KEY TECHNOLOGY RESEARCH OF OPEN BIM-BASED CONSTRUCTION ENGINEERING MANAGEMENT INTEGRATED-INFORMATION CYBER-INFRASTRUCTURE (CEMIC)

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ABSTRACT

Lack of data interoperability between Building Information Modeling (BIM) software and Enterprise Resource Planning (ERP) software seriously prevents AEC companies from fully utilizing these types of software. To solve this problem, researchers have proved the technological feasibility of creating complex construction engineering information management solutions by integrating functions of BIM and ERP systems. However, these solutions require AEC companies to modify or replace their existing ERP systems, whose cost is generally exorbitant to the end users. Therefore, we propose to develop a Construction Engineering Management Integrated-information Cyber-infrastructure (CEMIC) which supports data interoperability between most widely accepted BIM software and ERP software, so that the problem can be solved perfectly in an economical way. In this paper, we will 1) Present the framework of CEMIC; 2) Expound the technology for creating the construction engineering management integrated-information model, which includes the data extracted from the IFC model and the integration of construction product, schedule, cost, and performance data that can be accessed directly by ERP software; and, 3) Based on the definition of 3D geometry class in IFC, present a technology for creating the full parametric data set that coexists with the full visual data set of 3D geometry in a relational database by analyzing and introducing several Model View Definitions (MVDs).

Keywords: Open BIM, ERP, IFC, MVD, 3D Geometry

1. INTRODUCTION

1.1 Background

ERP can integrate relevant information of business functions and resources, thereby strengthening the control of the process of production, quality, and human resources. Therefore, it is an important tool for business management in all kinds of companies. In the AEC industry, companies are project-based organizations providing services and products in the form of projects. This feature makes it necessary for AEC companies to deal with different requirements of time, tasks, resources and resource allocation of different projects, resulting in relatively dynamic and overlapping work arrangements. Therefore, for the vertical information exchange between the enterprise and its projects, a module of the ERP system is created as a project management information system (including Project Management Information System, PMIS; Project Information Portal, PIP, etc., PMIS is used as a representative system in this paper).

However, in practice the performance of these ERP/PMIS systems can hardly achieve this expectation, because of lacking sufficient data interoperability among those systems in the different companies involved in a project. For example, in China, the use of ERP / PMIS system is of mandatory compliance for construction companies in order to obtain the Highest Grade Qualification from the industry, a license that allows a company to bid large and complicated projects. According to statistics, the Chinese construction companies that have introduced ERP / PMIS software are accounted for 45.83% of all construction companies by the end of 2009 (Chinese Construction Enterprise Management Association, 2009). However, only 4.62% of these companies are satisfied with the outcome of adopting the system (China Construction Enterprise Management Association, 2009). The main reason for the disappointment of the majority of the companies includes that (1) the ERP/PMIS system cannot connect to the project participants outside of the company and, thus, fails to timely obtain the information regarding the allocation and use of project resource (Chung, BY, 2009; Arnold, P., 2012); (2) the inability to share the project information among the companies participating in the same project results in a large amount of repetitive manual input of project information, which greatly reduces the efficiency of the system (Arnold , P., 2012). Obviously, data interoperability of ERP/PMIS across the company level and the project level needs significant improvement in order to meet the needs of companies and projects.

Many researchers have noticed the problem and its serious impacts on the application of ERP in AEC companies, and have proposed many solutions to implement the interoperability by modifying their existing ERP and BIM systems. For instance, Faraj et al. (2000) integrated 3D building information models with additional features to form the conceptual framework of a construction project management information integration system, based on which they developed the software “Web and IFC based collaborative construction environment-WISPER". This software includes the functions of project evaluation, construction planning, construction instructions generation, and supply chain information distribution, etc. (Faraj I, 2000). Zhang Jianping et al. (2003; 2006) researched the 4D technology, and developed a 4D management system for a construction project, 4D-MCPRU, which combines the 3D models of buildings and construction sites with the construction management information. More research efforts are committed to integrate BIM models with the project management functions in ERP, and to form the integrated software prototype system of information sharing and collaborative work. Its feasibility was verified by empirical and experimental studies (Feng Liang et al, 2009; Wu et al., 2012; Halfawy et al., 2007). All these studies show that it is technically feasible to realize data interoperability among functional modules by establishing the relationships of data between the modules of the PMIS/ERP system based on the components in BIM models.

