A framework for facilitating multi-dimensional information integration, management and visualization in engineering projects

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This research proposes an application framework, named PIIM Framework (Project Information Integration Management Framework), to effectively solve the problems of integrating project information and system interfaces among different participating parties and engineering application systems, as well as to provide five kernel modules to encapsulate complicated management and visualization functions. The PIIM Framework is constructed on the basis of object-oriented techniques, such that users can take advantage of object-oriented programming to easily develop applications required. In addition, this research conducted an actual engineering project example, and developed a prototype system based on the PIIM Framework to verify its feasibility. Through the feasibility study, it has been demonstrated that the PIIM Framework can provide not only provide a more efficient method to integrate, manage and visualize project information, but can also save programming time for the project management team when developing a project management system from scratch.

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1. Introduction

Today's construction projects are becoming ever more complex and time driven, especially as the amount of project data and active project participants increases. Several known issues pertaining to this phenomenon are described as follows. Firstly, the construction industry continually seeks to apply new information technology (IT) based methods to substitute the traditional paper-based management methods, with the need for information to be created just once and used over the entire project lifecycle, rather than the generation of the same information multiple times in current processes. However, the diverse range of project participants still wish to maintain their own data, structured to suit their own specialized needs. Hence, the differences of data definition, data format, and data storage increase the difficulty of integrating the data from diverse sources in engineering projects. Secondly, current information management methods are based on file collection approaches, which have no relationship with each other. Therefore, project managers cannot consider engineering information synthetically in performing project control. If they desire increased accuracy and total control of engineering projects, project managers must spend time collecting and handling data which are generated from different systems. Thirdly, although much of this engineering information is produced electronically and is visual in nature, teams primarily use paper-based views of engineering information to share information with one another in project meetings.

The project participants would not be able to understand the project status comprehensively due to the lack of an intuitive and user-friendly visualization tool to display the related project information. Fourthly, the participants in the project need to communicate and transfer information with each other, either within a phase or between two phases. However, information exchange between project parties is limited to the digital files, a medium in which retrieval and exchange is inconvenient and inefficient.

In addressing the abovementioned issues, the project management system has become increasingly important in a project management effort. The role of the project management system is to provide assistance to the project management team in handling complicated project information, and providing useful and significant information for controlling the project and supporting decision-making. At present, the project management systems which are employed in the construction industry can be divided into two types. The first type is commercial software, in which projects are managed using mostly Gantt Charts, Program Evaluation and Review Technique (PERT) [1–3] and Critical Path Method (CPM) [4]. These management techniques have spread quickly into many private enterprises and represent significant commercial value. Thus, much of the related software and modules have been developed by commercial software companies, for example, Microsoft Project, Oracle’s Primavera P6 Professional Project Management, Daptiv Project Portfolio Management (PPM) and Project Management Module in SAP’s ERP solution. The second type of project management systems is in-house software, which is usually utilized where the commercial software does not offer sufficient or special functionalities for use in particular engineering projects or firms. Therefore, some firms will develop the in-house
software to meet their needs. Examples of this include Bechtel [5], Parsons Brinckerhoff [6,7], Kajima [8,9], CECI, CTI [10,11], RUENTEX, SINOTECH among many others.

While the abovementioned systems can assist project manager in managing the engineering project, they still leave significant issues unresolved. This may be considered as two issues: (1) Traditional project management systems mainly provide text, graph and complicated network schedules for controlling project and making decisions. Today's complex and time-driven projects, coupled with increasingly large project information volumes and active project participants, require more effective integration, management and communication tools than that which traditional project management systems can provide. Because of the complexity of the construction industry, the multiple phases of the construction project life-cycle combined with project participants using various heterogeneous systems causes information integration to be an important and imperative step in achieving efficient and effective collaboration for the project's success. For example, the construction project team can understand the conflicts in relation to time and space in advance by using the conflict detection mechanism, where the computer informs team members of parts of the building which are in conflict or will clash, by the integrating schedule information and 3D model. In addition, this allows quality control to occur at any time and at any place during the engineering project. The aim of quality control is to oversee for the completion of the engineering project in a timely manner through the most profitable and cost-effective way. These questions arise in relation to multi-dimensional information integration, management, and visualization of engineering projects. It follows from what has been discussed above that an effective project management system should provide not only provide sufficient and comprehensive information to facilitate project management, but also the various visualization tools to assist with information distribution and communication; (2) In the construction industry, the contents of project management will be changed to meet special engineering requirements and contract stipulations in every project. Even though commercial project management systems can provide the most commonly required functions, they often do not have enough flexibility to change management workflows or enhance certain functionalities when required. On the other hand, some construction management firms develop in-house project management system for fulfilling specific project requirements, at an immense cost of time and money on development and maintenance efforts.

