then be designed in detail in accordance with logical model.

2.5. Program design

2.5.1. Coding rules

In a bid to enable code design to be highly readable and expandable, we referred to some common international coding rules in the first place to formulate a set of internal standards — C# Coding Rules that code development is based upon. The "C# Coding Rules" covers almost every aspect of coding and makes relevant recommendations as well. There are 4 major modules with 31 minor aspects, and nearly 300 separate items being included. For instance, file name, name space, declaration/members of class and interface, declaration/parameters/function/field/delegation of method, attribute declaration, declaration/initiation/enumeration/definition of field, event, bracket styles, number of spaces, empty line suggestion, note writing, exception handling and control naming and so on.

2.5.2. Application of design patterns

Several usually-adopted design patterns in the software engineering are employed to carry out code layer design so as to increase code

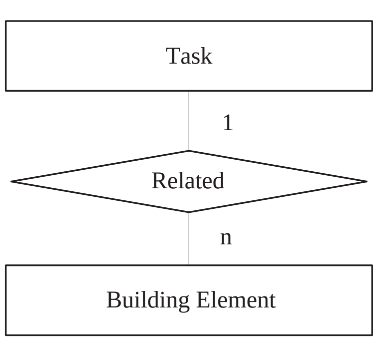

Fig. 4. E-R diagram of partial database.

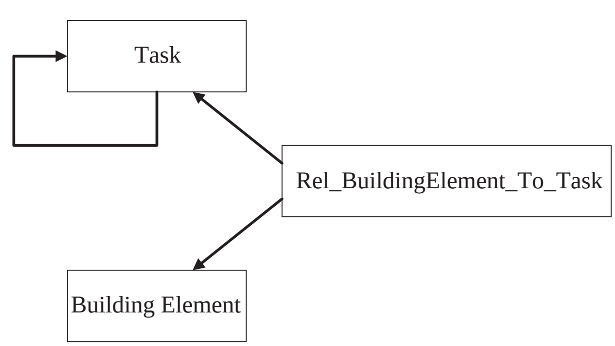

Fig. 5. Conceptual model of partial database.

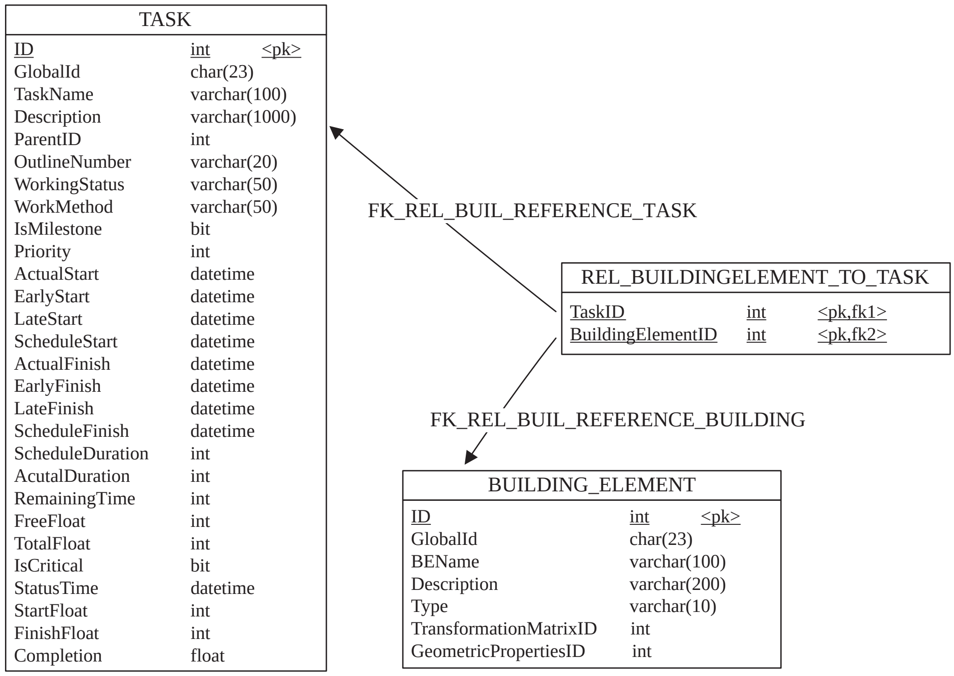

Fig. 6. Logical model of partial database.

expandability. The concept of Pattern was first introduced by the master architect Christopher Alexander in the 1970s and then gradually got popular in the software industry [12]. Pattern refers to a description about a problem rising around us repetitively and the core of its solution. If necessary, the solution can be used over and over again to solve the problem when it recurs rather than figuring out a new solution.

2.5.2.1. Proxy Pattern. The Proxy Pattern renders delegations to control accesses to objects. It can also be comprehended that it forms a layer between departure and destination. Through this layer, programs can make its own choice about how to get corresponding information.

In 4D-GCPSU 2009, data can be stored in either SQL-Server database or local buffer files. In the process of data access, it is required to decide whether to obtain data from remote database or from local files. Therefore, it will be convenient if a data access proxy is applied to realize automatic selections.

Take a “Task” as an example, two user-defined classes like “TaskSqlAccessor” and “TaskLocalAccessor” are created first of all to access remote and local data, respectively. Then a proxy class “TaskAccessorProxy” is written to combine both foregoing classes. By comparing the remote version number with the local version number, the proxy class decides which one of the two mentioned above should be loaded. Furthermore, the three classes share the same interface class “IAccessor” and so they are quite convenient to load their

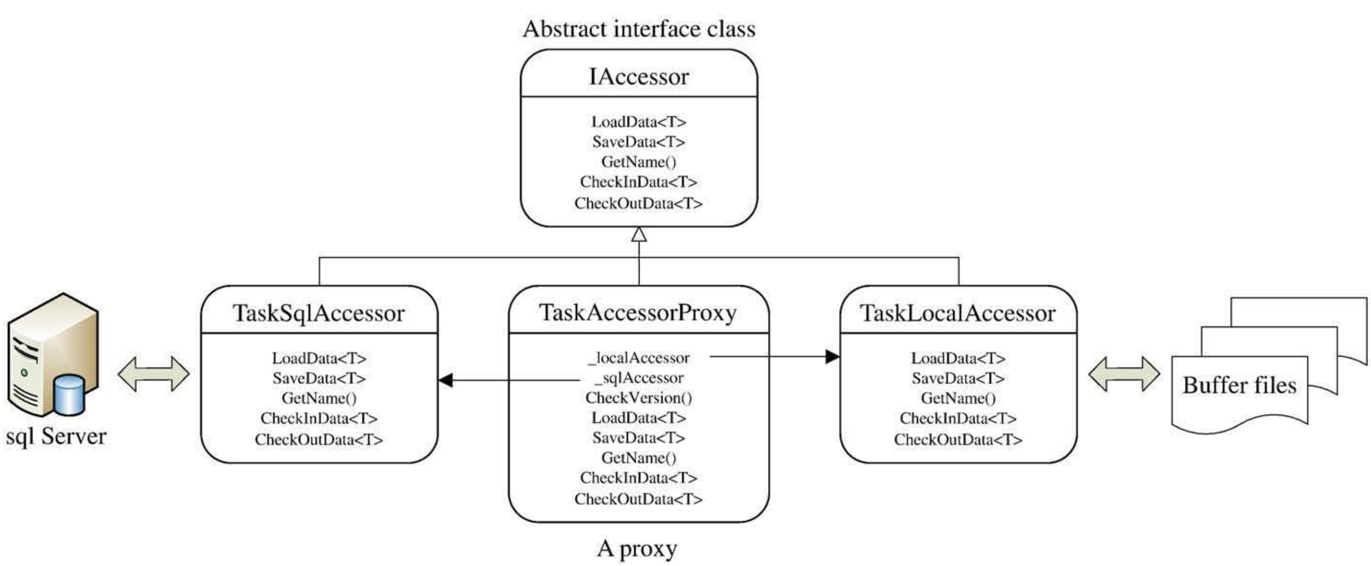

Fig. 7. Operation principles of the Proxy Pattern in 4D-GCPSU 2009.

methods. Fig. 7 shows the relations of these four classes. In this case, only the following two lines of code are needed to load a "Task" table:

GlobalAccessors.Load();//load and initiate all accessors to "GlobalAccessors"
TaskTable = GlobalAccessors.TaskAccessorPorxy.LoadData <TaskRecords>();//load "Task"

If another data access method is required in the future to obtain data from, e.g., the Oracle database, programmers may just simply add a class of **OracleAccessor to each data table and modify relevant proxy slightly.