However, the cost of these solutions may be too high for users to afford. Generally, ERP/PMIS involves many departments and administrations in an enterprise, and a large number of corporate officers have participated in the training and applications of the system. In the process, some modules of the system such as project costs and finance have been applied and important historical data for enterprises have been accumulated. As a result, the replacement cost of such a system is relatively high. Therefore, replacing the ERP/PMIS system with a more integrated information system in order to improve the use of BIM data is unlikely to be welcome by AEC companies. On the other hand, if the BIM model and PMIS/ERP are to be integrated into one software or system, the data interface between BIM models and PMIS/ERP is the one-to-one internal interface. This approach cannot achieve data interoperability and horizontal collaborative work among the PMIS/ERP system of project participants based on BIM models. Repeated information processing and input among the PMIS/ERP of different participants or the "information islands" problem remains unresolved.

1.2 Research Objectives

To solve the above problems, we focus on the fundamental need of improving the data interoperability between PMIS/ERP system and BIM, and propose a concept of Construction Engineering Management Information Cyber-infrastructure (CEMIC), to integrate data originating from widely accepted BIM software and ERP software, and thereby achieving their data interoperability.

The CEMIC can integrate the building product information, production process information and production organization information into a Construction Integrated Information Model. It provides data interoperability for the ERP/PMIS system of project participants through the Application Program Interface (API) (). CEMIC serves as the bridge that horizontally links the PMIS/ERP of project participants, and vertically channels internal communication within the ERP/PMIS system of each participant company, as shown in Figure 1. This solution would provide basic project data shared among project participants, which can be used for different purposes. Project participants can use different statistical tools to transform the basic project data into information that supports managerial decision-making of specific users.

CEMIC itself does not include the existing functions of PMIS/ERP, enterprise databases and the corresponding user interface. It enhances the timely information exchange and improves the efficiency and performance of ERP/PMIS system by achieving the data interoperability and collaborative work among the ERP/PMIS of different project participants.

Based on the above concept of CEMIC, this paper firstly reviews the relevant technical research about CEMIC, and then analyzes the requirements of CEMIC in order to lay out the data types as well as 3D geometric data content and form that meet the requirements of CEMIC. Next, this paper introduces the technical approach for integrating the product data, process data and organization data, and the technical approach for creating the Construction Integrated Information Model (CIIM) database. Thirdly, based on a re-categorization of 3D geometry class definition in IFC, this paper proposes a technology for creating the full parametric data set coexisting with the full visual data set of 3D geometry in a relational database. Finally, the paper concludes with a discussion of the findings and limitations.

