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Research Article

Developing an IFC-Based Database for Construction Quality Evaluation

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Quality evaluation and control are increasingly important concerns in construction projects. Construction quality evaluation, as a systematic method, must be discussed in light of quality information extraction and storage, while a traditional construction quality control program cannot meet these requirements. In moving beyond quality indicators to evaluate quality performance that is comparable across construction entities, two fundamental factors must be considered: quality information standardization and multiquality data integration. The purpose of this study is to extend the interoperability of a construction quality database in the evaluation process by employing the industry foundation classes (IFC) data model. Taking a cast-in-place steel-concrete structure as an example, this study explores the implementation of building information modeling (BIM) in quality management and proposes integrated solutions to improve current quality management processes with the assistance of an IFC-based working environment. To better utilize the performance of the BIM model and database on construction quality control, various BIM-based evaluation frameworks are proposed. Also, this paper discusses how these IFC and neutral network models operate together to facilitate construction quality management. Project participants can better understand quality progress and collaborate more effectively, thanks to a visualized data format. The objective of evaluating the proposed model is to understand the effectiveness of an IFC-based database when implemented in practice. A questionnaire was developed considering the opinions of construction firms and design institutes regarding identified factors. In designing an IFC-based quality database, the method proposed in this study reduces the complexity of the database substantially and improves quality evaluation efficiency.

1. Introduction

Quality management is an approach to management that improves the effectiveness, flexibility, and competitiveness of an entity or project [1]. The notion of quality and its importance to the construction industry has been an area of great concern for many years [2]. The construction industry is widely criticized for low-quality delivery of construction projects, especially in terms of finished products, as well as for the processes used during the project design and construction stages [3]. Significant time and costs can be spent correcting problems during the snagging process, and most projects either suffer from time overages, cost overages, or both. Shao and Fu [4] suggested that the lack of an integrated evaluation method and a poor attitude towards quality on behalf of engineering stakeholders can lead to snagging problems.

In the construction industry, successful and long-term implementation of quality programs has been hampered by the fact that, unlike safety, no single measure and integrated expression of quality is applicable to the lifecycle of construction projects. Past attempts to monitor quality within construction have focused on identifying key factors because quality is subjective: what one person may accept as high quality may be considered insufficient by another. In addition, previous efforts have evaluated quality via key factors, such as the number of punch list items, the number of requests for information, or the number of callbacks for projects. The problem with only focusing on quality factors or indicator selections is that it is impossible to connect quality factors with the given attributes of a construction project, especially in terms of locating and distinguishing indicators of unsatisfactory quality associated with a specific structural element. Therefore, a comprehensive approach to indicator analysis integrated with multidimensional data is required to better understand quality management in the evaluation process. Furthermore, to go beyond quality indicators and evaluate quality performance that is comparable across construction entities, two processes are paramount: quality information standardization and multiquality data integration.

Quality evaluation and control represent increasingly important concerns for project managers. Construction quality evaluation as a systematic method must be discussed in light of quality information extraction and storage, whereas a traditional construction quality control program cannot meet such requirements [5]. Building information modeling (BIM) has gained popularity in the AEC industry [6]. BIM is a new technology that can control the construction process, construction conditions, and model links to resolve communication problems between relevant parties. Due to the consistency of design data and quality data, the potential of BIM implementation has been supported in quality management, namely, when presenting multidimensional data [7]. Nepal et al. [8] found that the rapid development of BIM has cultivated numerous opportunities for design and construction.

To effectively retrieve and utilize multidimensional information in construction quality evaluation via BIM, industry foundation classes (IFC), an international standard in BIM modeling, can be used to share data [9–11]. However, IFC standards do not currently accommodate entities with unstructured quality-related information or relationships involved in the quality database. This study seeks to realize the requirements of visualization and data integration in construction quality evaluation. Specifically, it applies the visual evaluation method to render the evaluation process more effective and convenient in identifying quality problems while providing comprehensive, reliable data resources for quality management of construction enterprises and construction administrators. These developments can further improve quality management, playing an important role in the standardization, digitization, and informatization of construction project management. Finally, the proposed method was evaluated by construction quality management specialists.

2. Related Study

BIM technology offers new approaches to construction quality evaluation; however, unified standards for the development of a quality system are lacking [12], as not all quality information can be integrated into a single model due to different data formats that may be tied to other data resources, such as quality records or design specifications. To overcome this limitation, IFC presents a solution to integrate and standardize all quality information, particularly with respect to user-required data mapping mechanisms [13].

Due to the absence of unified standards across application fields, the integration of different quality information sharing systems between databases is poor [14]. Currently, IFC data are managed by a file system, including files in ifc [15] and ifcXML [16] formats. Recently, studies on database storage of IFC data have been conducted to overcome deficiencies in file-based storage with some achievements. Since the traditional database structure does not support storage of object-type data, conflicts between a relational database structure and IFC element features are unresolved [17]. Therefore, the main goal and contribution of this paper lie in the creation of an IFC-based database consisting of qualitative quality data that can serve as the basis for construction evaluation management. Moreover, by designing this database, a few tables can store all IFC instances without the need to create a table for each entity in IFC; this feature significantly reduces the complexity of the database and improves quality evaluation efficiency. On the contrary, unified standards for the development of a quality system are lacking [12], as not all quality information can be integrated into a single model due to the different data formats which may be linked to other data resources, such as quality records or design specifications. Mazairac and Beetz [18] believed that the large amount of information generated by the integration of models from different disciplines in a common virtual model also increases the size and complexity of data repositories. Industry foundation classes (IFC) seem to be a solution to integrate and standardize all quality information, particularly with respect to data mapping mechanisms required by the user [13].