2.5.2.2. Composite Pattern application. The Composite Pattern organizes objects into a tree-shaped structure that expresses the idea of "whole-part". Through such a hierarchical structure, either simple atomic objects or combined objects can be combined and share the same code-behaviors. Moreover, it reduces computational times by realizing continuous recursion. On the other hand, a serious of objects that have the same graphic properties can be joined to share a single display list (refer to reference [13]) in an OpenGL platform. This significantly enhances the graphic efficiency.

Both WBS data and 3D models in 4D-GCPSU 2009 are managed based on a tree-shaped structure, which makes the Composite Pattern suitable for designing data structure. Take 3D model management as an example, a building can be considered as a combined object, so does a floor or a construction segment. Their atomic objects at the bottom layer are building elements. The whole structure of these objects is revealed in Fig. 8.

In the data structures of GCPSU-2009, "Entity" is an abstract base class, from which two abstract classes of "CustomEntity" and "EntityList" are derived. The former represents an atomic object while the latter a combination of atomic objects or itself. "BuildingEntity" is a specific building element that directly succeeds "CustomEntity", standing for that a building element is an atomic object. Moreover, a building element can be further described as "BeamEntity", "ColumnEntity", "WallEntity" and "SlabEntity" etc. "EntityList<T>" is a generic class and T restricts each atomic object in the list of entities to be either T class or T subclass. "SegmentEntity", describing a construction segment, is a combination of all the building elements that under simultaneous construction. Then a list field of _buildingEntities is used to store all the building elements in the segment. Through this tree-shaped structure in the Composite Pattern, programmers are enabled to set up a hierarchical relation for 3D models and implement standardized and simplified operations upon building elements. Fig. 9 describes the relations of all these classes for details.

3. Site trials

In this section, three real construction projects are used to testified the methodologies and the system.

3.1. Application example of the National Stadium

The National Stadium is the main stadium for the Beijing 2008 Olympic Games [14]. It occupies an area of 258,000 m^2 in Olympic Park of Beijing. The stadium comprises two main parts: 1) thousands of steel elements forms the saddle-shaped roof of the stadium and are united to a shape of bird's nest which also gives the rise of the nickname of the stadium. 2) Inside the stadium, a 7-floor bowl-shaped concrete grandstand, including a giant in-situ concrete framework and precast concrete stands, can accommodate up to 91,000 spectators.

3.1.1. 4D structural information modeling

The CABR (China Academy of Building Research) modeled the concrete framework and realized interaction via Industrial Foundation Classes (IFC) neutral files. The IFC file was composed of columns, beams, slabs and elevator walls, where columns and beams were formed by stretching rectangular cross sections and walls and slabs arbitrary 2D polygon cross sections.

In accordance with the construction schedule submitted by the constructors, a WBS containing 2459 nodes was established. The system, based upon a 4DSMM+ model [15] from our former researches, provided swift and convenient correlating tools to link WBS nodes (containing time information) with 3D models, resources and construction load etc., and materials with building elements as well, thus forming a 4D structural information model.

3.1.2. 4D construction process simulation

During simulation, the system visualization controller searched for each currently active element, color-coded them on an OpenGL graphic platform to indicate different states. Meanwhile, the system could automatically calculate resource demand at any time point or in any time period. Fig. 10 reproduces the construction process of the National Stadium.

3.1.3. Safety analysis of time-dependent structure

In this case, the 3D model from the CABR was selected to execute mechanical analysis. The system automatically created APDL text files according to the time-dependent structure theories and states of all the components at each time point. The files contained as follows: unit type, key points, elements, mesh intensity, load condition and boundary

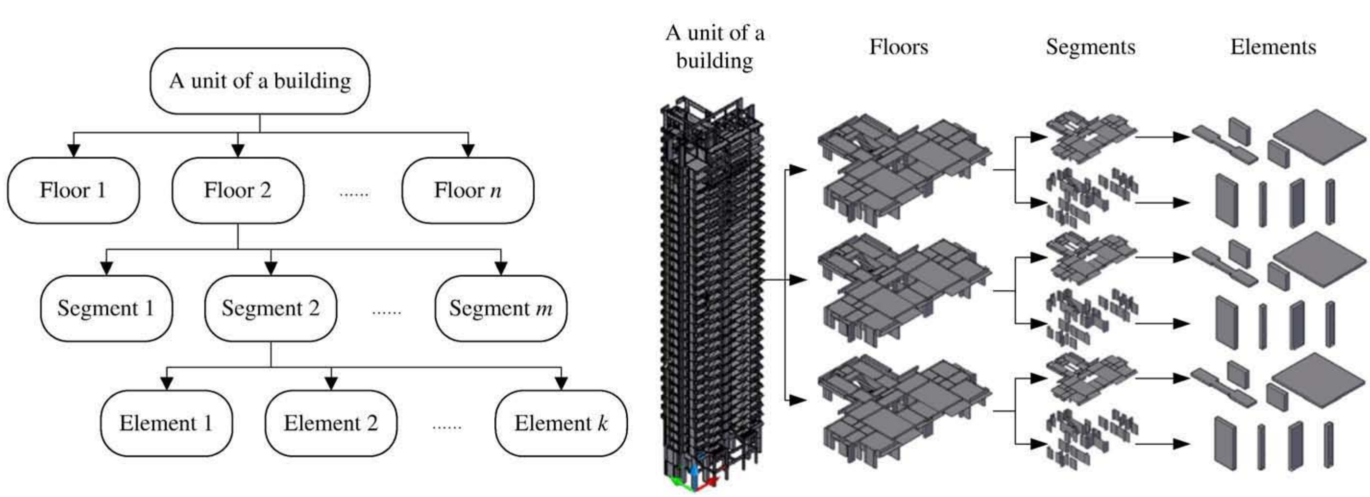

Fig. 8. Building structure hierarchies.