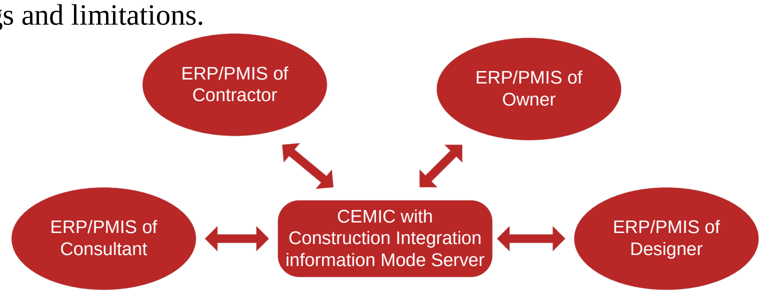

Figure 1: CEMIC as a bridge links all the ERP/PMIS systems of participants

2. RESEARCH BASIS OF RELATED TECHNOLOGY

2.1 Research of Open BIM and Supporting Standard

IFC is the core standard for supporting data interoperability in the field of AECO (Architecture, Engineering, Construction, and Operation). So far, more than 100 software applications declare that they support this standard. The design intent of IFC is to describe complete building-related information from feasibility studies, design, construction and operation, and support full life-cycle data exchange (IAI, 2007). Despite that the goal of IFC is laudable and has drawn continuous attention from the industry for years, it has no significant effect on data interoperability issues in the field of AEC (Eastman C. et al., 2010). Steel et al. (2012), through the systematic research of IFC technical defects, pointed out that the most prominent problem of IFC is at the semantic level: it does not support a unified modeling style and does not cover all types of facilities, which tend to result in misjudgments of the data receiver regarding the object described by IFC. This problem can be resolved within the standard framework advocated by Open BIM. If OmniClass categorical codes are assigned to the objects defined by the IFC, the objects are able to be recognized by the receiver software. However, IFC is designed for model data exchange based on file format. With file format only, software is unable to perform data queries on object-level, it is difficult to track data changes, and it is difficult to manage the permission of data modification.(Bazjanc 2003; Froese 2003; Kininiemi et al. 2005; Nour 2009). The parametric definition of IFC is poor and its support to data interoperability between analyzing software and modeling software is insufficient. Including the recently released version IFC4, the parameterization of complex shape definitions in IFC is still imperfect and cannot output interoperable data files by fully parametric data format. For complex shapes it mainly uses Brep-model or a Surface-model to define. Brep-model and Surface-model have the function of geometric modeling, so that they can form geometric visual expressions inside the computer after processing the geometric model, which no longer includes modeling methods and parameters. Obtaining modeling methods and parameters from these definitions is extremely difficult, and in some cases impossible.

IDM/MVD is proved an effective method to eliminate redundancy of IFC class definition and makes the IFC files adapt to the specific application areas. But this method requires BIM software output different IFC files according to different MVD, which generates such a problem: how many MVD are needed in a project that implements BIM? In a commercial environment, is it possible to require software that supports a number of MVD? When we see more than 50 kinds of MVD proposals, this question is worth pondering. In fact, software developers' complaints about MVDs have emerged (buildingSMART, MVD Internationalization, 2013).

2.2 Technology of Building Database of BIM

File-based data management of BIM lacks version management, data security management and object-level data query capabilities. BIM database becomes the inevitable development trend of data interoperability (Eastman., 2008; Froese, 2003). Relational databases are widely used in various industries for data storage and management with a relatively high level of maturity. However, the performance problems of the relational IFC database restrict its development. This is because a relational database is not efficient at managing object-oriented data with a long inheritance mechanism (Nour, 2009; Lee G. et al, 2012). Although the object-oriented IFC database performs better than the relational IFC database in terms of querying, reading and writing on the server (Borrmann and Rank 2009a; Borrmann and Rank 2009b; Lee G.et al, 2012), the inefficiency of transferring huge amounts of IFC data files remains the bottleneck that constrains the development of the IFC database towards the network database. From the analysis of existing technical defects of IFC, we can see that, regardless of which type of database, simply shifting the IFC data structure from a file to a database cannot solve the genetic defects of IFC. Based on the research on parametric modeling technology, we have proposed a fully parametric BIM database technology. The volume ratio of this parameterization data and the corresponding IFC data is about 1:100. The parametric BIM data server performs significantly better than IFC file based BIM data server (Liu et al., 2010). This paper proposes a CIIM database to meet the data interoperability requirements of CEMIC for BIM based on the openness concept of Open BIM and a large number analysis of MVD.

