A MULTIDIMENSIONAL INFORMATION MODEL FOR MANAGING CONSTRUCTION INFORMATION

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Abstract. With the increasing scale of construction projects, coupled with their complexity, information management in the construction process becomes more complex and trivial. Moreover, the communication among project participants is hindered by the large amount and scattered structure of the information involved in the construction process. Most present studies on the information management of construction focus on the special needs of construction sectors rather than a total information integration of general aspects. This paper presents a multidimensional information model that combines Workflow, Work Breakdown Structures (WBS) and Time factor to manage information based on process control. Unlike previous researches, the present work puts emphasis on process control to enhance the communication process. The proposed information model uses the WBS and Time factor to manage information in the spatial and time dimension and control the process information of each work package during project execution through the workflow technology. In order to test the proposed information model, a web-based project management system (WPMS) was developed using the three layer architecture. The system structure realizes the invisible logic of the information model through the business logic layer and the data access layer. The system has been applied to a construction project of an underground cavern group in a hydropower project in the southwest of China. The application has shown that it achieves managing information based on process control and provides structured information.

1. Introduction. As construction projects become larger and more complicated, the information structure and communication problems involved in the construction process become more intricate. The thorny issue is the information management and communication process which constitutes a determinant factor for the efficiency of construction management. Many studies indicate that the construction industry is fragmented due to many stakeholders and phases involved in a construction project and this fragmentation is often seen as one of the major contributors to low productivity [11] [14]. Moreover, the fragmentation has led to problems with communication and information management. Those problems are due to the diversity of forms of construction information which include detailed drawings and

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photos, cost analysis sheets, risk analysis charts, contract documents, planning schedules, etc., and the great amount of information generated and exchanged during the project lifetime. Furthermore, the wide variation of specialties, expertise, and working environment among the project participants impedes the communication in the construction process. The application of information and communication technology (ICT) has significantly improved the information management and communication problems in the construction industry. Various research studies have developed electronic document management (EDM) system and Web-based Project Management System (WPMS) for managing information that is produced throughout the different stages of the life cycle of a project. Many commercial software systems also provide multiple services for the information management and communication in the project. However, most researches focused on the specific needs of the project rather than the total information integration of general aspects, which means the information management and communication of the construction process is incomplete. This paper focused on the information management and communication in the construction process. A multidimensional information model is established by combing the WBS, Workflow and Time factor together to manage construction information based on process control. A web-based project management system (WPMS) is developed and applied in an underground cavern group project in the southwest of China.

A number of research efforts have been conducted on the usage of information and communication technology (ICT) for improving the efficiency and control of the information involved in the construction process. Some research studies have discussed conceptual frameworks of information management systems, while other studies have developed electronic document management (EDM) system or Web-based project management system (WPMS) to enhance construction project documentation and control. As pointed out by Pollaphat [19], there are three options in regard to WPMS implementation: customized WPMS in-house, commercial web-enabled packaged software, WPMS from an Application Service Provider (ASP). However, these studies direct mostly to documentation management and rarely to information modeling.

The vast majority of information generated and exchanged during the construction process is stored in documents [15] [30], which highlight the importance of document management. Some research studies have developed EDM for managing the documents that are produced throughout the life cycle of a construction project [3] [12]. Other studies have proposed framework and solutions to the problems of integrity and consistency of the information conveyed using document-based medium [25] [28]. Moreover, Qady and Kandil [24] presented the results of a survey of practitioners on various aspects of document management. The findings serve researchers and developers by identifying deficiencies in current practices and highlighting important issues from the perspective of industry practitioners. Those researches follow a document-based philosophy, which manages documents themselves rather than the information contained in them. The advantage of the document-based information management method is the EDM systems are easily deployed in the construction process. However, the information structure is still scattered and information contained in the documents cannot be searched and analyzed effectively. Moreover, data redundancy of the construction information cannot be guaranteed.