Meanwhile, because there are no unified standards across the application field, the integration of different quality information sharing systems between databases is poor [14]. Currently, IFC data are managed by file system, including ifc [15] and ifcXML [16] format files. In recent year, studies on database-based storage of IFC data have been continuously carried out to overcome the deficiencies in file-based storage and have made some achievements. But since traditional database structure does not support the storage of object-type data, the conflicts between relational database structure and element features in IFC are still not resolved [17]. Therefore, the main goal and contribution of this paper lies in the creation of an IFC-based database consisting of qualitative quality data that can become the basis for construction evaluation management. Moreover, by designing the database, a few tables can be used to store all IFC instances and no more need to create a table for each entity in IFC, which not only significantly reduces the complexity of the database but also improves quality evaluation efficiency.

3. Methodology

This study aims to extend the interoperability of construction quality database in evaluation process by employing the industry foundation classes (IFC) data model. To achieve this, by referring to construction quality inspection and acceptance specification, we connect IFC data and BP neural network algorithm to construction quality evaluation to improve the efficiency and accuracy of evaluation. Considering the large number of quality evaluation database created in BIM domain, we focus on two scenario analysis process: (1) to realize specifically the IFC data mapping in construction quality domains which include evaluation indicators, quality score, and quality grade; (2) to realize all quality data involved in evaluation need to be classified and unified encoded to construct the quality evaluation database. Then, we try to discuss the logical framework and physical structure design of the database to integrate the heterogeneous construction quality data. Finally, we use a case study to verify the methods proposed in this study.

In previous studies, researchers have developed their own approaches to obtain the quality data of construction projects. Some studies focus on limited elements such as doors, windows, and spaces with corresponding descriptive information. Many of these approaches are practice specific. However, for BIM projects, there is a need to create quality data for all model elements and to create it to standards that allow structured data to be utilized efficiently and reliably by the evaluation process. In this study, we define quality data in IFC-based parameter fields and convert related information directly into IFC and BP models. This means we aligned evaluation information with open international standards IFC (ISO 16739:2013) according to which the BP neural network model can be trained and tested as expected, and then the approved model can be used to predict the construction quality score. This process has the potential to reduce the need for collecting manually big data of construction projects, particularly as more design software adopt open principles. Finally, this approach obtains the quality score and grade according to the open data to be mapped.

We created a workflow (Figure 1) illustrating the prototypical framework to build a construction quality database with essential data sources from graphical evaluation, parameter evaluation, IFC model, construction field data collection, and user information. To collect reliable data, the approach depended on effective IFC file extension for construction quality and adding a description to the construction site to support the corresponding operations (extract, transform, and load) by users. Therefore, mapping adds the ability to take a piece of structured data that already exists in the BIM model and put it into a unified field related to construction quality. Any piece of IFC data can therefore automatically be placed into a corresponding evaluation program. Furthermore, this paper discusses the classification and encoding approach to enter data into the evaluation database, which uses the conceptual model proposed in this study to model the input data required and produced in the previous stage from a construction quality perspective to achieve integrated construction quality management.

4. Quality-Oriented Evaluation Model Based on IFC and BP Neutral Network

4.1. Selection of Construction Quality Evaluation Index. To compute the value of quality content, it is important to establish an evaluation indicator system that accounts for performance testing, quality records, allowable deviation, and appearance quality. As quality has no specific definition, briefing documents must clearly outline the necessary quality level. Official documentation, standards, and specifications can aid in the appraisal of construction entities. Taking the cast-in-place steel-concrete structure as an example, referring to the *Acceptance Standard for Construction Quality of Constructional Engineering (GB 50300-2013), Acceptance Specification for Construction Quality of Concrete Structure Engineering (GB 50204-2015), Evaluation Criteria for Construction Quality of Constructional Engineering (GB/T 50375-2016)*, and work by Zhu and Zhang [19] and Fu et al. [20], 16 quality evaluation indicators were determined among the aforementioned four categories (i.e., performance testing, quality records, allowable deviation, and appearance quality) to reflect the overall appraisal of construction quality, represented by the 17th indicator as shown in Table 1.

4.2. Overall Appraisal of Construction Quality in BP Neural Network Model

4.2.1. Evaluation of Model Structure. A single hidden layer neutral network is adopted in this paper. The evaluation model includes an input layer, single hidden layer, and output layer. The index values in Table 1 can be used as the input parameters for the BP neural network model, so the number of nodes in the input layer is 16. The quality scores (a hundred-mark system) of the steel-concrete structure can be obtained through the evaluation model; thus, the number of nodes in the output layer is 1. The number of nodes in the hidden layer is usually determined by a formula $L = \sqrt{m+n} + a$, where L is the number of nodes in the hidden layer (a positive integer), m and n are the number of nodes in the input and output layer, respectively, and a is a constant between 0 and 10. According to this formula, the number of nodes in the hidden layer of the BP neural network model is a constant between 5 and 14. The constants in this range must be tested, and the constant corresponding to the optimal training result is ultimately selected as the number of nodes.

4.2.2. Sample Data Classification. Classification is based on the initial value of each indicator as shown in Table 2. The first-level indicators were marked using a 10-point system based on experts' opinions. The indicator values in the 2nd level were obtained from *Construction quality acceptance records* of the inspection lot in the steel-concrete structure. The 3rdlevel indicator values represent the appearance quality of structural entities, obtained from *Construction appearance-quality acceptance record*s in the inspection lot. In terms of construction quality acceptance, observation methods are normally used to verify whether the evaluation indicators satisfy specifications and design requirements. The 17^{th} indicator "overall appraisal" usually classifies the inspection results as either *Good* or *General*. This paper utilizes a percentage where the number of inspection sites labeled as *Good* occupies all sites to achieve a quantitative description.