3. KEY TECHNOLOGY OF CEMIC FRAMEWORK BUILDING

3.1 Data Interaction analysis of CEMIC

The core function of CEMIC is to support data interoperability between BIM software and PMIS/ERP systems via providing a CIIM Server. The CIIM Server acts as a basic data-sharing server of construction projects; most of the data in the CIIM Server comes from the application software that is used in the project including BIM software. In order to support the interoperability of BIM data required by the PMIS/ERP systems of all the participants, CEMIC should be able to provide data interoperability support for the following software:

1) 3D-BIM modeling software: This software is used for creating 3D-BIM models. CEMIC can support data interoperability between different BIM model editing software on each phase of the project.
2) Design analysis software: This kind of software is a tool for design that can extract 3D model data from the CIIM database for professional analysis.
3) Quantity take-off software: This software calculates the quantity of all the components and form the bill of quantities (BOQ) according to the BIM model data that is read by CEMIC.
4) Project Cost Analysis Software: This software generates project cost and cost structure according the data of quantity or BOQ, which are read from CEMIC in accordance with the rule of cost analysis. The project cost data shared by the project participants will serve as part of BIM model data and managed by CEMIC.
5) Project planning software: It generates a series of tasks and associated attributes in project planning using the CPM method, of which the most important attribute is the name of the task and the scheduled time.

CEMIC can receive such project plan data generated by this software, and establishes the relationship between these data and BIM models to build 4D models.

6) 3D/4D/5D visualization software: This software will read the 3D/4D/5D model data provided by CEMIC and provide visual browsing functions.

Table 1: Data Type Included in CIIM Server

No.	Date Type	Content or Usage	Main Source
1	Project Info.	Include Project Name, Usage, Location, Site Elevation, etc.	BIM Modeler
2	Building Info.	Include Building Name, Function, Coordinate, First Floor Elevation, etc.	BIM Modeler
3	Floor Info.	Floor Number, Floor Height, Elevation	BIM Modeler
4	Component Classification	Number according OmniClass table 21, Used for Identifying the Component	BIM Modeler
5	Material and its Classification	Include Material Name, Specification , Fabrication Method , Number according OmniClass table 23.	BIM Modeler
6	3D Geometry	Used for Model Editing, Model Analyzing, Quantity take-off, and Visualization.	BIM Modeler
7	Object Annotation	Information in text format of review or coordination.	Model coordinator, Model Reviewer
8	Attached Files	Attached Files linked with Object	BIM modeler, Model Coordinator, Model Reviewer
9	Quantities of Component	Used for Produce Budget, BOQ of Contract, Construction Cost, etc.	Quantity take-off
10	Unit Price of Component	Used for Budget Management or Cost Management	Estimator
11	Estimate	Used for Budget Control	Estimator
12	BOQ	Attachment of Contract between Owner and Contractor	Estimator
13	Construction Schedule Data	Tasks with planning date and actual date.	Project Engineering
14	Construction Organization	Construction Organization	Project Engineering
15	Construction Performance	Performance of tasks have been finished, include cost, quality, etc.	Project manager

3.2 CIIM Database Frame Building

It is the basic function of CEMIC to provide safe, long-term, controllable data interoperability using CIIM database for the software it supports. Under the premise of automated data combination and relationship conversion through the computer, " What, When, Where, Who, Why, How (5W1H)" method is more flexible than the technical rules that traditional work breakdown structures (WBS) follow (Cho, D., 2012). This method is more suitable for forming a variety of data relationships associated with processes and organizations. For example, project participants need to manage the cost data of different statistics for different purposes. The general contractor may simultaneously handle enterprise quota data for cost verification and the cost inventory data for settlement of project payment with the owners. Similarly, the cost consultant may require the cost inventory data to deal with the construction management and design estimates data organized as OmniClass Table 21. These statistical data for different uses must have a relationship in order to effectively support decision-making, to achieve process controlling in all the participants' individual PMIS/ERP systems. Studies have shown that this association can only be established in support of the minimum granularity of building components data provided by BIM (Wu et al., 2012; Halfawy et al., 2007). Additionally, using the "5W1H" approach in combining information of product, cost, schedule, and implementation performance can establish a flexible, integrated construction management framework. Because a relational database has the higher level of maturity and is widely used in PMIS/ERP, CIIM database is designed based on a relational database. CIIM categorizes the 15 kinds of data listed in Table 1 into the 6 data types using the technical concept of "5W1H", show in Figure 2.