The concept of web and its associated technologies has been widely used to manage construction projects by researchers in recent years. Many researchers have
developed web-based systems for various purposes, such as cost control [1], manage
design information [18], communication [9] [16], project performance monitoring [7],
construction information [6] and optimize project management processes in dredg-
ing operations [26]. The aforementioned researches have mostly met the specific
needs such as the cost control, monitoring and communication in the construction
sector, design information, et al. Those researches have provided structured and
reliable information service for the system users. Therefore, a system covered com-
munication, cost control, quality control, schedule control and security control, et
al is need in the construction project.

Meanwhile, a number of commercial software systems are developed by Appli-
cation Service Providers (ASP) for the Architectural, Engineering, and Construc-
tion (AEC) industry. Some of the famous applications are: Microsoft Project by
Microsoft, Primavera by Oracle, ProjectTalk by Meridian, Aderant, Teamflow by
CFM, Buzzsaw and Constructionware by AutoDesk, ProjectWise by Bentley, Docu-
mentum Centerstage by EMC, e-Builder Enterprise by e-Builder and Project Center
by Bricsnet. Those products have applied successfully in various projects. The most
significant performance measures for commercial WPMS were: (1) helping search
for files and documents; (2) improving quality of documents; (3) enhancing compet-
itive advantage; (4) facilitating document transfer and handling; (5) reducing the
number of postage and shipping; and (6) reducing barriers in communications [20].
Those systems are practical for small or mid-sized construction projects and they
require minimal technical, financial, and human resources [21]. However, they can-
not meet the needs of excessive information management of large scale projects such
as hydropower projects, which involve a great amount of information in the con-
struction process. Table 1 exhibits the significant features of those applications
mentioned above. Although some of the applications have covered those significant
features, such as Aderant and e-Builder, they are not Web-based integrated systems
which will exacerbate the difficulties in communication.

This paper presents a multidimensional information model to manage construc-
tion information based on process control. Modeling construction information is
achieved by using WBS as the index of work package and using Time and Workflow

### Table 1. Features of commercial software

| Products                  | Document management | Visualized project workflow | Advanced search and calendar | Data statistic | Web-based integrated system |
|---------------------------|---------------------|----------------------------|-------------------------------|---------------|------------------------------|
| Microsoft Project         |                     | Y                          | Y                             |               | Y                            |
| Primavera                 | Y                   | Y                          | Y                             | Y             | Y                            |
| ProjectTalk               | Y                   | Y                          | Y                             |               | Y                            |
| Aderant                   | Y                   | Y                          | Y                             |               | Y                            |
| Teamflow                  |                     |                            | Y                             |               | Y                            |
| Buzzsaw                   | Y                   | Y                          | Y                             |               | Y                            |
| Constructware             |                     |                            | Y                             |               | Y                            |
| ProjectWise               | Y                   |                            | Y                             |               | Y                            |
| Documentum Centerstage    |                     |                            | Y                             |               | Y                            |
| e-Builder Enterprise      | Y                   | Y                          | Y                             |               | Y                            |
| Project Center            | Y                   | Y                          | Y                             |               | Y                            |
to manipulate information as the project forwards. The WBS and Time factor are used to manage information in spatial and time dimensions and the workflow is used to control the process information of each work package. The main contributions of the proposed information model are: (1) provide efficient communication and information transmission among project participants through the workflow technology; (2) provide agile data retrieval and statistical analysis through the data index in the information model such as a specific WBS code, time and workflow. A web-based project management system (WPMS) is developed with a three layer architecture which separates the intricate business logic from the functions shown in the user interface. The case study was conducted at the construction project of an underground cavern group in a hydropower project in the southwest of China to illustrate the application of the information model and provide the implementation of the WPMS.