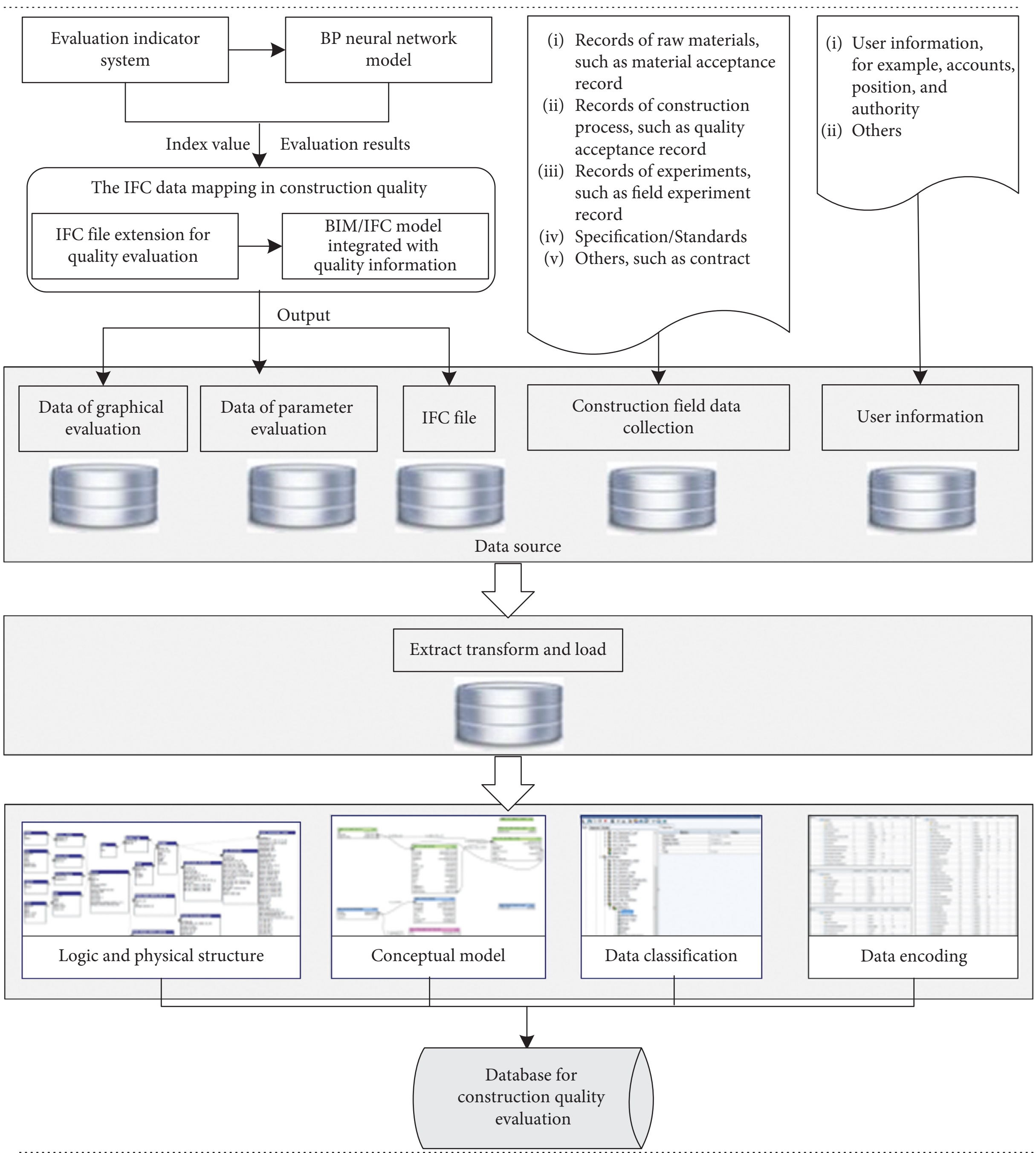


Figure 1: Method proposed.

4.2.3. MATLAB Implementation of the Evaluation Model. In this study, 24 groups of sample data were collected through investigation and surveys, as shown in Table 3. MATLAB R2016b software was employed to establish the construction quality evaluation model based on the BP neural network. The training situation and graphic outputs are shown in Figure 2. The processing time of the neural network was 15 seconds, and it achieved optimal output over 10706 rounds of training with a mean squared error (MSE) of $9.99 * e^{-9}$, gradient of $3.49 * e^{-5}$, and degree of fit reaching 0.99642. The expected values of the test samples were 86.15, 91.50, 89.80, and 96.30, respectively, and the predicted results were 86.33 93.02, 93.04, and 95.60. The absolute error was in the range of −0.7 to 3.2 with error rates of 0.21%, 1.66%, 3.61%, and −0.73%. The absolute value was less than 5%. The prediction results satisfied the precision requirements. According to *Evaluation Criteria for Construction Quality of Constructional Engineering* (GB/T 50375-2016), an overall appraisal of structural quality of 85 and above is rated as "Good".

4.3. IFC Data Mapping in Construction Quality Domain. In this work, a formalization structure is suggested for database tables to facilitate the exchange of IFC-based evaluation indicator information via the information

Table 1: Evaluation index for construction quality of reinforced concrete main structure.