CEMIC supports the PMIS/ERP system for all the project participants. Part of the data processed by the participants' PMIS/ERP is the enterprise or project team private data. In normal circumstances, these data, such as the cost plan data in the construction department, do not allow to be shared with external parties. CEMIC supports PMIS/ERP to process, control, and manage this type of data, but this type of data is not stored in the CIIM Server, and it does not support either controlled data sharing. Data stored in CIIM Server can be shared by all the project participants.

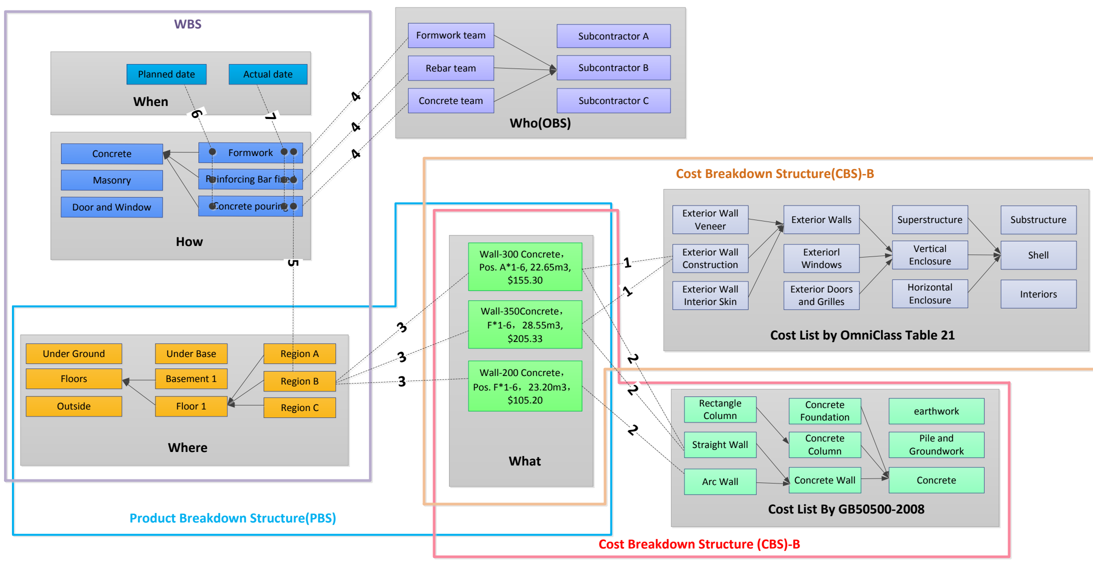

Figure 2: Logic Model of CIIM Based on "5W1H"

4. 3D MODEL GEOMETRIC DATA SETS IN CIIM DATABASE

4.1 Requirement analysis of 3D model geometric data format

3D geometric data are the most widely used and the core data in all the data classes that the CIIM Server contains. The availability and accessibility of CEMIC is an important manifestation of its capability to support various types of software. In the interoperable data analysis mentioned above that CEMIC supports, there are three usages of 3D model data in CEMIC supported software: model editing, model analysis, and visualization. The "Precast Concrete Exchanges" MVD proposed by Eastman et al. defines 46 MVD views, and offers an important point of departure for this study: it provides systematic definition for the geometrical properties of 3D models. It categorizes the geometrical properties of 3D models into four types of requirements: "Geometry Deformations", "Geometry Function", "Geometry Accuracy" and "Geometry Level of Detail" (Eastman C. etc. 2009). The "Geometry Function" focuses on how the geometry will be used:

- Viewable - the user can only view the objects without the ability to edit or use them as reference to create associated geometry (e.g. not being able to use the grid lines from one model as reference in another);
- Referenceable - the geometry is viewable and referenceable (e.g. the fabricator can associate geometry in this model to geometry coming from the engineer, geometry can be used for clash detection);
- Editable – the geometry is fully editable (typically parametric).