In this research, we propose a Project Information Integration Management Framework (PIIM Framework) to address the aforementioned issues. The PIIM Framework is a reusable and semi-complete application that can be customized to deliver specific applications. We hope that future developers will be able to efficiently develop a useful system for construction project management on the basis of the PIIM Framework. We also develop the prototype Visual Project Management Information System (VisPMIS), based on the proposed PIIM Framework, to assist project management teams in resolving the issues of integration, management and visualization of construction project information. Through this example application, the PIIM Framework proposed in this research is demonstrated and the functionality is verified.

2. Related works

In this section, we briefly review the main literature related to our work, with the purpose of highlighting our contributions in this research area. Construction project management is responsible for the application of modern management techniques and systems to the execution of a project from start to finish and to achieve predetermined objectives of scope, quality, time and cost to the equal satisfaction of those involved. However, development is required on various related topics under the following focus areas: (1) Because of the complexity of the construction industry, the multiple phases of the construction project life-cycle, and the project participants using various heterogeneous systems, information integration becomes an important and imperative step to achieve efficient and effective collaboration for project success; (2) The use of visualization to present engineering information is an effective and efficient method for the distribution of information and communication with project participants during project meetings. A detailed discussion is presented in the next section.

2.1. Multi-dimensional information integration

During the life cycle of an engineering project, a voluminous amount of data and information is usually created along the delivery processes of construction products. The construction project team must consider a wide variety of information when controlling the project and making project decisions. In general, teams primarily use paper-based views of project information and share information through files. Because the information defined in the information distribution systems of various parties are usually different, they are always difficult to integrate with one another for the purpose of information communication and distribution. Important relationships between different pieces of project information are not communicated effectively as construction information is not effectively integrated and used. At present, some data models have been established for integration purposes. The Building Information Model (BIM) [12] is a computer model database of building design information, which may also contain information about the building's construction, management, operations and maintenance. Some research examples include Azhar et al., who demonstrated the use of BIM for sustainable design and the LEED® certification process [13], and Hu et al., who applied BIM technology to address conflicts and structural safety problems during construction [14,15]. However, as these solutions are based on different and incompatible standards, an open and neutral data format is required to ensure data compatibility across the different applications (e.g. Autodesk Revit, Bentley Triforma, Graphisoft ArchiCAD and so on). Industry Foundation Classes [16], developed by the International Alliance for Interoperability, can provide such integration and interoperability capabilities. The IFC data model is an object-oriented data model based on class definitions representing the items (elements, processes, shapes, and so on) that are used by software applications during a construction or facility management project. Implementations of IFC have been reported in various construction IT system integration projects [17–20]. In addition, Salford University proposed the concept of nD Modeling, enabling multidimensional information integration, which it foresees as essential in the future of construction management [21,22]. Although IFC can fulfill the goals of data sharing and information integration, it still falls short of providing the related objects and processes for project management. The current research attempts to integrate multi-dimensional information into the database through programming, or provide related project data on 3D models using CAD software API. This approach, relying on proprietary software, is difficult to reuse without the particular software, and is constrained by fixed development methods. In this research, we provide a more flexible and simple mechanism to handle the multi-dimensional information integration. Firstly, we design and develop the integrated data model to describe and store all the project information. Therefore, the integrated data model can be used to demonstrate the entire construction lifecycle including project management, the processes of construction, and facility operation. Following this, we provide not only a special module that contains a number of importing functions to address the existing project information into the integrated data model, but also provide a management module to access the integrated data model including functions such as data creation, data query, data
deletion, data insertion, data update, and so on. Users will be able to
employ our modules and the integrated data model to build their ap-
lication to address the multi-dimensional information integration
without any commercial software.

2.2. Visualization for communication and information distribution

Treicher [23], an experimental psychologist, conducted a famous
psychological experiment to determine how human beings obtain in-
formation. Through a large number of experiments, he proved that
83% of the information received by human beings is by the sense of
sight, and the remainder is by the senses of hearing, smell, touch
and taste, supporting the view that information visualization is the
most essential for communication and information distribution.