No.	Evaluation indicator	Structural element	Evaluation item	Description of indicator
1	Concrete strength	Beam, slab, column, wall	Performance test	The concrete strength of the structure entity shall be reflected to meet the specifications and design requirements
2	Reinforcement cover thickness deviation	Beam, slab, column, wall		The measured deviation value of the cover thickness of longitudinal carrying bars in the structural entity is within the range of ±5 mm
3	Column cross section dimension deviation	Column		The measured deviation value of the sectional dimension of cast-in-place reinforced concrete columns should be within the range of (+10, −5) mm
4	Wall thickness deviation	Wall		The measured deviation value of wall thickness of cast-in-place reinforced concrete should be within the range of (+10, −5) mm
5	Beam depth/width deviation	Beam		The measured deviation value of the beam depth and width of cast-in-place reinforced concrete shall be within the range of (+10, −5) mm
6	Plate thickness deviation	Slab		The measured deviation of slab thickness of cast-in-place reinforced concrete shall be within the range of (+10, −5) mm
7	Completeness of raw material record	Beam, slab, column, wall	Quality records	The material qualification certificate, the incoming acceptance record and the reexamination report shall be complete
8	Completeness of construction record	Beam, slab, column, wall		The record of the working performance of premixed concrete, the concrete construction record, the reinforcement installation record and the construction quality check, and acceptance record shall be complete
9	Completeness of test record	Beam, slab, column, wall		The test report of concrete mix proportion, the strength report of concrete specimen, and the test report of steel joint connection should be complete
10	Axis deviation	Beam, column, wall	Allowable deviation	The measured deviation value of the axis position of structural element should not exceed 8 mm
11	Elevation deviation	Beam, slab, column, wall		The measured deviation value of storey height elevation shall be within the range of ±10 mm
12	Verticality deviation	Column, wall		The measured deviation value of height and verticality of component should not exceed 10 mm
13	Planeness deviation	Beam, slab, column, wall		The measured deviation value of the surface evenness of the component shall not exceed 8 mm
14	Crack	Beam, slab, column, wall	Appearance quality	Any defects that affect the transmission performance of the structure should not exist in joints of the entity
15	Joint reliability	Beam, slab, column, wall		
16	Exposed reinforcing steel	Beam, slab, column, wall		Any serious internal steel exposure should not exist in the structure entity
17	Overall appraisal			Integrate 16 indicators to evaluate construction quality

provider (i.e., quality-related information stored in the IFC model) and information receiver (i.e., heterogeneous database integration system). All quality evaluation data are uniquely identified via unit ID, which maintains the information exchange between the IFC model and database tables. Under this condition, a new type of ID is necessary along with mapping between process resources and IFC objects to support cost-information exchange. Therefore, IFC data mapping and extension comprise a primary step to link evaluation information generated in the IFC model with database tables.

As shown in Figure 3, in terms of standard level, quality evaluation information has to be extended and expressed in IFC standards. In this process, EXPRESS-G as a graphical modeling notation is developed within STEP and used for IFC definition. It is used to identify classes, the data attributes of classes, and the relationships that exist between classes. In terms of the application level, Revit software for BIM was employed in this paper to describe quality attributes as additional parameters in the BIM model, thereby integrating evaluation information in IFC documents as shown in the exported IFC validation document.

4.3.1. IFC Extension Process Based on AttributeSet of Construction Quality. Evaluation information related to

Table 2: Classification of construction quality evaluation indicators.

Category	Index	Item
First category	Concrete strength	Performance test
	Completeness of raw material record, completeness of construction record, completeness of test record	Quality records
Second category	Reinforcement cover thickness deviation, column cross section dimension deviation, wall thickness deviation, beam depth/width deviation, plate thickness deviation	Performance test
	Axis deviation, elevation deviation, verticality deviation, planeness deviation	Allowable deviation
Third category	Crack, joint reliability, exposed reinforcing steel	Appearance quality

Table 3: BP neural network sample data.