According to the definition proposed by Eastman et al., some MVD proposals which have the requirements of 3D model geometric definition are distributed as shown in Table 2.

Table 2: Geometry Function of 3D model defined by MVDs

Geometry Function	MVDs
Viewable	Precast Concrete Exchange.
Referenceable	Architectural Design to Building Energy Analysis; Architectural Design to Circulation/Security Analysis ; Coordination View; Precast Concrete Exchanges; etc.
Editable	Architectural design to structural design; Architectural Design to Quantity Takeoff for Cost Estimating; Precast Concrete Exchanges; Structural Design to Structural Detailing.

3D geometric data with Editable ability is the data for parametric modeling, such as the data defined by the IfcSweptAreaSolid. This data can form a visual 3D model expression data mainly as Brep-Model and Surface-Model after geometry processing and conversing in modeling software, in order to achieve geometric analysis and visualization. Therefore, “Editable” data have the highest geometric ability, and they also have “Referenceable” and “Viewable” ability. The data amount of parametric modeling is much smaller than the corresponding visualization 3D model data. Also it is easier to output 3D geometric data using the parametric data format by encoding for the components, which have large number and simple shapes. Therefore, some MVD that are only required to achieve “Referenceable”, often mix the uses of the parametric modeling data and visualization 3D model data. For example, 3D geometry components class defined in "Coordination View Version 2.0" contains both parametric class definition and visualizational class definition. In fact, the definition of 3D geometric data in IFC does not strictly define the parametric class and visualizational class. This requires that the software having the ability to receive 3D geometry data with “Referenceable” must have geometric modeling capabilities. 3D-BIM model editing software and design coordination software usually have geometric modeling capabilities. In contrast, the software that only supports “Viewable” does not need geometric modeling capabilities nor need to manage complex 3D modeling data. Therefore, nD visualization module can be made into lightweight web browser plug-ins (such as .ocx executable code files) to provide excellent visualization functional modules for PMIS/ERP software.

4.2 Design of 3D Geometric data in CIIM Database

In order to support model editing and lightweight nD visualization, 3D model geometric data in the CIIM database will be managed separately according to the parametric data sets and visual data sets. These two data sets will coexist in the CIIM database, so the software application can choose one according to its own requirements when it calls for the 3D geometric data of components.

Parametric data sets are used to support application software with geometric modeling capabilities. The type of software comes from the application software with geometric modeling capabilities, such as BIM model editing software, quantity measurement software and design analysis software, etc. IFC4 includes 27 parametric modeling class definitions of 3D models. As shown in Figure 3, it can be divided into the following 6 types in accordance with the 3D geometry:

1) (ABS) IfcSweptAreaSolid: It is a class definition that makes a series of 2D shapes into 3D geometry, including six kinds. The IfcFixedReferenceSweptAreaSolid that IFC4 newly added can create spirals, and it is a commonly used components modeling method. The current six definitions cannot fully meet all the building components modeling needs, so we are looking forward to the IFC5 that buildingSMART promised to give a more flexible modeling method.
2) (ABS)IfcCsgPrimitive3D: Its sub class is the definition of simple geometric shape, including rectangular, cylindrical, spherical, conical and pyramidal. All 3D geometry defined here can be achieved by IfcSweptAreaSolid, so this class definition can be seen as an easy way of part of the IfcSweptAreaSolid class.