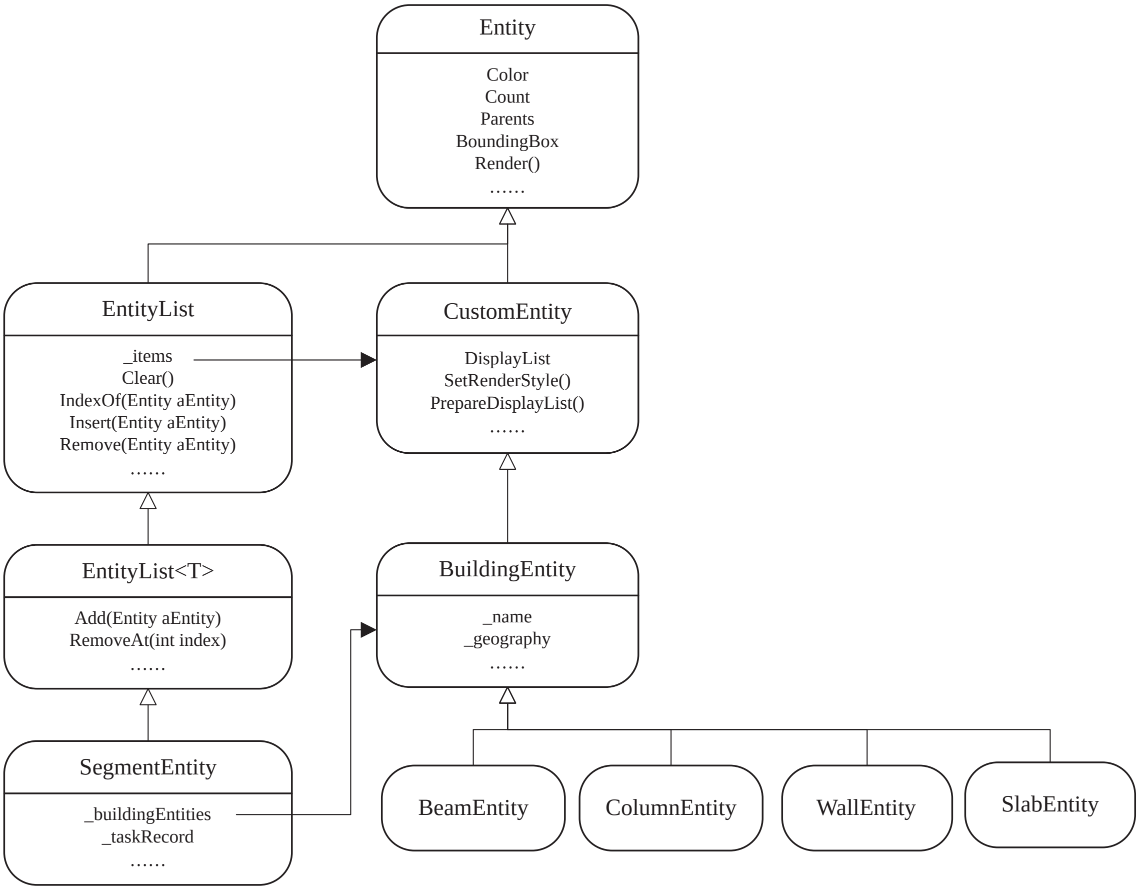

Fig. 9. Data structures of the composite pattern in 4D-GCPSU 2009.

conditions etc. Part of the APDL file, modeling and meshing of a beam, is shown in Fig. 11.

As for the calculation results at some key time points done by ANSYS, please refer to Figs. 12 and 13. According to the calculation results, the maximum slab displacement occurred when the 5th floor was under construction and the value of the displacement was 114 mm. The maximum displacement took place in the floor slab that was far away from elevator walls and contained only a few columns. In order to avoid displacements from increasing in those places, scaffold system should be reinforced during the actual construction

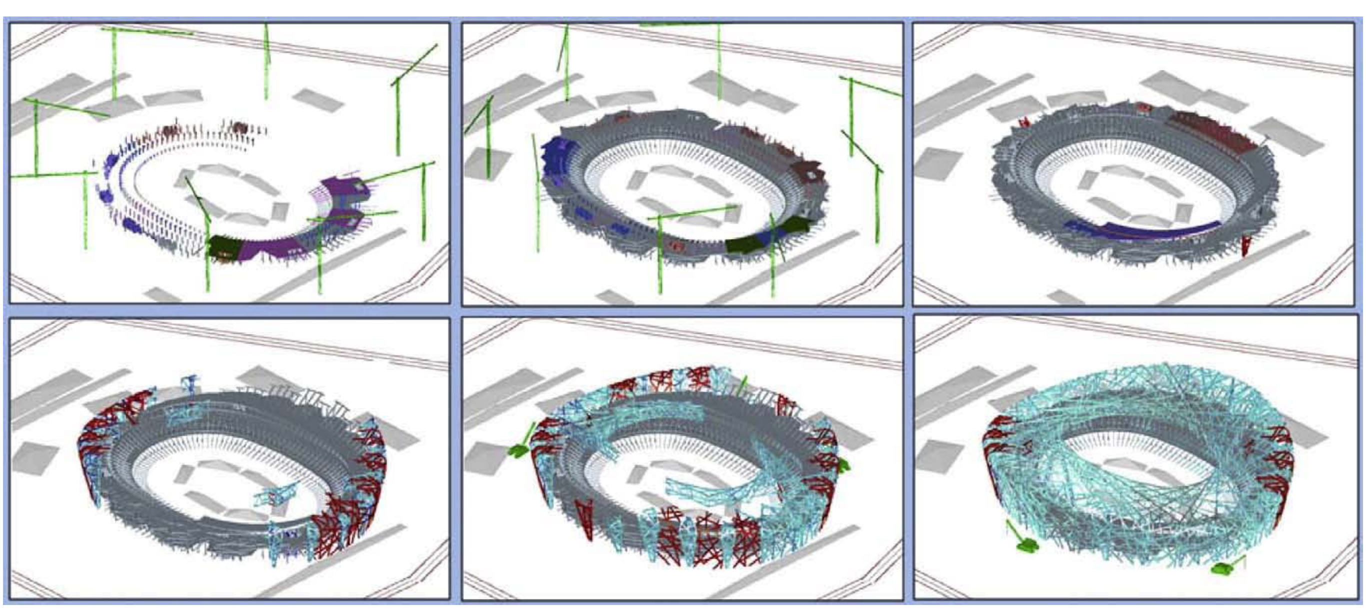

Fig. 10. 4D construction process simulation of the National Stadium.

Modeling a finite -element beam in APDL text file that is generated automatically according to time-dependent structure theories and state of element at a certain time point

```
/prep7                                            //start modeling
Et,1,beam188                                      //define a beam element

K,7,-152.89090625,28.398,7.8                      //two key points for the beam
K,8,-150.573583751217,36.2536368632106,7.8

LSTR,7,8                                          //generate a line from two key points

Sectype,4,beam,RECT                               //define section properties
Secoffset,USER,0,0.35
Secdata,0.5,0.7

Mp,ex,4,34500e6                                   //define material properties
Mp,prxy,4,0.2
Mp,dens,4,2.7e3

K,1320,-152.89090625,28.398,8.15                  //define a key point for section direction

Latt,4,,1,,1320,,4                                //attach element attributes to the beam

Smrtsize,10                                       //mesh attributes and mesh
Lmesh,all
```

Fig. 11. Typical part of APDL file — beam modeling.

process and extra attention exercised, e.g., enhancing monitoring. The maximum stress of the beam also occurred in this stage and the value was 14.6 MPa, which was in the safe range.

The abovementioned results justified that the most unsafe moment was not attached to the structural system under design conditions but the stage before construction was completed. Construction managers should keep that in mind at all times, especially focus attention when the 5th floor was under construction. In addition, the floor slabs far away from the elevator walls undertook considerable deformation, which complied with the results of qualitative adjudication. Extra safety measures, e.g., strengthening formworks in the said position etc., were advised so as to prevent safety issues from happening due to substantial structural deformation or the problem of design requirement incompliance, especially in the latter stages.