Evaluation index no. (Ei)	Ei1	Ei2	Ei3	Ei4	Ei5	Ei6	Ei7	Ei8	Ei9	Ei10	Ei11	Ei12	Ei13	Ei14	Ei15	Ei16	Ei17
1	10	3.07	4.82	6.6	5.4	5.33	10	10	10	3.77	3.95	4.91	3.68	1	1	0.9	96.3
2	10	2.94	4.5	5.92	5.1	5.29	9	10	9	3.42	2.6	4.55	5.11	0.95	0.9	1	94.9
3	8.5	3.88	6.27	5.5	7.19	5.5	8.5	8	8.5	5.26	6.1	7.33	6.54	0.8	0.85	0.8	83
4	8.5	4.17	6.4	7.39	6.4	6.96	7	8.5	8	4.92	5.97	8.5	7.29	0.8	0.92	0.8	79.75
5	7	4.28	6.97	7.21	6.99	8.1	8	8	7	7.2	8.9	8.94	7.11	0.84	0.9	0.95	76.7
6	7.5	4.05	7.83	5.5	7.93	5.22	7	9	8.5	6.91	9.22	9.59	7.36	0.82	0.88	0.8	77.75
7	8	4.39	7.1	8.87	8.2	9.24	8.5	8	7	7.09	8.36	8.91	6.8	1	0.91	0.95	79.05
8	10	2.97	5.15	4.2	4.96	5.52	9	9	9	3.42	4.22	3.88	4.07	0.8	0.95	0.9	93.15
9	9	4.05	7	7.27	6.9	6.08	8	9	7	6.18	7.01	9.12	7.03	0.9	0.84	0.8	80.1
10	10	3.31	4.91	6.11	4.92	8.34	9	10	10	3.81	4	6.21	5.7	0.85	0.9	0.86	92.3
11	8.5	4.02	5	6.6	4.37	5.13	8.5	9	8.5	5.3	6.12	7.52	6.21	0.8	0.8	1	85.15
12	7	4.67	7.44	5.59	7	7.19	7	8	7	7.1	8.76	9.71	7.6	0.85	0.9	0.9	73.9
13	9	3.04	5.11	4.9	5.34	4.98	8.5	10	8.5	4.05	2.92	5.8	4.5	0.82	0.85	0.8	89.95
14	8.5	3.95	6.44	3.92	7.02	5.71	9	10	10	4.3	6.97	7.17	6.22	0.9	0.9	0.8	87.65
15	9	4.01	6.67	5.5	5.41	7.32	7.5	8.5	8.5	3.59	6.16	6.93	5.63	0.95	0.94	0.85	86.15
16	10	3.4	5.66	4.74	6	7.99	10	10	9	4.89	5.05	5.3	4	0.85	0.8	0.9	91.5
17	9	3.25	7	8.81	5.03	6.77	9	10	8.5	7.29	8.17	8.69	7.6	0.8	0.95	0.85	85.35
18	10	3.5	7.83	5	7.95	5.2	10	9	9	4	5.26	5.61	3.9	0.9	0.9	1	91.85
19	10	3.44	5.16	6.11	6.81	4.73	10	10	10	6.5	9.73	9	7.4	0.8	0.82	0.8	88.3
20	8.5	4.1	5.55	5.45	5.17	6.59	9	10	9	6.11	6	7.95	7.03	0.85	0.8	0.95	85.35
21	9	4.34	6.77	6.65	7	8.09	10	10	10	6.08	9.29	9.19	7.83	0.9	1	0.9	86.6
22	10	3.91	6.71	8.19	7.22	4.54	10	10	9	4.07	3.87	4.96	6.6	0.85	0.8	0.9	89.8
23	9	3.19	6.9	4.15	5.02	5.54	10	10	9	5.01	8.8	8.36	7.73	0.85	0.8	0.8	87
24	8.5	3.02	3.95	5.9	5.06	7	9	10	9	5.5	8.14	7.9	7.11	0.93	0.85	0.9	86.15

construction quality based on the IFC file extension describes the quality of the beam, plate, column, and wall, which are collectively regarded as the entity in the IFC model. This evaluation information is equivalent to entity characteristics described by the IFC standard. The existing IFC4 standards already include standardized definitions of beams, plates, columns, and walls. In this paper, the extension mechanism based on PropertySet was utilized to extend the quality attributes. The property set is a container class that holds specific properties within an IFC resource file. This extension approach was adopted because it was unnecessary to change the system structure of the original IFC standard, and the extension satisfied the requirements of incorporating evaluation information into the IFC standard. This approach was therefore convenient and feasible; the specific extension process is displayed in Figure 4 and proceeds as follows. First, the corresponding entity, attribute, and their relationship in the IFC standard must be determined according to the characteristics of quality evaluation in the structure construction. Second, attribute sets must be categorized according to different characteristics of the entities. Finally, attribute sets must be defined in terms of construction quality to complete the extension process of evaluation information based on the IFC.

(1) Identification of IFC Entities and Properties. The correspondence between the structural elements including beam, plate, column, wall, and the IFC entities are shown in Table 4. Each entity in a database is described by certain properties. Properties refer to pieces of element information on an entity required for processing via quality evaluation. Each quality evaluation indicator and overall appraisal calculated by the BP model align with the entity attributes. The overall appraisal also applies to its child elements' property set.