Liston et al. [24,25] studied the problem of communication in en-
ingineering workspaces, which could be variably defined as physical or
virtual spaces where people work, share and use information. From
observations of numerous design and construction review meetings,
they discovered that teams spent most of their time on descriptive,
explanative, evaluative and predictive tasks. All these tasks are critical
to enabling better decision-making by project managers. In this re-
search, we employed the aforementioned four tasks to analyze the
current information distribution system in construction projects to
determine whether sufficient information was being provided. The
information distribution system may be classified into four types
according to their characteristic of information visualization. The
first type is the 1D system, which conveys information through text,
attributes and tables. Examples of these include project websites, da-
tabases and general management information systems. Such systems
record and describe the project information in detail. The second type
is the 2D system, which presents information mainly in the forms of
graphs, charts or maps, such as output from GIS, ERP, 2D CAD, and
so on. These systems assist the project manager in explaining project
decisions, the rationale of the project schedule, and also support them
in evaluating project goals and ensuring that project requirements
are met. The third type is the 3D system which uses 3D models to pre-
sent the actual project status and analyze space conflicts, with exam-

ples including 3D CAD and virtual reality systems. These applications
harness 3D visualization to assist descriptions of engineering project
status, and enhance communication and discussions during project
meetings. The fourth type is the 4D system which binds 3D models
with their corresponding construction schedules in their simplest
forms. This has recently emerged as a method of providing engineers
with an effective tool for managing the complexity of coordination as
well as conflicts before the actual commencement of construction.
Some examples include 4D CAD and construction simulation systems.
The realization of 4D CAD technology has also been greatly accelerat-
ed by the availability of powerful commercial 4D CAD tools, such as
Bentley's Navigator, Intergraph's SmartPlant Review, BALFOUR's
FourDscape, Common Point's Project 4D and ConstructSim [26].
There have been numerous, albeit similar, research studies into the
use of 4D systems. The important detailed study by Stanford Univer-
sity was instrumental in initiating interest in this area [27–29]. Chau
et al. built a 4D-GCPSU for construction management [30,31]. Hsieh
et al. developed a Construction Director, a 4D simulation system for
plant construction [10,11]. Huang et al. developed a virtual prototyp-
ing system for simulating construction processes [32]. Dawood and
Sikka [33] provided quantitative evidence that a 4D model can in-
crease the efficiency of communication along with the interpretive
ability of a construction project team. Even though 4D technology
can increase the ability of project managers in providing better man-
agement and visualization in construction project management, there
is room for further development in providing sufficient information
for uncovering problems and making better decisions. Table 1 sum-
maries the different task emphases and possible outcomes of the
four information visualization systems that have been described.

Based on Table 1, we are of the view that an efficient information
distribution system ought to support all four kinds of characteristics
of information visualization at the same time. Therefore, this research
proposes a new concept of information visualization, named the 4D+
Multi-Data-View, to present the integrated data of engineering pro-
jects, with advances towards providing significant useful information
for use in project management and decision-making. The meaning of
“4D+” is to provide the additional characteristics of information visu-
alization on top of the base 4D information visualization. Hence, users
will be able to view the text which describes the project information,
the graph to view the project statistics and progress, the 3D models to
present the building status and the 4D models to display the construc-
tion simulation in the same view. Furthermore, the “Multi-
Data-View” implies that users will be able to query and view the inte-
grated data with the different views according to their requirements
as shown in Fig. 1. In this approach, users will be able to find the nec-
essary and relevant data they need in a more direct and accessible
way. This research developed a visualization and management mod-
ule to realize this concept. The management module provides func-
tions to acquire the required data the user needs, and passes it on
to the visualization module to display the results in different ways
according to the user’s requirements.

3. PIIM Framework

3.1. Overview

As shown in Fig. 2, the PIIM Framework is an application frame-
work which can be divided into three tiers. The first tier is the inte-
grated data model, which describes and stores information about
entire engineering projects; the second tier is the data access inter-
face, which mainly deals with data access between the integrated
data model and kernel module; and the third tier is the kernel mod-
ule, which provides core project management services and encapsu-
lates complicated project management functions into five easy-to-
use modules: DataAdapter, DataManager, DataAnalyst, DataViewer
and DataExporter.

3.2. Integrated data model

This research proposes an integration data model which can be
used not only for storing engineering information, but also providing
internal system data in the PIIM Framework. As shown in Fig. 3, the
integrated data model can be broken down into three parts. The first part is the IFC Data Model, which is employed to describe most
of objects in engineering project management, for example, 3D ob-
jects, schedule objects, cost objects and document objects. The second part is the User-Defined Data Model, which works with the IFC Data
Model to extend its insufficient management objects, such as quality
statistics objects and scope objects. The third part is made up of Rela-
tionShip Objects which define the relationship between IFC objects
and User-Defined objects. Both User-Defined Data Model and Rela-
tionShip objects are described by XML.