2. The proposed information model and key technology. In order to increase the efficiency and effectiveness of construction information management, a multidimensional information model has been established by combining the Workflow, WBS and Time together as shown in Fig.1. In order to increase the efficiency and effectiveness of construction information management, the information model of construction project should be structured and avoid redundancy. The following principals are needed when establish the information model. (1) The dimensions of the model should be independent. The dimensions are the abstract criteria of classification for construction information. Therefore, the dimensions must be independent with each other, which means that no influences and interactions between the dimensions. Otherwise, the information structure of construction project will in a state of chaos. (2) The hierarchies of each dimension can be classified easily and clearly. The hierarchy is the inner characteristic of each dimension and classified the information from a concrete level. A clear and explicit classification of hierarchy can guarantee the uniqueness of information in the database. (3) The combination of all dimensions can cover the vast majority of information in the construction project. The dimension and hierarchy in it have classified the information to establish the structured information model and reduce the redundancy. However, the completeness must be considered when combining all the dimensions and hierarchies together. This rule can be used to check each dimension and its hierarchies. The purposes of the model are to manage the construction information based on process control, provide the end user with the agile information interfaces and reduce the data redundancy of the database. Features of the model include agile information interface, more controllable and clear working process and professional statistical results.

The mathematical model of the multidimensional information model is:

\[
\begin{align*}
D &= F \otimes W \otimes T \\
F &= \bigcup_{i=1}^{l} f_i \\
f_i &= [p_{ri}, d_i, e_i, c_i, m_i, pm_i] \quad i = 1, 2, ..., n \\
W &= \bigcup_{j=1, k=1}^{m, n} w_{jk} \\
d_p &= \text{search}(F, W, T) = \{f_p, w_p, t_p\} \\
F &= \text{sum}(W, T) = \sum_{j=1, k=1}^{m, n} (w_{jk} \otimes t)
\end{align*}
\]
where $D$ is the mathematical set of the information in the construction process which is integrated by $F$, $W$ and $T$; $F$ is the mathematical set of Workflow dimension and the each workflow $f_i$ consists of $d_i$(Doing), $e_i$(Evaluation), $c_i$(Check), $m_i$(Measure), $pm_i$(Payment); $W$ is the mathematical set of WBS dimension and the $w_{jk}$ is the basic unit of WBS; $T$ is the mathematical set of Time dimension. The multidimensional information model helps the information management by efficient information retrieval and statistic through the search and sum function. The information of a specific work package $d_p$ is obtained by search function through the positioning variables including $f_p$, $w_p$ and $t_p$. The statistic result of a specific dimension such as Workflow dimension is obtained by accumulation of WBS and Time dimension.

2.1. **The structure of the multidimensional information model.** The structure of the multidimensional information model is shown in the form of data cube [13]. The rounded point in Fig.1 represents the base cuboid of the data cube. The three dimensions represent the three primary aspects in the construction information. (1) The information model uses the WBS code as the index of the information in the information framework to make the information more structured and organized. (2) The traditional information management of construction project is extensive and rough. As a result, the information of the construction process is in a state of chaos. The problem is further compounded with the notions of fast-track and concurrent engineering, in which successive activities are reorganized to perform simultaneously [17]. The information model uses the workflow to control the working process and the flexible workflow engine allows users to custom the workflow. (3) Time is a key factor in the construction, and it is involved with the schedule, working efficiency etc.

The multidimensional information model with the WBS, Workflow and Time contains a great amount of construction information. With the proper operations, the information model shows the construction information in multiple aspects and hierarchies. The combine operation joins two of the dimensions together and gets a dice of the data cube. (1) Combining the WBS with Time factor, it is the Gantt chart for the construction which provides the schedule of the project and it allows the information model to track the schedule. This operation fulfills the consultants schedule management demand. (2) Combining the WBS with the Workflow, it depicts the construction process information about each item and hierarchy. It is important to check those items by different stages of workflow and different hierarchies. At last, the workflow is naturally combined with the Time factor, as the workflow is promoted by time. (3) The combination of workflow and Time can provide the executive efficiency of the work process and thus to find ways to improve the work efficiency.

However, the widely searched information is the real time construction items and the historical information is used for Data Mining and decision making. The base cuboid contains the information of minimal construction items and the following search operations can get the construction information of a specified cuboid.