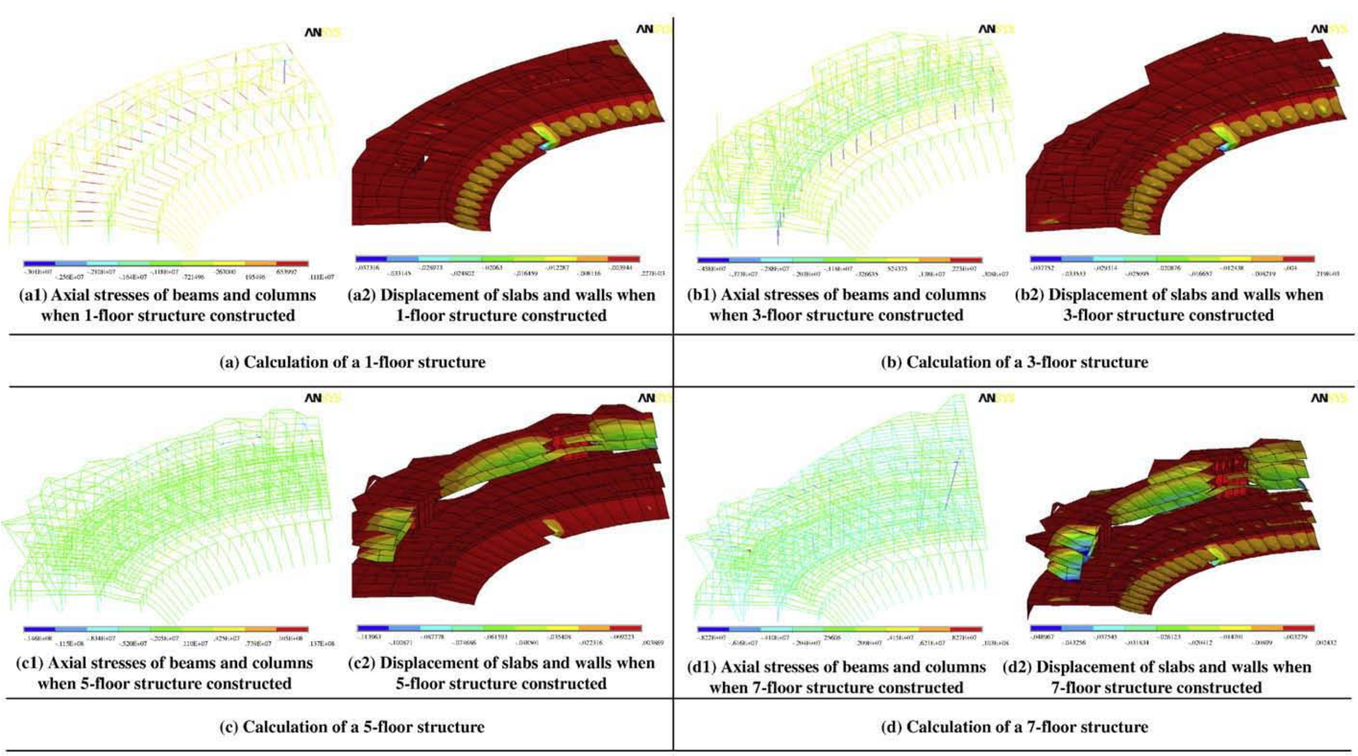

Fig. 12. Structural calculations at typical time points.

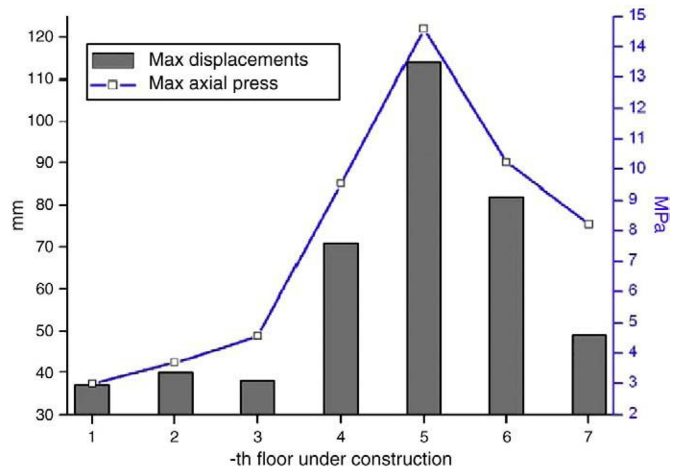

Fig. 13. Time-dependent structural calculation results.

A survey on workloads comparison between traditional method and proposed integration method is illustrated in Table 1. The results showed that the 4D structural information model significantly simplified the process of modeling and analysis, especially in the aspects of information share and dynamic generation, such as 3D modeling for construction management, structural modeling, and re-calculation caused by schedule alternation.

3.2. Application example of the Guangzhou West Tower

With a total investment approximating 1 billion US dollars, the Guangzhou West Tower (hereinafter referred to as "West Tower") locates in the center of Central Business District (CBD) in Guangzhou, the capital of Guangdong province in China. Covering an area of over 31,000 m^2 and an aggregated construction area of 450,000 m^2, this project is comprised of 3 parts like an office building, an accessorial building and a 103-story 440 m high main tower building.

3.2.1. 4D information modeling

The 3D model of the West Tower was made up of as follows: core tube, floor slabs inside the tube, core tube steel structure, outer frame steel structure, outer frame steel beams, outer frame slabs and other components (e.g. parking apron). The entire model of the West Tower (as shown in Fig. 14) and 3D models concerning various site facilities and construction machinery (as shown in Fig. 15) were established in AutoCAD. For the purpose of effectiveness and convenience, the system offered users two site modeling methods: 1) modeled by script files so as to materialize the aims of modeling in batch and swift modification, which was suitable for advanced users; 2) modeled by dialogue box interaction, which was suitable for normal users.

As the 4D information modeling method and process of the West Tower bear much resemblance with that of the National Stadium described above, omission was exercised herein.

Table 1
Workloads comparison of two methods.

Works	Traditional method (person · day)	Integration of sub-BIMs (person · day)
3D architectural modeling	8 (in CATIA)	10 (IFC-based parametric modeling method)
3D modeling for construction management	8 (in AutoCAD)	0 (by IFC files created above)
4D modeling (including schedule arrangement and resources linkage)	3	4 (more detailed information about activities)
Material data preparation	3 (in ANSYS)	1 (in the system)
Structural modeling	9 (in ANSYS)	0.5 (automatically generated)
Re-calculation caused by schedule alternation (per time)	3 (adjusting structural model according to new schedule)	0.5 (automatically generated)

3.2.2. Schedule conflict analysis and management

3.2.2.1. Daily report and actual progress entry. 4D-GCPSU 2009 provided functions of daily report entry and statement printout. Each construction department should write down daily progress situation and construction arrangement for the next day. When receiving the first entry of a daily report for a certain WBS node, the system set date to the actual start-up of the WBS node automatically. Likely, when the administrator assigned a certain daily report entry as the last task, the date was considered as the actual completion date of the WBS node. Schedule managers were allowed to print out data filled out by each department through this self-contained statement printout function and then submitted to superior department or directors for review.

Fig. 16 shows statistics list and output results of daily report. Managers were able to master daily construction details and the entire construction process through daily reports.

3.2.2.2. Milestone setup and milestone conflict analysis. Managers were able to configure certain WBS nodes to milestone nodes in accordance with degrees of importance of WBS tasks, and designated the latest completion date. Later on, milestone tasks could be tabulated through query function. When analyzing milestone conflicts, the system compared already-finished milestone tasks with its planned date and as for yet-started milestone tasks, thus making predictions for the management as reference depending on relationship of milestone tasks and the situation of current progress — lagged or advanced. The whole process of milestone setup and conflict analysis is shown in Fig. 17.

3.2.2.3. Priority configuration. Depending on relationship of tasks, the situation of current progress and the factors whether the task was on the critical path or was a milestone task, 4D-GCPSU 2009 was able to analyze each task automatically in terms of importance levels and then made recommendations concerning priority as shown in Fig. 18. Priority 5 was the highest level, thus managers should ensure resources to satisfy construction requirements. On the contrary, Priority 1 was the lowest level.