This integrated data model has the important characteristic of the
multi-directional data link, as shown in Fig. 4. The “Scope” item
is parent to a lot of “Activity” items and “Activity” item is related to
many other items, which can be “3D Object” items, “Cost” items,

<table>
<thead>
<tr>
<th>Table 1 Characteristics of different information visualization.</th>
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<td>1D system</td>
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“Document” items, and so on. Each of the items records the “related” and “relating” relationship. Thus, users will be able to easily find the related items through these multi-directional links. For example, a designer would be able to understand the related cost and schedule information through linking from the relevant “3D object” items; a planner would be able to view the related 3D model by linking from the relevant “Scope”, “Cost” and “Schedule” items.

As Fig. 5 shows, we adopt the XML technique to organize and construct the integrated data model. The XML structure can describe the User-Defined Data Model and Relationship Objects, as well as saving the key attribute of IFC Objects for use as a link for matching and obtaining the data from the IFC Data Model.

Establishing the integrated data model provides four benefits: (1) it can be used for storing the information of the entire project; (2) it can be employed to decrease errors made. For example, the construction project team will be able to understand in advance the conflicts in terms of time and space by using the conflict detection mechanism where the computer informs team members about parts of the building in conflict; (3) it can be utilized to provide significant information for project management and decision-making. For example, a construction project team could conduct the Earned-Value analysis method, which includes schedule and cost data for analyzing and reviewing the relationship between schedules and cost overall; (4) users will be able to find the data they need efficiently and effectively through the relationships of multi-directional links.

3.3. Data access interface

The data access interface will increase the ease of posing basic queries and update requests to the integrated data model to which it is connected, regardless of the native language of the integrated data model. It will also allow access to the integrated data model in their native language for more complex requests. As mentioned above, the integrated data model is established on both the IFC Data Model and the XML Data Model. Thus, the PIIM Framework involves two types of data access interface, one being the IFC data access interface and the other being the XML data access interface.

In this research, the IFCvr ActiveX Component [34], an open source library for handling IFC data, is employed. It includes features such as a dictionary of IFC schema information and functionality for representing and manipulating instances of IFC objects. Furthermore, we developed the XML data access interface using Microsoft products and technologies. The System.Xml namespace provides standards-based support for processing XML, which is available in the .NET Framework.

3.4. Five kernel modules

The PIIM Framework allows for the segmenting of complex items into manageable modules according to the particular purpose, and encapsulates complex implementation details behind a stable interface. The modules of PIIM Framework are similar to Lego pieces which can be assembled in many ways to suit different purposes. This approach enables applications to be built quickly, and saves development effort. A more detailed discussion follows.

3.4.1. DataAdapter

DataAdapter provides functions for receiving and transforming the common data formats encountered in construction into the PIIM Framework. DataAdapter can support approximately 80% of the data
formats generated from commercial software packages. This module provides three functional classes. The first is C3dObjectAdapter, which assists the program to import 3D models created using any commercial CAD software (for example, ArchiCAD, Triformala, and Revit). The second is CScheduleAdapter, which is capable of importing Project XML data which is generated from MS Project or Primavera P3, and then transforming it into the IFC 2 × 3 data format which is employed in the integrated data model for integration. The third is CCostAdapter, which can adapt and manipulate the Microsoft Office Excel data format for cost data integration.

3.4.2. DataManager
DataManager is responsible for data management and manipulation. The main functions are divided into four parts, as follows: (a) Objects Management: the DataManager includes many different classes which enables the provision of functions for manipulating objects, such as create, modify, delete and query; (b) Data Structure: the DataManager defines some data structure for use in the PIIM Framework, such as class CPiimTreeNode for viewing multi-dimensional information; (c) Simulation Table: the class CSimulationTable can provide functions for collecting and storing the required data for simulating construction processes, which can decrease data handling time; (d) Others: the DataManager will provide functions for assisting the internal operations within the PIIM Framework, such as opening and saving the PIIM Project which includes the integrated data and the related views and graphs.