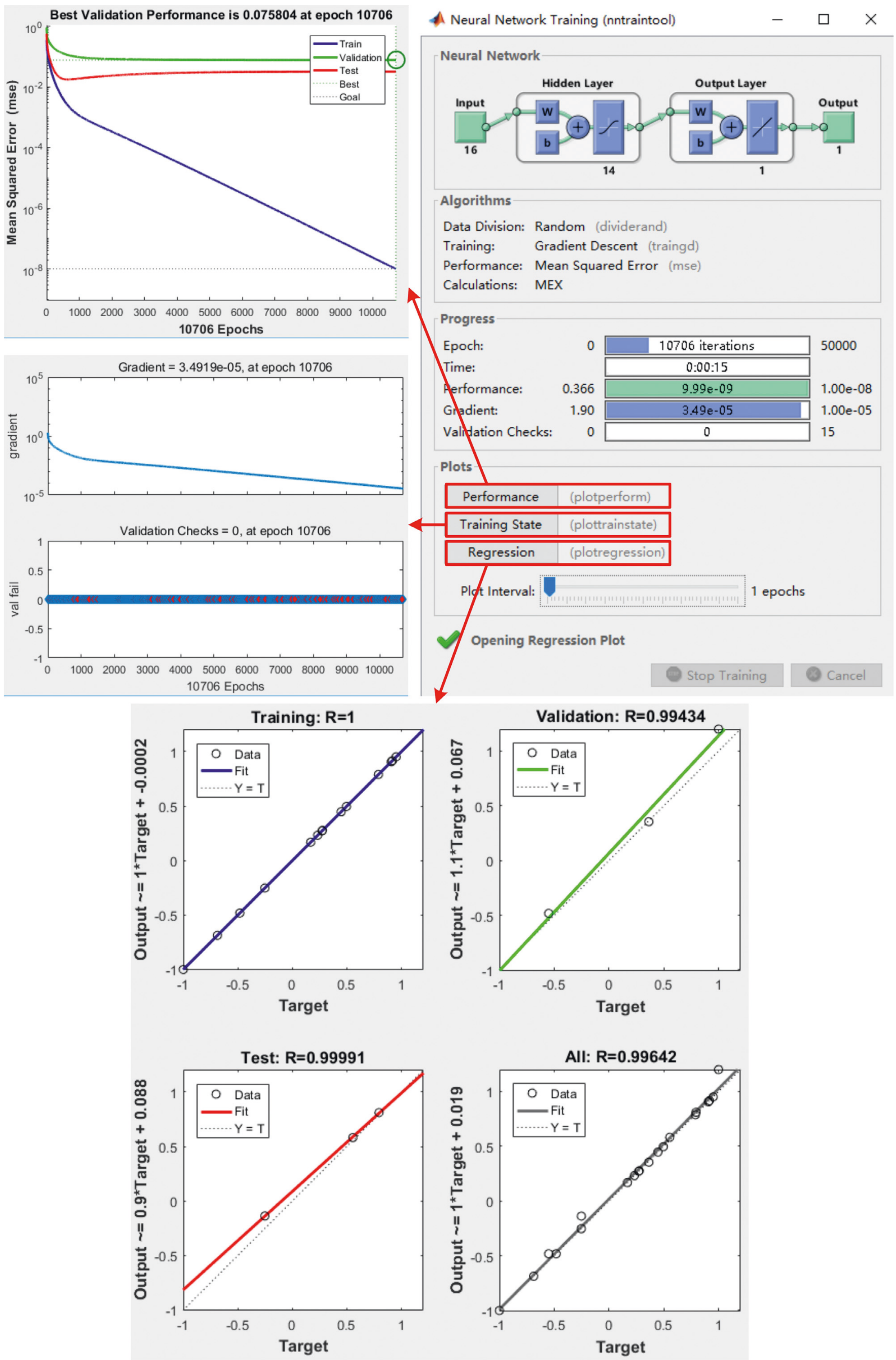


Figure 2: BP neural network training.

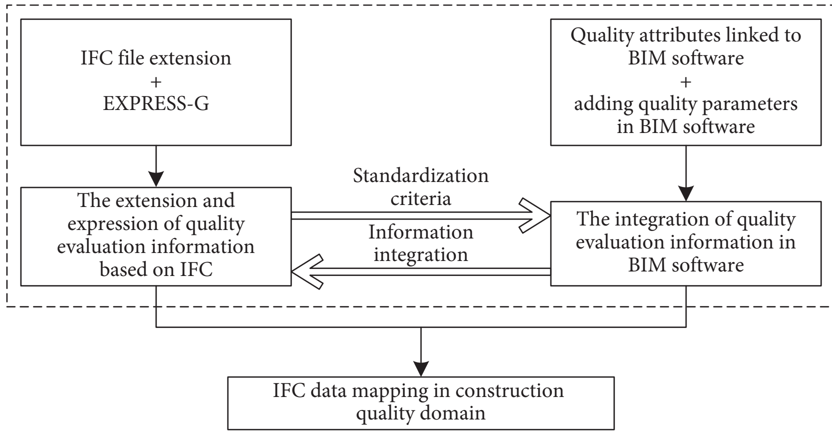


FIGURE 3: Implementation of IFC data mapping.

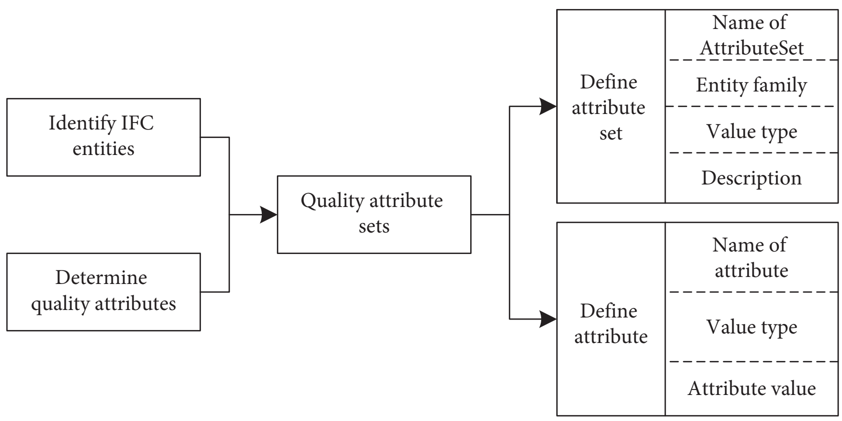


FIGURE 4: IFC extension process based on AttributeSet

(2) Determination of IfcPropertySet. A property set is a collection of attributes belonging to a particular entity. The quality attributes in this paper describe quality characteristics of structural elements; thus, IfcPropertySet is determined by four categories including PSet_OnsiteReinforcedConcreteBeam, PSet_OnsiteReinforcedConcreteSlab, PSet_OnsiteReinforced ConcreteColumn, and PSet_OnsiteReinforcedConcreteWall. The properties of each property set can be selected by referring to each evaluation indicator and structural element in Table 1.