3) IfcSewptDiskSolid：it represents the 3D shape by a sweeping representation scheme allowing a two dimensional circularly bounded plane to sweep along a three dimensional Directrix through space.
4) IfcSectionedSpine：it represents the 3D shape of a three dimensional object composed by a number of planar cross sections, and a spine curve. In other words, the sections can be different while sweeping along the spine curve.
5) Partial of (ABS) IfcSurface: IfcSurface contains two classes definition of a limited range of surfaces created by parametric, which are (ABS) IfcSweptSurface and (ABS) IfcBoundedSurface. They can be used for irregular surface roof or floor surface and other shapes.
6) IFcBooleanResult: It generates new 3D geometry through “and”, “or” and subtraction between two 3D entities. This is the commonly used method for producing more complex 3D geometry, cutting overlap components and accurately measuring quantity.

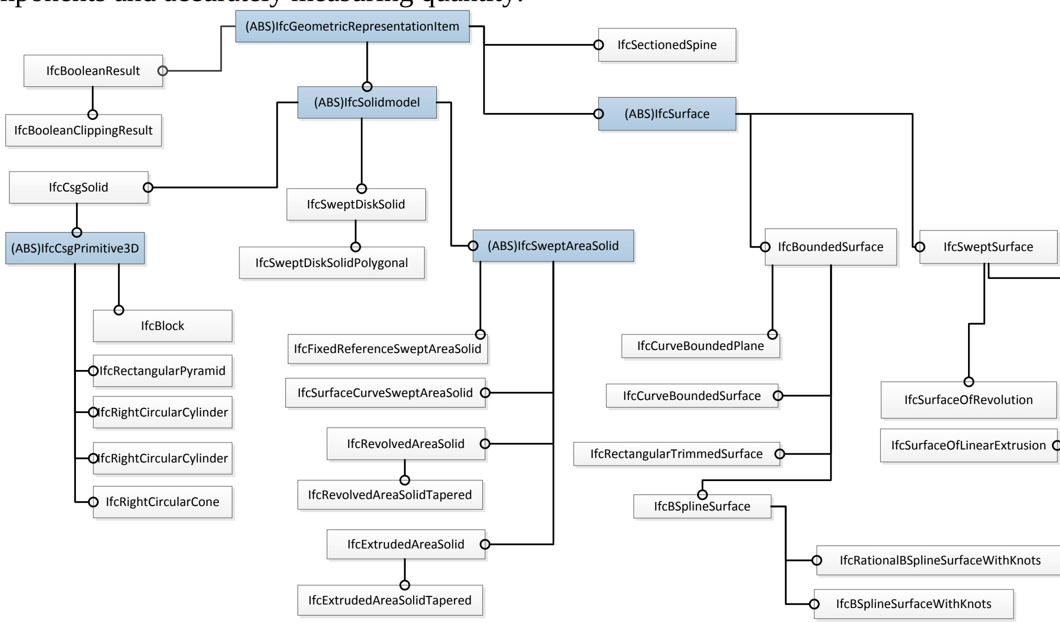

Figure 3: All Parametric Geometry Class Definition of IFC4

Visualization data sets: it supports software that only needs visualization, and the data are processed and generated by the specialized module in CEMIC according to parametric data sets. IFC4 contains 7 visual definitions of 3D geometry, as shown in Figure 4. Wherein, the IfcRriangulatedFaceSet that IFC4 newly added is the data format that is supported by all mainstream graphics display devices. The other 6 can be easily converted to such format, so we only use IfcRriangulatedFaceSet in CIIM database.