3.2.3. Site layout collision detection and conflict management

As the West Tower was located in the hustle-bustle CBD of Guangzhou, it led directly to the characteristics of confined construction site and tightened schedule. Therefore, site management became essential. As the structure became higher and higher, the tower crane would hit the structure with its arm if the climbing speed was not in compliance with that of the building in construction, thus triggering safety accidents. The simplified hierarchy bounding boxes algorithm based on 4D space-time model was conducted to collision detection between tower crane and structure, so as to assist the technical department in terms of tower crane climbing schedule stipulation and also helped them get ready in advance. In this way construction efficiency could be improved and construction safety be guaranteed. As for the tower crane conflict and collision detection as well as adjustment results, please refer to Fig. 19.

3.3. Application example of the Qingdao Bay Bridge

The Qingdao Bay Bridge is located in the Jiaozhou Bay, situated in the middle of China Yellow Sea and the southern part of the Jiaodong

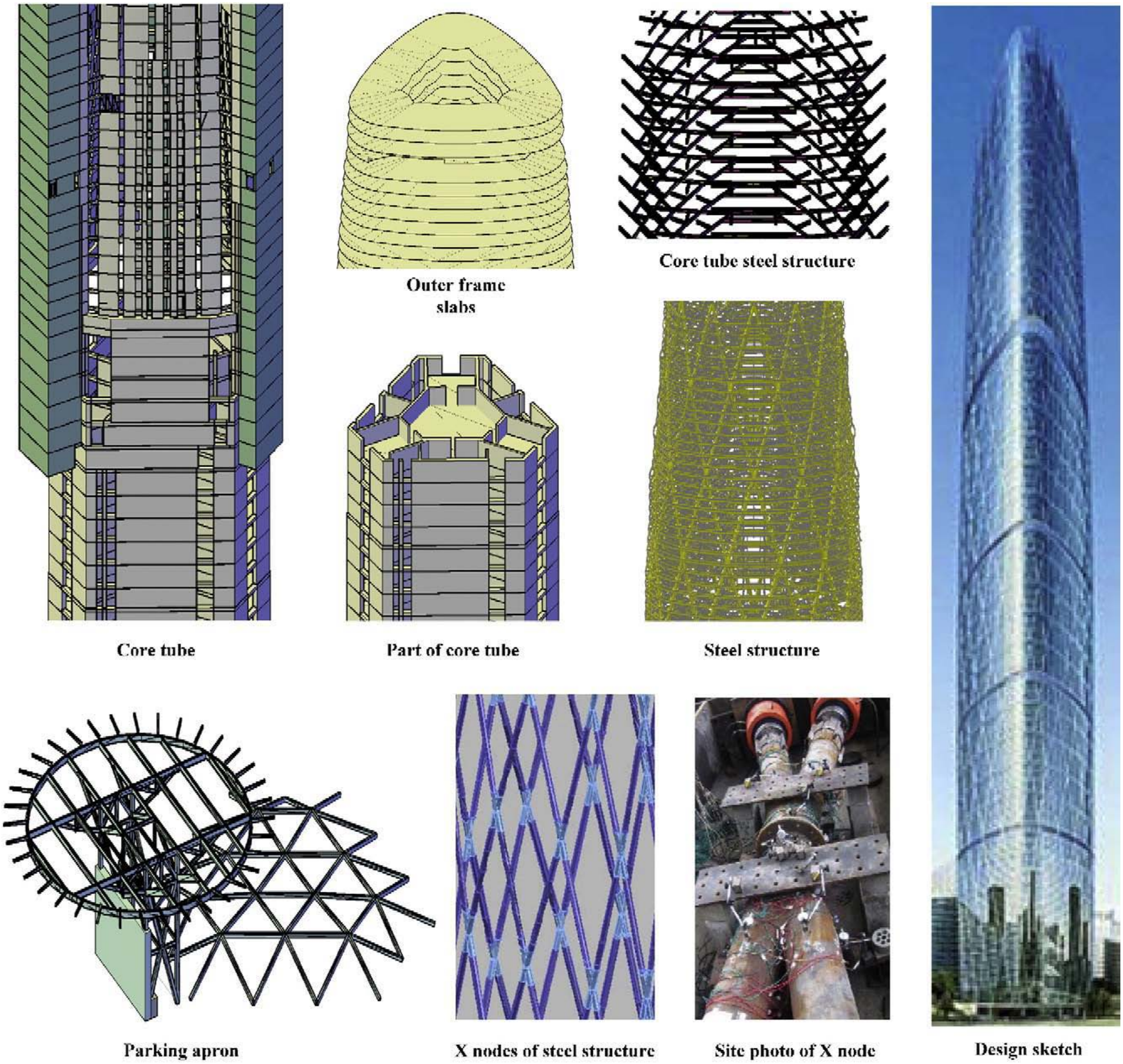

Fig. 14. 3D modeling of the West Tower.

Peninsula. The bridge has a total span of 28.880 km, with a 27.089 km long part above sea. The 35 m wide main bridge contains 6 bidirectional lanes with designed speed of 80 km. With a total investment of around 1.5 billion US dollars, the project has been constructed since December 16th 2006 through 13-section simultaneous startups (11 sections of main bridge and 2 of the rest) and is planned to complete in 2010.

3.3.1. 4D information modeling

The main part of the Qingdao Bay Bridge consists of 11 sections and was built through many structure formats, i.e., cable stayed bridge, suspension bridge, communicable bridge, and continuous girder bridge included. The 3D modeling fell into four parts of main tower, bottom structures, bridge decks and pulling ropes in accordance with different bridge structures. On the AutoCAD platform, a quick modeling module for bridges was developed based on ObjectARX.

In accordance with construction sections, 4D-GCPSU 2009 set up eleven 4D projects. As for each 4D project, the 3D quick modeling module was employed to create 3D elements firstly. Secondly, detailed WBS division and progress schedule were formulated for each section based on the planned schedules put forth by the constructors and self-defined WBS standard template. The WBS standard template was comprised of four layers, namely section layer, position layer (i.e. stake base, bearing platform, pier, and top structure), numbered layer (e.g. piers of 20# bearing platform) and component layer (e.g. left pier of the 20# bearing platform). The next step was to import WBS and schedule into the system through the schedule interface. Finally centered on WBS, dynamic links between 3D models and schedule, resources etc. were set up. Till then, the information model of the Qingdao Bay Bridge had been set up preliminarily. In the actual construction process, the constructor of each section entered states of the actual progress and resources etc. to update the information model.