3.4.3. DataAnalyst
This research employs the Earned-Value analysis method [35–37], which is a project management technique used for measuring the project progress in an objective manner, and for controlling and monitoring the construction project. The EVM function in the VisPMIS combines measurements of schedule performance (i.e., behind/ahead of schedule) and cost performance (i.e., under/over budget) within a single integrated window. When properly applied, EVM can provide an early warning of performance problems and communicate this to all stakeholders. After the integrated data model is established, the class CCalEarnedValue of DataAnalyst can provide the calculation functions of Earned Value analysis, including for example, Budgeted Cost of Work Schedule (BCWS), Budgeted Cost of Work Performed (BCWP), Actual Cost of Work Performed (ACWP), Schedule Variance (SV), Cost Variance (CV), Cost Performance Index (CPI) and Schedule Performance Index (SPI). DataAnalyst also provides the indispensable calculation functions of the schedule progress and quality statistics.
3.4.4. DataViewer
A good visual representation of data can assist people in efficiently acquiring applicable information. To achieve this, DataViewer provides five styles of visualization for communication among the project participants: (a) 1D Visualization: to show the attributes of objects and general project information; (b) 2D Visualization: to show the important graphs and charts related to the objects and project information; (c) 3D Visualization: to display the 3D models of the building; (d) 4D Visualization: display of the various 3D models incrementally at the various stages of construction activities as construction progresses over time; and (e) nD Visualization: to show the integrated data after data binding.

3.4.5. DataExporter
For data exchange and sharing, DataExporter can provide functions for exporting project data to three different file formats. The first is the IFC data format, which is used for data exchange with IFC-based systems. The second is the ifcxml data format, which is utilized for data exchange with general information management systems using XML technology. The third format is the GML data format, which is used for integrating with 3D-GIS geo-data [38].

3.5. Summary
The PIIM Framework is constructed on the basis of object-oriented techniques. Object-oriented analysis and framework design are characterized by features such as modularity, reusability and extensibility, which are recognized as facilitative to the evolution and the maintenance of application systems.

In terms of modularity, the PIIM Framework segments complex objects into manageable pieces or modules according to particular purposes, and encapsulates complex implementation details behind stable interfaces. The modules are similar to the Lego pieces which can be assembled and connected in many ways, to construct different applications easily. Fig. 6 illustrates how the import function for 3D objects is developed. Users can utilize the functionalities of the DataAdapter for receiving 3D Objects, the DataManager for transforming data structure and the DataViewer for viewing 3D models into the application system. Hence, applications can be built quickly and development effort can be reduced.

In terms of reusability, the PIIM Framework enhances reusability by defining generic components that can be reapplied to create new applications. For example, coding is achieved in the same way as calculating the percentage of scheduled progress and quality statistics in engineering projects, and so a class CCalPercentage which calculates the percentage is provided in the DataAnalyst for both to use, as shown in Fig. 7.

Lastly, the PIIM Framework is designed to include hook methods and mechanisms for enhancing the system with new capabilities, without requiring major changes to the system infrastructure. Fig. 8 shows an example of extensibility in PIIM Framework. The interface IGetEntityAndAttribute is used to specify the required attributes and behavior of object querying. From the research above, two positive achievements are derived for application development. One is that the same interface can be inherited to implement the different classes. Once the application is based on the PIIM Framework, the developer can add new querying features to an existing application without having to change any existing code. Another is that new attributes and behavior can be added into the interface, which would be
updated for the related class automatically. In this way, the functions of classes will be effectively extended.

4. Prototype system

This research prototyped a visual project management information system for a construction management firm named VisPMIS to test the feasibility of the PIIM Framework.

4.1. Engineering example

In this research, we selected an actual engineering project in the campus of National Taiwan University (NTU) as a case study. The project involved the construction of an underground parking area and an information center. As illustrated in Fig. 9, the organization of this project is divided between three main participants and areas of responsibility: (a) NTU, the property owner with contractual relationships to Company A and Company B; (b) Company A, a professional engineering and consulting service provider which provided professional construction management services to NTU, while supervising and managing Company B; and (c) Company B, a construction firm which provided the physical workforce for the design and construction of this engineering project. Each of the major project participants executed their respective project management responsibilities. However, in this research, the majority of the work was the responsibility of the construction management firm. We analyzed the project management requirement by interviewing Company A and NTU. After interviewing NTU, we were able to understand the responsibilities of Company A as stipulated in the contract and as requested by the owner. After interviewing Company A, we were able to visualize the project management process in a practical context.

4.2. Requirements analysis of prototype system

The main objective of Company A was to monitor and control all aspects of a project to achieve project goals, such as completing the project on-time and to the specified cost, quality, and performance. The work performed by Company A was mainly focused on project management during engineering construction. As shown in Fig. 10, the main work activities could be divided into three phases: (1) the Project Preparation Phase, (2) the Project Construction Phase, and (3) the Project Completion Phase.

During the Project Preparation Phase, the main focus of Company A before construction was project information collection and verification. Company A obtained the planned project information from Company B and other project participants. The information included schedule information, cost information, 3D models of the project, and relevant documents. After receiving the project information,
Fig. 23. GML exporting function in VisPMIS.

References