(3) Definition of IfcPropertySet. Per the IFC standard, major entities of structure elements including columns, walls, beams, and plates are separated into a general definition and a specific specialization to represent the standard entities for a parametric exchange of shape, material, and underlying element type [21]. Some property sets, such as the 17 quality attributes listed in Table 1, are excluded from the IFC specification and lack a predefined set of properties indicated by structure element assignment. The definition of an IfcPropertySet includes a name, entity family, applicable type of value, and description, as shown in Tables 5–8. A definition and illustration of how IFC properties can be used to structure external library quality information is shown in Figure 5, in which the property type and value are determined by the quantized results of the quality evaluation indicators in Table 3. Various properties of the IFC entities are indeed a set of instances which are encapsulated in an IfcPropertySet entity. IfcPropertySet is a container class that holds properties within a property tree. This allows adding user-defined properties to IFC elements or types. In this study, four property sets "PSet_OnsiteReinforced ConcreteBeam," "PSet_OnsiteReinforced ConcreteWall," "PSet_OnsiteReinforced ConcreteColumn," and "PSet_ OnsiteReinforced ConcreteSlab" within the property set are defined as part of the standard. In this example, an on-site reinforced concrete model is structured as an instance of IfcPropertySet, and its properties are instances of the subclasses of IfcProperty. IfcObjectReference and IfcLibraryReference reference the property value.

TABLE 4: The correspondence between structural elements and IFC entities.

Mainbody structural component	Beam	Slab	Column	Wall
IfcEntity	IfcBeam	IfcSlab	IfcColumn	IfcWall

4.3.2. Expression of Quality Evaluation Information Based on IFC. After completing the IFC extension of quality

Table 5: The definition of IfcPropertySet of cast-in-place reinforced concrete beam.

AttributeSet name	PSet_OnsiteReinforcedConcreteBeam
Entity family	IfcBeam
Application type of value	IfcBeam/Userdefined/OnsiteReinforced ConcreteBeam
Description	Properties in this property describe quality of the on-site reinforced concrete beam, which can provide the basis for construction quality evaluation

Table 6: The definition of IfcPropertySet of cast-in-place reinforced concrete slab.

AttributeSet name	PSet_OnsiteReinforcedConcreteSlab
Entity family	IfcSlab
Application type of value	OnsiteReinforcedConcreteSlab
Description	Properties in this property describe quality of the on-site reinforced concrete slab, which can provide the basis for construction quality evaluation

Table 7: The definition of IfcPropertySet of cast-in-place reinforced concrete column.

AttributeSet name	PSet_OnsiteReinforcedConcreteColumn
Entity family	IfcColumn
Application type of value	OnsiteConcreteColumn
Description	Properties in this property describe quality of the on-site reinforced concrete column, which can provide the basis for construction quality evaluation

Table 8: The definition of IfcPropertySet of cast-in-place reinforced concrete wall.

AttributeSet name	PSet_OnsiteReinforcedConcreteWall
Entity family	IfcWall
Application type of value	OnsiteConcreteWall
Description	Properties in this property describe quality of the on-site reinforced concrete wall, which can provide the basis for construction quality evaluation

evaluation information, it is necessary to further describe the quality information. EXPRESS-G is a graphical modeling notation developed within STEP and used for IFC definition. In this study, it was used to identify the data attributes of IFC quality classes and the relationships that exist between classes as shown in Figure 6 [22–25]. Considering the five entity classes of IfcProduct, IfcElement, IfcBuildingElement, IfcPropertySetDefinition, and IfcPropertySet, an inheritance relationship can be expressed by thick lines between two adjacent entity classes, with circles directing to its subclasses. The relationship between IfcPropertySet and IfcEntity is established by IfcPropertySetDdfinition; thus, the construction quality condition of IfcEntity can be expressed by the construction quality information contained in IfcProperty. In the IFC standard, the entity IfcBulidingElementType and its subtypes are used to describe the type of components. However, the predefined type classification in the IFC entities is too simple to cover the quality-related information which has been listed in quality standard for construction projects. Therefore, it is necessary to use the entity IfcPropertySet, which is a container class that holds dynamically extensible properties as a property set. The contained properties in the property set are described by using the entity IfcProperty which is the abstract supertype of the entities IfcSimpleProperty and IfcComplexProperty. IfcSimpleProperty is used to define a single property object, and its subtypes can be used to define various properties. IfcComplexProperty is used to define complex properties that may logically contain other properties. IfcProperty covers two subtype classes, IfcComplexProperty and IfcSimpleProperty, of which IfcSimpleProperty includes six subclasses. The contents in the elliptical dashed box in Figure 6 represent the quality properties defined previously, which are linked to PropertySet OnsiteReinforcedConcrete Beam/Column/Slab/Wall through thin full lines as explicit properties. The properties are assigned enumerated values or simple values that are connected to PropertySet by thin full lines.

Accordingly, an IFC-based quality evaluation information library was constructed to support building element compositions to be mapped to identify IFC objects such as IfcWall, IfcSlab, IfcBeam, and IfcColumn. In this study, the IFC model was proposed for integration with a quality-oriented database. Several external libraries, including structural elements and evaluation results, were loaded into the database as IfcLibrary and IfcPropertySet instances. The quality information collected from acceptance records and inspection files with calculation results in the BP neural network were used as data sources. In the expression process, the cast-in-place reinforced concrete elements were defined as property sets (IfcPropertySet) with inspection and evaluation records representing external product libraries (IfcLibrary). Seventeen properties such as concrete strength were defined as IfcSimpleProperty. The property values were defined by either IfcPropertyEnumeratedValue or IfcPropertySingleValue.