3.3.2. Graphic schedule comparison

Following input of the actual construction information, different colors were used to express the states of comparison upon planned and actual progress, giving a clear picture so as to facilitate relevant

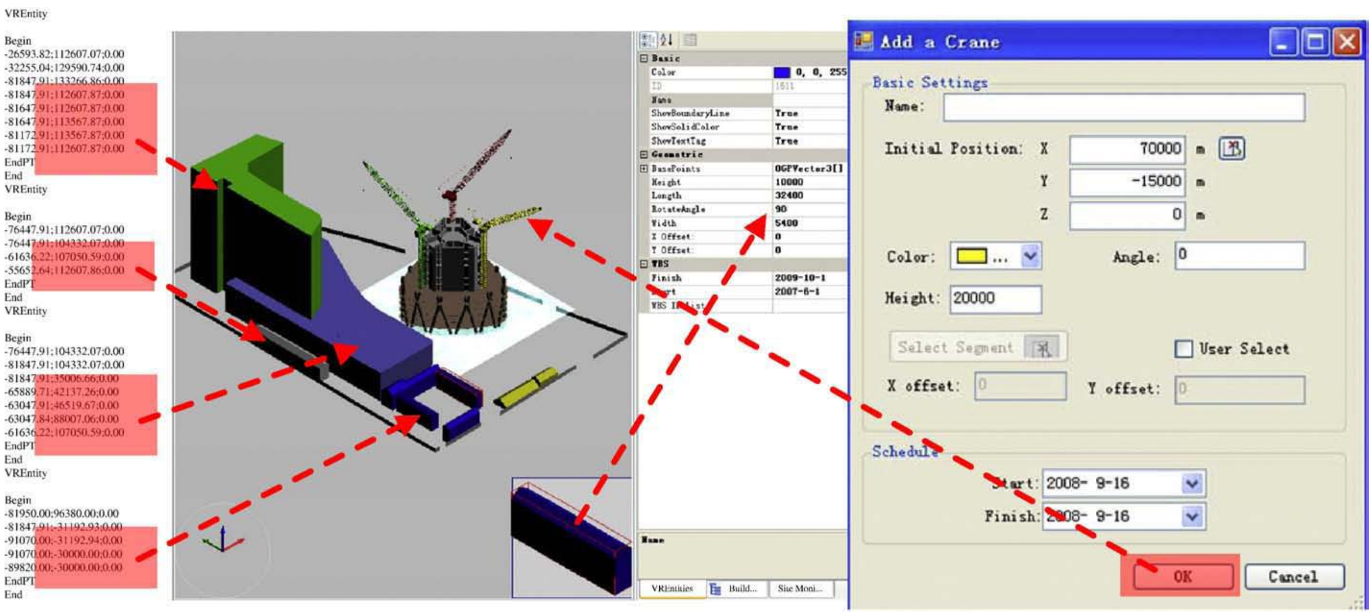

Fig. 15. Site entity information modeling of the West Tower.

management. For the construction states of the bridge deck, pier, bearing platform and stake base, they were "postponed", "punctual", "no actual schedule entry", and "ahead of plan" respectively in Fig. 20.

3.3.3. Resource demand conflict analysis and management

Fig. 21(a) reveals the demand and total amount of special workers in the area of human resources for a certain section from October 1st 2007 to July 20th 2008. The relationship between both items was summarized as follows: the total amount of special workers was able to satisfy the demand of the entire construction process, ensuring construction to proceed normally. However, there was a noticeable waste of human resources from too much blank in the figure. Therefore, human resources cost could be conserved in appropriate areas. For example, the total number of special workers could be cut down to 80 from October 15th 2007 to January 31st 2008, 65 from February 20th 2008 to May 20th 2008 and 44 from June 20th 2008 to July 20th 2008 as shown in Fig. 21(b). The optimized plan successfully saved 15% of the human resources cost.

3.3.4. Cost conflict analysis and management

As for the budget cost curve for the bridge section mentioned above over a certain period of time, please refer to Fig. 22. It was revealed that the actual expenditure was, as a whole, in compliance with budget cost but in the later stage, deviation was obvious due to

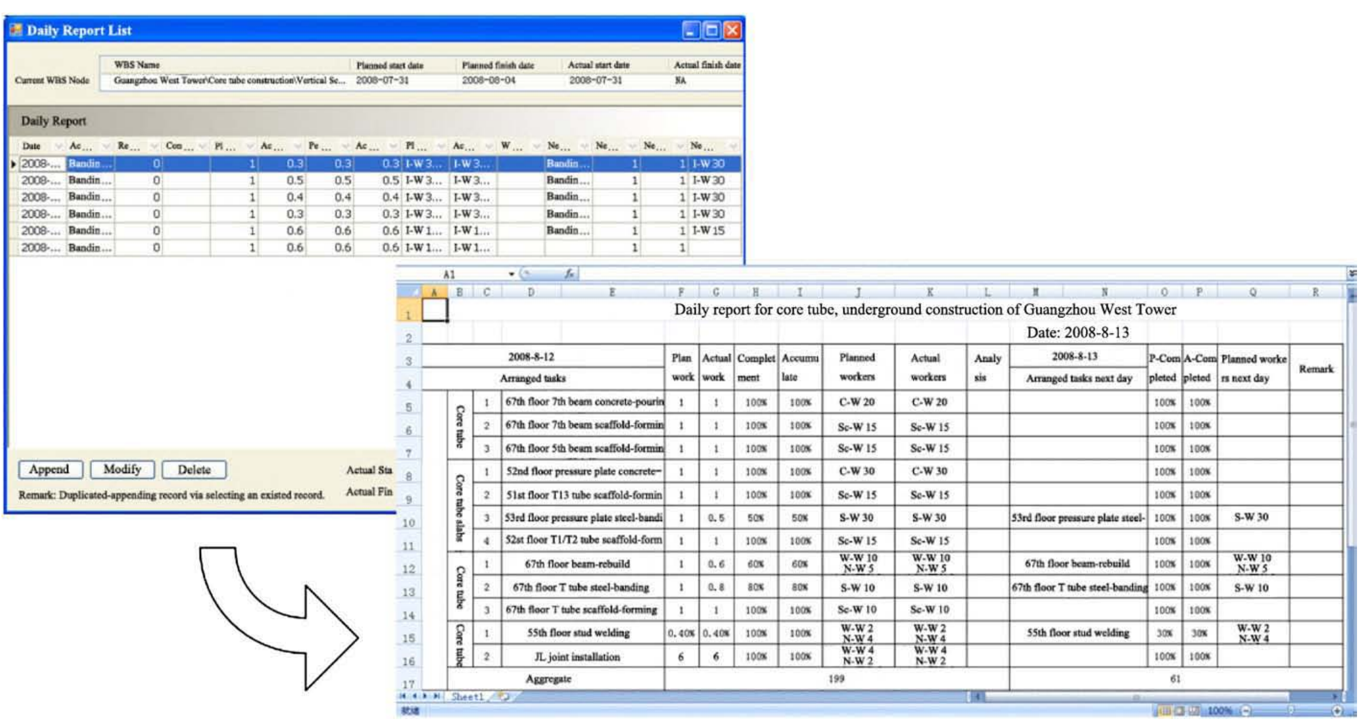

Fig. 16. Daily report and statement output.