(1) Use the WBS code for positioning the item.
(2) Input the time (the current time or a special time) to get further screening results.
(3) Check the stages of item in the workflow.
(4) If the item has not been started yet, check if it is on the critical path and adjust the Gantt chart if necessary.
(5) If the item is under the construction, check the stage in the workflow and check whether the process is working well.

(6) If the item has already finished, check the qualified rate or the excellent rate and find the reason according to the process data if the performance is not good.

![Figure 1. the structure of the multidimensional information model](image)

As there are three aspects, the information model provides three entrances. (1) WBS entrance. Using the WBS code, the framework can provide the items with full information including the process data and the position in the whole schema; (2) Time entrance. Inputting a date or time quantum, the information model provides all the process data happened in this time, which makes the information trace more convenience; (3) Workflow entrance. It allows users to check the information of a special stage. The search results will show the working efficiency in this project and check if the working efficiency is under a normal level.

2.2. **Workflow technology.** The workflow of the project can represent the whole information flow of the project, as the entire information collection is the extension of the workflow in the time dimension and space dimension. Therefore, the information model provides a normalized workflow as the templates of common business processes. The template can be modified individually or collectively into a new workflow to meet the business specification.

The right part of Fig.2 shows the workflow template and the current constructing item is shown in the left part. The workflow template covers the pre-construction, constructing and post-construction stages in the traditional management. Most of the construction businesses are included in this workflow template. For example, in the constructing stage, businesses include quality control point examination,
security check, material check, etc. The workflow template can also be changed according to the users demand. During the pre-construction stage, there are lots of approving tasks and the approving flow path varies in different projects. The workflow engine is flexible and agile and allows the user to modify the workflow and thus reduce the rigidity of the system.

The workflow template can restrict the businesses to operate in a rational order and the flexibility can ensure the workflow template can be commonly used in various projects. Workflow modeling design is the task of defining structured workflow schedules from informal business requirements that satisfy a variety of business logic, organization and resource constraints [17]. Workflow modeling involves the definition and selection of appropriate tasks, and sequencing the tasks to satisfy data and logical dependencies, allocation of resources consumed by the tasks [27].

3. **System architecture and implementation.** As the system is focused on the information integration and sharing, it is necessary to build a web-based information management system based on Browser/Server (B/S) mode. The system uses the three-layer (user interface layer, business logic layer, data access layer) architecture as shown in Fig.3. Within the three layer architecture, each layer of the system is isolated, which provides benefits such as maximum control, scalability, and flexibility [5] [22] [23]. The system has followed the following principals. (1) The architecture of the system must be high cohesion, low coupling, scalable and easily to development. A flexible architecture will ensure the system can adapted to various demands. (2) The functions of the system should follow the operating mode of the users. An important thing in the deployment of the system is the system should not bring about extra works to the users. As a result, the main functions of the system should be classified according to the specialties of the users. (3) The presentation of the information should in the form of original data and statistic results simultaneously. The statistic results will show the overall trends of the project while the original data will show the details of the project. The combination of original data and statistic results will help the users to analysis the project in macroscopic and microcosmic aspects.

At the lowest level of the system architecture, the data access layer (DAL) divides the construction information into three categories: Standard Data, WBS Data and
Construction Process Data. Standard Data and WBS Data serve the Construction Process Data and the former is used as a criterion to judge whether the Construction Process Data is qualified, while the latter provides indexing and eases the data input and search. The main project database has been developed using the object-oriented method. Microsoft SQL Server 2008 is adopted as the DBMS.

The business logic layer (BLL) includes three components: Workflow Engine Component, Data Handling Component and Data Analysis Component. Data are stored directly through the Data Handling Component from DAL such as standard data and process data. Moreover, Data Handling Component provides plentiful data search entrances according to the aforementioned three information dimensions. With the support of Data Handling Component, the Workflow Engine Component uses the workflow technology to define, promote and control the work process. Data Analysis Component reads construction process data in the DAL through Data Handling Component and exports analysis results in multiple forms.