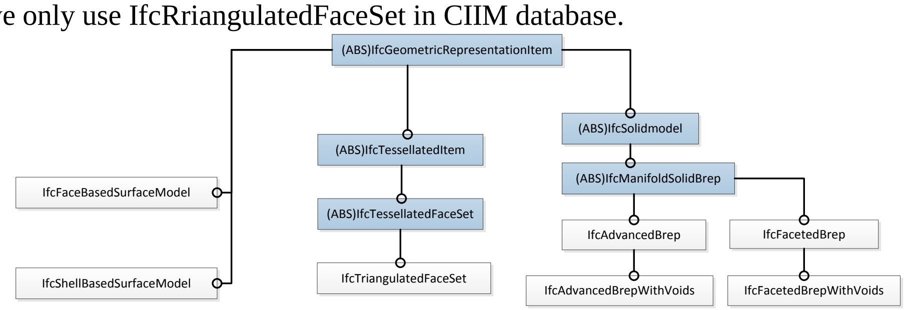

Figure 4: All Visual Geometry Class Definition of IFC4

Directly using STEP or IfcXML data format in a relational database will seriously affect the system performance, as has been proven by many studies (Lee G.et al, 2012). So we rewrite IFC's original definition of the geometry in the CIIM database to eliminate this efficiency bottleneck. The rewritten data is still seen as the geometrical properties of components, in which each attributes can completely express the final geometric shape after finishing the geometry. And it has a clear corresponding relationship with the definition of IFC. The input and output modules of IFC files in CEMIC will be coded with this correspondence. The rules for rewriting the IFC definition include the following two:

1) Keep the full semantics of the IFC geometric definition and the geometric definition elements;
2) Improve the integration degree of IFC geometry definition elements, and reduce the relevance across the database table among the geometry definition elements.

5. DISCUSSION, CONCLUSION, AND LIMITATION

In the paper, we proposed the concept of CEMIC to improve data interoperability between widely accepted ERP and BIM systems in AEC industry in an economical way. Compared with existing research, the features of CEMIC include:

(1) The greatest value of this paper is taking a step in exploring a new approach of data interoperability based on Open BIM.

A lot of studies have proposed methods to improve IFC in order to overcome the genetic defects that exist in IFC. IDM/MVD absorbed by buildSMART is a gradually matured technology based on these studies, and on IFD also. In support of such technologies, IFC is more likely embodied in a standard framework, which guides BIM model data interoperability, rather than confined to generating single data content and data format. The openness concept of Open BIM and rich class definition of IFC provide more options of technical solutions for data interoperability of BIM models. This paper does not follow a standardized STEP or ifcXML data format to explore the usage or class definition extending of IFC, nor establishes a BIM database that corresponds to IFC-MVD data file according to simple data mapping. Instead, the paper employs a variety of IDM/MVD analysis to propose a new approach for using the IFC class definition flexibly. This approach starts from the actual data interoperability requirements of BIM from CEMIC, aiming at achieving the data interoperability required by PMIS/ERP based on CIIM database. This method reclassifies 3D geometry definition of IFC as parametric classes and visual classes, and these two types of data coexist in the CIIM databases: constitute CIIM parametric data sets and visual data sets respectively. Through the complete parametric data sets, CIIM can provide full parametric BIM model data for application software to meet the need of model editing. Furthermore, using triangle facet definition, which is provided by IFC4 as the only form of the 3D geometric data definition in visual data sets, CIIM enables the multi-dimensional visualization capability that CEMIC supports to be used by PMIS/ERP as a web browser plug-in with light code set.

(2) The implication of providing software with full parametric BIM models is not merely to enable model editing. More importantly, it allows BIM software that receives the model data from CIIM to cut the overlapping components in 3D models and meet the professional requirements when obeying the rules within the professional scope. CIIM database can cover the most application software needs in 3D geometric shape. It not only eliminates the two aforementioned defects of IFC, but it also avoids software vendors and end users from being confused when multiple MVD subsets are needed (as required to support 50 IFC different output files will not be an easy task no matter for the software vendor or the end user).

However, since CEMIC prototype is still under development, the preliminary testing in the prototype development can only verify the feasibility of the proposed technical solution. We will further verify the effectiveness of CEMIC after running CEMIC experimental data.

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