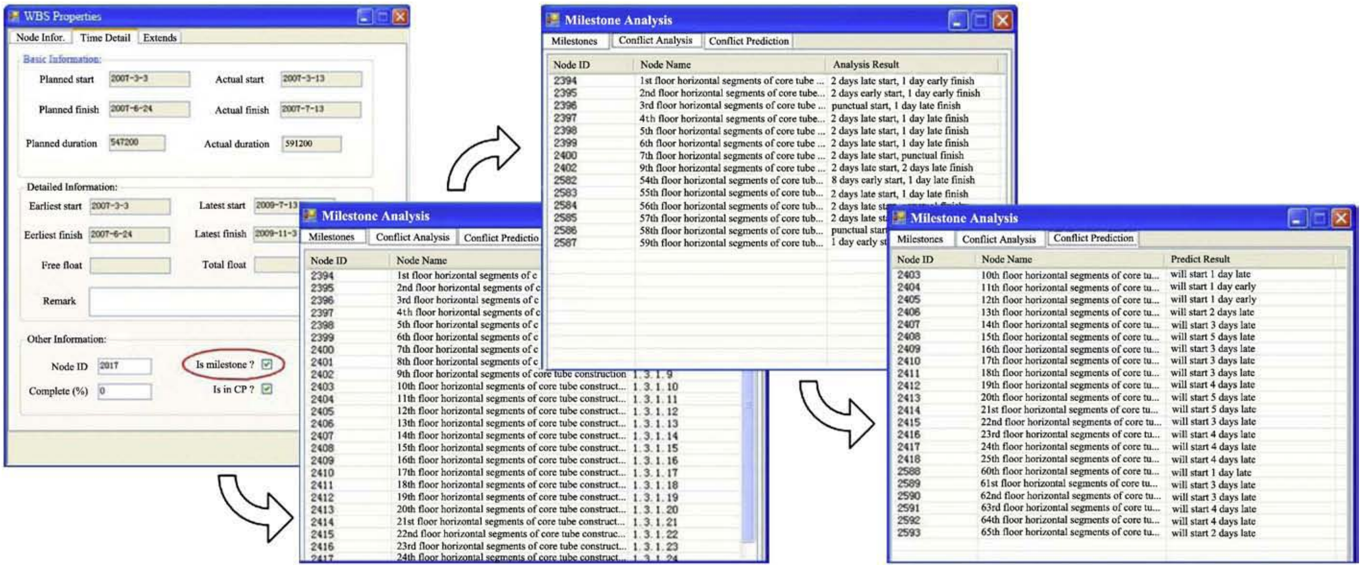

Fig. 17. Milestone setup and conflict analysis.

various reasons and the final actual expenditure was 6 million RMB (about 0.88 million US dollars) higher than the budget cost. In addition, the actual cost approached or even broke through the operational fund curve, indicating that capital tightened up during construction, even the advance situation occurred.

4. Utilization experience

The 4D technology itself is able to benefit construction management, including good communication among site personnel, swift identification of potential sequence errors and clashes, flexible reflection of design and work sequences changes, etc. Based upon such technology, this research focused on how to manage construction conflict and structural safety problems in a detailed and profound means, and developed an integrated software platform that was relatively easy to operate. Managers on site applauded information integration advantages realized by BIM and were excited toward historical data accumulation and further application.

Irreversibly, some troubles come out when using this new tool. First of all, the information required to be prepared in advance exists in large quantities and it also involves vast fields and organizations. However, this difficulty in information entry can still be solved. For instance, as BIM technology is developing, more and more architecture design systems are able to realize BIM modeling and offer data share methods such as through IFC neutral file. As long as users consult well with design institute in respect of design model, the procedure of 3D modeling can be simplified. Currently, almost every project has a rough WBS division and progress schedule in the submission of tender. Before construction, it is usually required to subdivide WBS further and therefore this integrated solution is

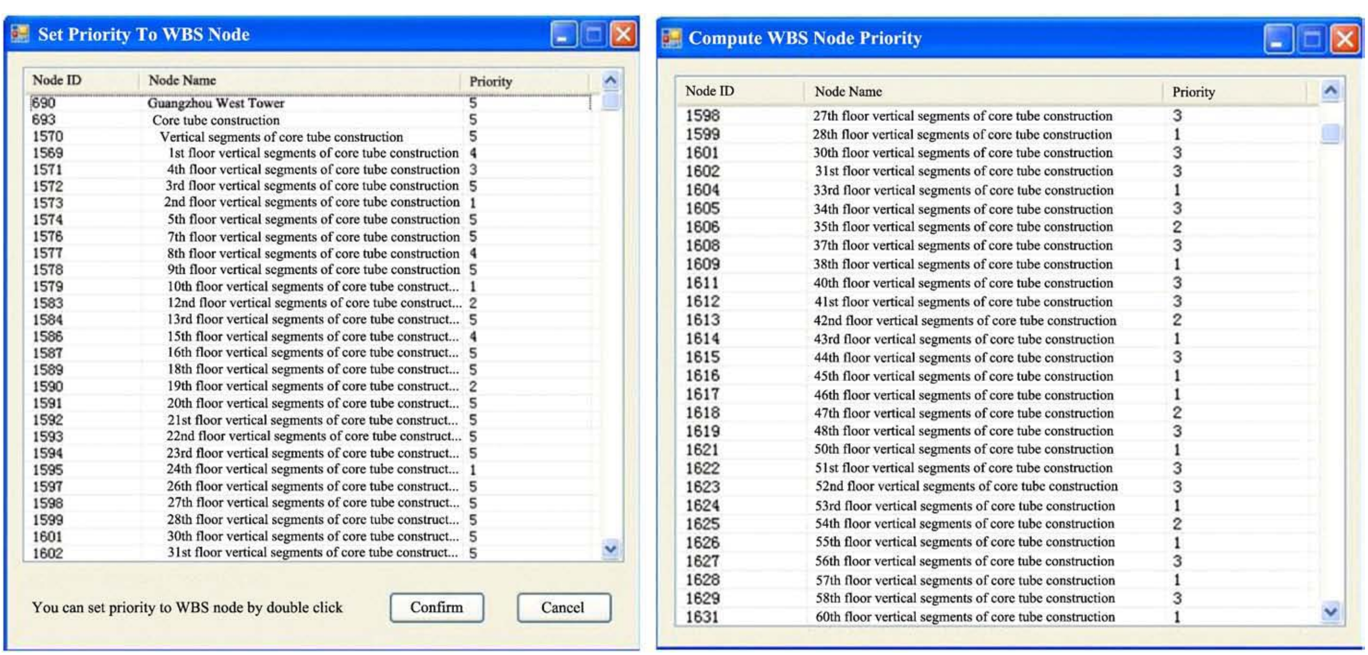

Fig. 18. Priority analyses and suggestion.

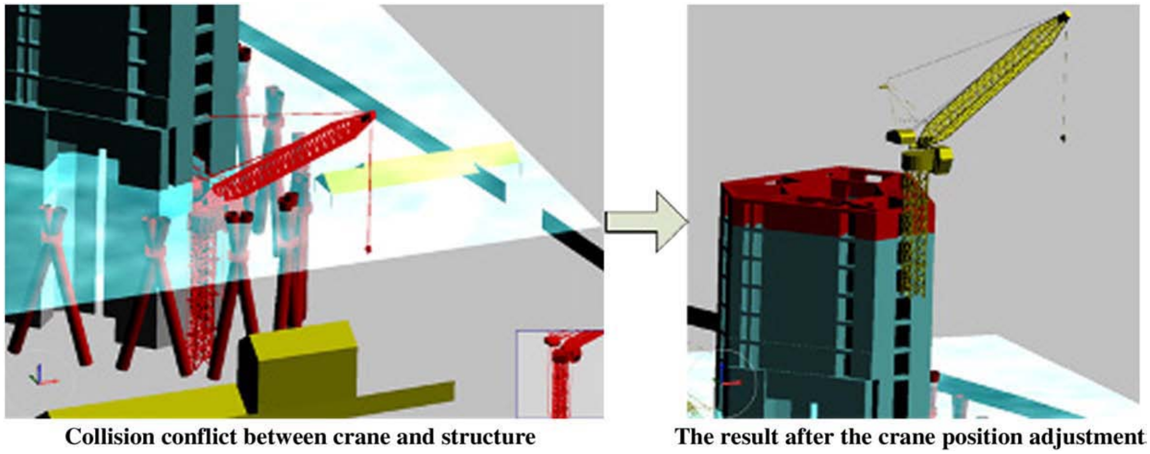

Fig. 19. Collision detection between tower crane and structure.

considered as a fuller extent without costing constructors any extra expenditure. Meanwhile, supplement functions into the system such as pre-entry in budget quota from various sources, swift customization of resource template, and immediate correlation between material and element etc., to assist entry of basic information so as to improve data preparation efficiency of the system at initial stage.