Finally, the top layer of the system provides the interface to the overall system. The user interface (UI) has been implemented as a set of Web pages. According to the scope of the function, the web pages can be divided into four categories, i.e. the workflow pages, WBS pages, data-list pages and statistic result pages as shown in Fig. 4. The information involved in the construction process is shown in the form of data list and statistic result. The workflow pages and the WBS pages are used as the index to get the specific information from the massive construction information. With the support of Workflow Engine Component in BLL, users check and control the work state and construction information through the workflow pages. The WBS pages provide the creation and editing of the WBS code. Construction information can be searched according to the specific WBS code by popup windows. On the
statistic result pages, data are presented in multiple forms, such as histogram, pie chart and bar chart which represent the stability and general performance of the project. The BLL and UI are developed based on the Microsoft .NET Framework.

4. System applicability in practice. The developed web-based information management system was applied for the construction of an underground cavern group in a hydropower project in the southwest of China as shown in Fig.5. This underground cavern group consists of one water inlet, six diversion tunnels, and one underground powerhouse, three tail water tunnels. The water inlet is 168m long and 30m high. The diversion tunnel is 348m long and its diameter is 11m. The Main powerhouse is 267m long, 29.8m wide and 77.2m high. The tail water tunnel is 561.08m long and its diameter is 18m. The project scheduled duration is five years and five months.

The main functions of the system are classified according to the specialties of the end user as shown in Fig 6. Each specialty gets its information in the form of data records, statistic and reports, such as quality, safety and investment. The end user can check the work state in the Workflow function and modify the basic information in the Settings function.

Fig.7 shows the start page of the system. Users need the User ID and Password to log in the system and guarantee the security of the system. Moreover, the specific User ID can classify the responsibility of each user and facilitate the process control by the workflow engine. The project was decomposed into several work zones in the preconstruction stage, which is the first and second level in the Work Breakdown Structure (WBS). Generally, those two levels are relatively stable as the WBS is designed according to the construction organization plan. However, the third level of the WBS is usually defined in the construction phase by the contractor and then approved by the supervisor and owner. As a result, the WBS code will change along with the construction process. Fig.8 is the WBS definition and modification interface, and users can create a new node or change the information of a selected node. Based on the WBS, users can define the start and end date of each work package. As a result, the schedule of the project is presented to the end user as shown in Fig.9.
The information in time dimension is shown in the format of workflow. The state of a construction item is shown in Fig. 9. Users can define and edit the nodes, process and relationship of the workflow according to the actual construction circumstances. There are five types of nodes to represent the current state of the workflow: inactivated, initialization, waiting, processing, and completion. The state named inactivated means that the node is temporarily prohibited in the construction process. In the construction process, users can check the construction process through the pre-designed workflow. Users can get the construction information through the WBS index. By clicking the enter link, the details of the clicked node are shown.
to the user. Moreover, besides the workflow entrance, users can search the construction information by WBS index. Click the select button will activate the WBS searching dialog as shown in Fig.10. Additionally, the information involved in the construction process can be added and modified if the corresponding node in the workflow is not finished yet. Users can add, edit or delete data by clicking the Add, Details and Delete buttons. The interface of add and edit data is shown in Fig.10. Construction information is shown in the form of Data List and Statistics. Users can change the form of data presentation by shifting the Data List and the Statistic button.

Figure 7. the Login page of the system

The statistic results are generated by data cube operations such as roll-up, drill-down and star join etc. For example, the roll-up operation gets the statistic results of quantities as shown in Fig.11. Roll-up is a merge operation that needs one dimension merging function and one element combining function [36]. The result of the roll-up operation is:

$$C_a = merge(C, \{[D_1, f_1], ..., [D_m, f_m]\}, f)$$

where $C$ is the raw data; $f$ is the merging function for each elements; $D$ is the data of each dimension; the number of dimensions is $m$. In this case, the dimensions are: Time, Quantity, Material Name and WBS and the merging function is $SUM$.