The next is about data tracking and maintenance. As project proceeds in a gradual way, a massive amount of construction data is required to be followed up and maintained, including daily report and actual progress related information, etc. It directly adds burdens to constructor but if information entry is well combined with daily reports, user's passion about work can be completely lifted up. Therefore, it is required to tabulate information entered everyday in the way as claimed by constructor automatically so as to ease workload concerning data maintenance. On the other hand, constructor is supposed to understand how historical data are important from the perspective of conflict analysis and pre-warning and becomes initiative since then.

In the end, users must have rather professional backgrounds. To create 3D models requires formidable modeling abilities, to engage in time-dependent structural safety analysis structure design background and to take part in construction conflict analysis and management many years of working experience on site, which lays unbreakable barriers for ordinary users. This problem can be smoothened through the following two ways: one is to cultivate a comprehensive talent team that is capable of applying the system more profoundly. It is also helpful to drive the human resources of the enterprise to develop. The other is to perfect the collaboration capability of the system, assign departments with different authorizations and then realize system co-share via network. Through this way, each department only has to concentrate on its own work.

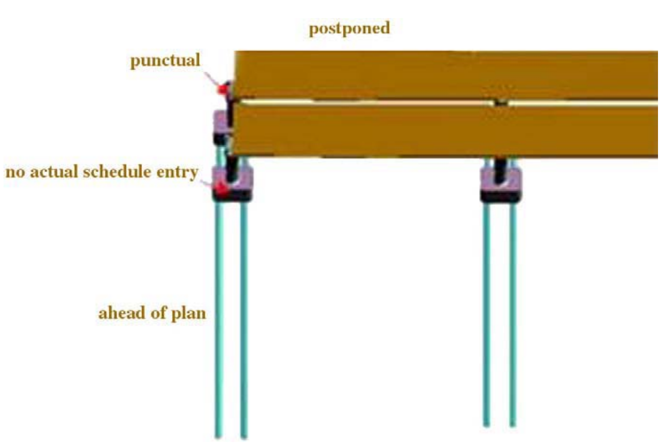

Fig. 20. Graphic schedule comparison and analysis.

5. Future directions and potentials of the prototype system

This research is the initial exploration and attempt of introducing 4D technology into the time-dependent structural safety analysis. In the near future, we will look further into the latest theories of time-dependent structural analysis with a view to obtain more precise analysis results. It includes three aspects. 1) Some adjustments like selecting different element types, exercising certain treatment upon nodes and implementing more harsh control over the mechanical behaviors of reinforced concrete materials etc., can be done to control structural analysis model. 2) Keep a record of stress and strain history concerning time-dependent structure and also take the factor of historical effect into the entire process analysis. 3) Apply this technique to more typical projects and obtain the actual test results so as to adjust methodologies and models.

The system is able to expand in the aspect of functionality. Speaking of construction safety management, other issues not covered by the system include safety of operating at heights, machinery operation safety and personnel safety management and so on. In future researches and applications, it is possible to incorporate the abovementioned items and informationization with BIM so as to put forth new safety management concepts and implement new safety management techniques as well.

Currently, structural calculation of the system is carried out in ANSYS and some difficulties occur in operation under this circumstance. This can be perfected through developing an interface to other universal finite element calculation software or working out a finite element analysis sub-module of proprietary intelligence right etc. in the future to substantially realize combination of 4D construction management and finite element analysis upon structures.

At last, the Back Propagation (BP) neural network arithmetic is the only prediction model that the system supports. Execution efficiency, application scope and accuracy differ from arithmetic to another. Accordingly, it is supposed to add more prediction models such as decision-making tree model, fuzzy comprehensive reviewing model etc., and compare the suitability of various arithmetics so as to improve the system's prediction capability and effects.

6. Conclusions

Based upon the methodologies and principles set forth in the reference [10], the paper begins with system design of 4D-GCPSU 2009, and then justifies the benefits of the system through three examples.

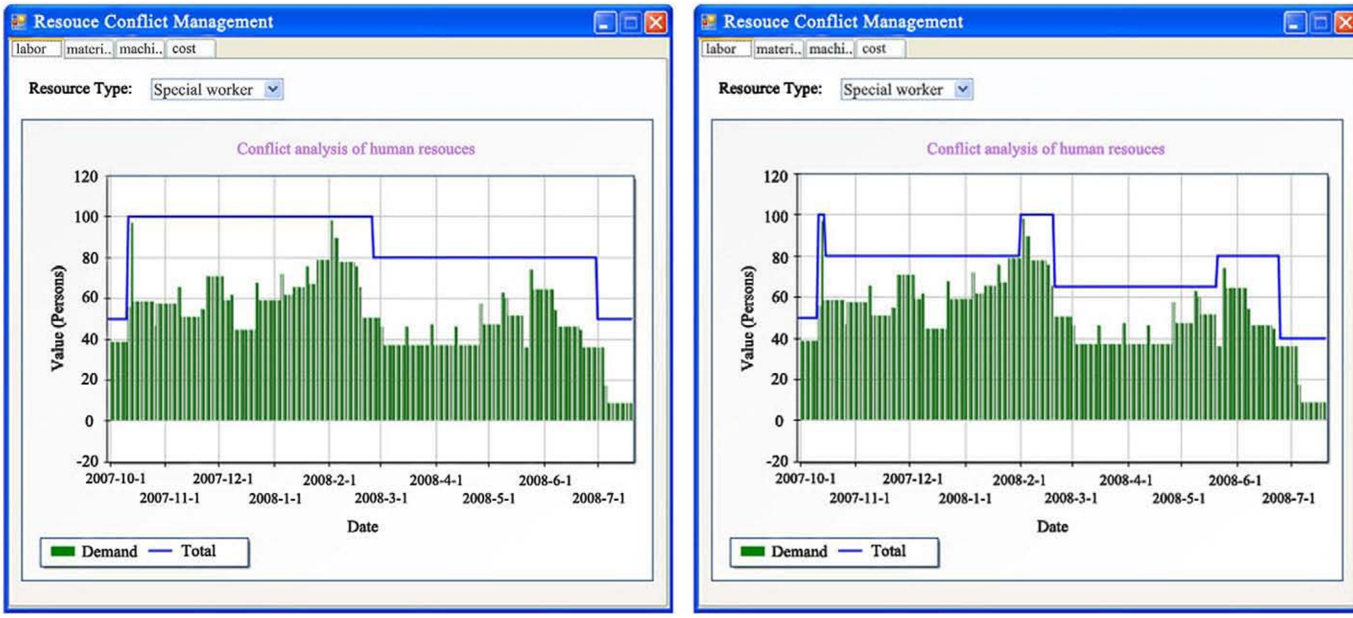

Fig. 21. Labor resources conflict analysis and management. (a) Planned state of resource utilization. (b) Optimized state of resource utilization.

Specifically, in the case of the National Stadium, implementing time-dependent structural analysis upon the concrete frame structure offers essential references for construction proposal review and modification. It also guarantees mechanic performances of stresses and displacements etc. involving safety requirements of both design and construction. In the West Tower project, schedule conflict analysis and management are carried out to provide references for real-time adjustment of schedule planning and resources allocation, thus improving construction efficiency and minimizing construction conflicts. Moreover, as it is located in a crowded commercial district and the construction site is relatively confined, collision detections are implemented amongst site facilities and structural elements to strengthen safety in the construction site. In the sea-crossing bridge case, schedule conflict analysis and resource/cost conflict analysis are primarily deployed. The former significantly facilitates owner's supervision, review and management of construction progress at each section and meanwhile, provides references through chart-diagram expressed analysis results for constructors in terms of schedule check and adjustment. The latter assists owners and contractors to put investment cost under control.

Fig. 22. Cost and expenditure conflict analysis.

Acknowledgement

This work was supported by the National Technological Support Program for the 11th Five-Year Plan of China (2007BAF23B02).

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