Before the system applied to the construction of hydropower project, the information management is relatively inefficient. Generally, project participants communicate through the phone, email and IM (instant message) tools. The problem is, the communication cannot be monitored and controlled, and even impossible to persisted. Moreover, the information management in the construction process is scattered. Most approaches of information storage are through the Microsoft Office software such as Microsoft Word, Microsoft Excel, et al. This cannot guarantee the persistence, security and compatibility of information, which will make the information management in a state of chaos.
Figure 8. WBS definition and modification

Figure 9. Schedule Checking
**Figure 10.** process control by workflow and data presentation

**Figure 11.** Statistic results of quantities
The system has provided a well mechanism of information retrieval and data statistic results based on the structured information in the multidimensional information model. The majority of information can be stored in the system, which will provide information sharing and guarantee the compatibility of information. With the support of workflow technology, the system has realized information management based on process control. The regular communication process can be promoted by the workflow engine. Accordingly, users can check the communication through the system, which will make the information management more controllable. For instance, in traditional ways, in order to obtain the quality information of the spillway project, project participants have to check the quality information of each work packages, which spread in multiple documents. However, with the support of the proposed information system, a simple search action will present the quality information of the selected WBS in the form of data list and statistic results as shown in Fig.10 and Fig.11. Furthermore, users can check statistic results in multiple forms as shown in Fig.11.

However, the system depends on plentiful basic data. For instance, multiple workflow templates and form templates are needed for the various situations in the construction process. The successful application of the system can ensure the system will deploy smoothly in next project. In addition, the workflow cannot cover all the communication scenarios in the project. Traditional approaches will be more agile in some of the emergency or unconventional situations.

5. Conclusions. Construction projects are often complex and unique, which involve a large number of activities. As a result, the amount of information generated and exchanged during the construction process is enormous, especially for large scale projects such as hydropower project. The fragmentation of construction industry makes the communication and information management more difficult. Most previous studies on the information management of construction focus on the special needs of construction sectors rather than a total information integration of general aspects.

This paper presents a multidimensional information model that combines the WBS, workflow and Time factor together for the information management of construction projects. With the combination of workflow, WBS and Time, this information model can break the constraints of time and thus manage the construction information based on process control, realize the agile information interfaces to the end user and reduce the data redundancy of the database. An integrated system was developed according to this information model and the system provides an agile information interface and manages the working process based on process control through the workflow engine. Moreover, the system provides multiple graphical statistical results to support decision making. A case study shows the application of the developed system in the construction project of an underground cavern group in a hydropower project in the southwest of China. Moreover, the proposed multidimensional information model can be adapted to manage multiple types of construction projects due to the universality of WBS and Time factor and the flexibility of the workflow technology.

Building information modeling (BIM) has been a growing development within the past few years in the design and construction industry due to BIMs ability to foster collaborations among many disciplines [2]. With the integration of 3D model and construction information such as progress, cost, safety and quality, BIM
can provide the following benefits: enabling concurrent collaboration, integrating separate tasks and improving separate tasks [4]. Some researchers have integrated 3D model with the construction information in metro construction project [10] [29]. Those studies have integrated the 3D model with WBS and other construction code structures to provide a convenient way to exchange information effectively and efficiently. Therefore, there is the potential for further developments to integrate the 3D model with the proposed multidimensional information model in this paper. Based on the effective communication and information management, the 3D model will improve collaborations among project participants by the visualization of construction process. For instance, the proposed information model provides the essential information of a special work package and the 3D model visualize the construction sites to improve the communication and collaboration among project participants. On the other hand, the proposed multidimensional information model is a three dimension data cube, which can be considered as a good foundation of Data Mining. Knowledge sharing can be a further study using the Data Mining technology. The construction process of large scale project may encounter various difficulties and the participants will accumulate plenty of construction experience in this process. At the end of the project, those valuable experiences are stored as sealed files. However, based on this information model, information is persistent and easily searched which makes the knowledge sharing possible. Therefore, further study about knowledge sharing is served for construction companies who can centralize the information about various projects and extract valuable information to build the knowledge database.

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