5. Integrated Database Construction for Construction Quality Evaluation

Data must be used accurately and effectively to enhance construction quality evaluation. If such data are integrated and visualized, then a reality-based virtual database environment can be constructed, which can then be used by an evaluation simulator and construction manager. Besides the quantitative information discussed above for mapping in the BIM model, the database should also include unstructured data, such as the BIM model (or drawings), site-quality documentations, and image and video records. These sources can be used to support visual display or auxiliary references for construction quality evaluation. To classify the structure of evaluation data reasonably, one must first identify the database composition according to the characteristics and functions of evaluation

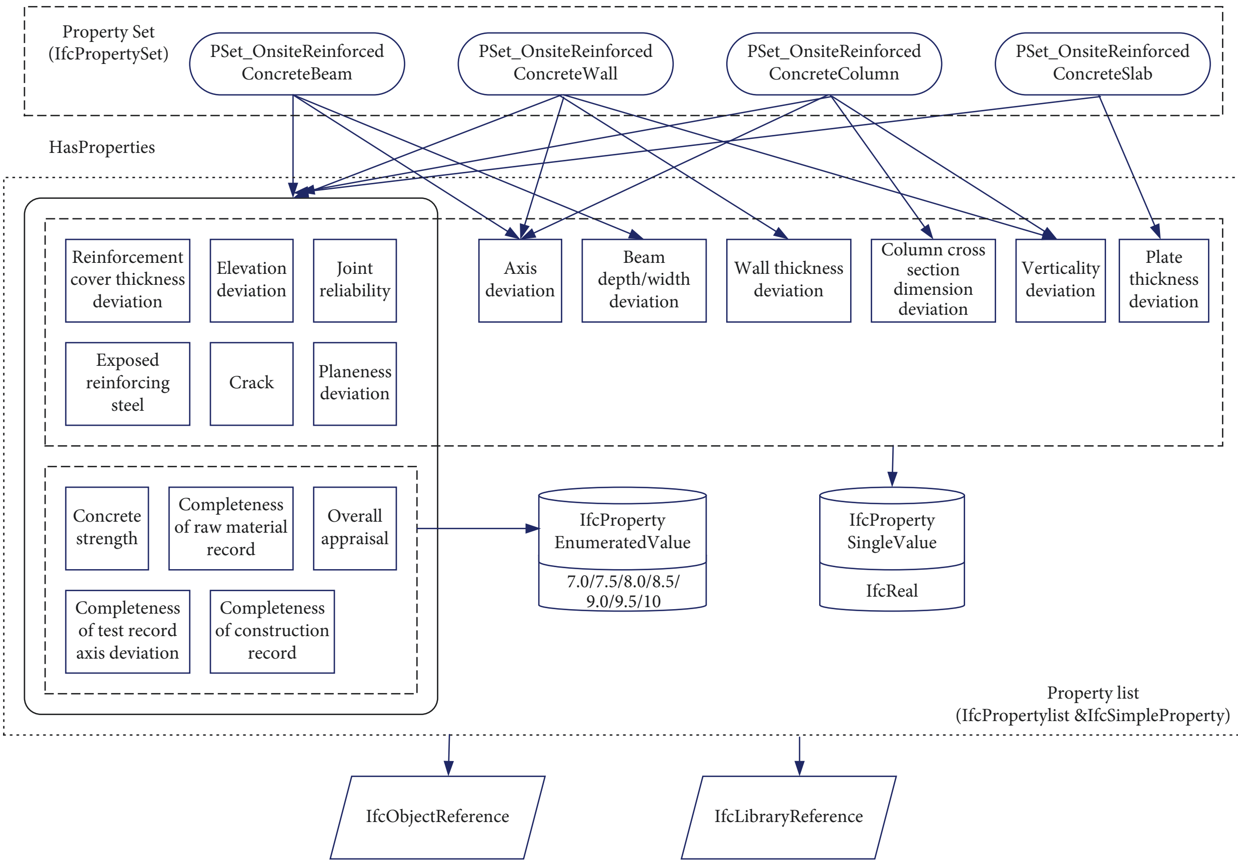


Figure 5: Instance model of IfcPropertySet

data. Three general categories were used in this study: (1) graphical evaluation data (i.e., the foundation of construction quality evaluation), normally obtained from views (or drawings) in the BIM model; (2) parametric evaluation data, which captures parameterized information with which the BIM model can reflect on the basic situation and quality status of a structure entity along with evaluation information that can be quantified in other construction quality record documents or described in a simple text format; and (3) other evaluation data involving raw materials certificates, on-site test records, construction quality acceptance records, contract documents, design documents, and related standard quality records as well as IFC documents, pictures, and video records, all of which provide reference material for construction quality evaluation.

5.1. Data Classification for Construction Quality Evaluation. Data classification is the process of organizing data into categories for effective and efficient use. With a complex composition and range of sources, the visual evaluation of construction quality consists of data with different storage structures. In Figure 7, graphical evaluation data are a type of unstructured data. Parametric evaluation data can be expressed via a two-dimensional logic relational table structure and extracted from attributes described in BIM models, which fall under structured data. Other evaluation data are usually classified to be graphical data and other data including pictures and audio and video form, belonging to unstructured data. These two kinds of data are integrated to support the evaluation results. Graphical evaluation data are a type of unstructured data. Parametric evaluation data can be expressed via a two-dimensional logic relational table structure, which falls under structured data. Other evaluation data are usually stored in documents, pictures, and audio and video form, belonging to unstructured data. According to the differences in storage structures for quality evaluation data, structured and unstructured data only apply; no semi-structured quality evaluation data exist (Figure 7).

5.2. Data Encoding for Construction Quality Evaluation. The approach to data encoding in this study relied on the process of converting quality-related data into a specific format using a given sequence of characters for convenient data storage and interpretation of the fractional project, constituent project, inspection lot, IFC element (i.e., structural element and evaluation indicator), and quality-related files, respectively.

5.2.1. Fractional Project and Constituent Project. Fractional project and constituent project information was encoded in the form of two letters. The first one is the entity title initial. For example, Fd represents *Foundation Engineering* and St represents *Structure Engineering* as shown in Table 9.

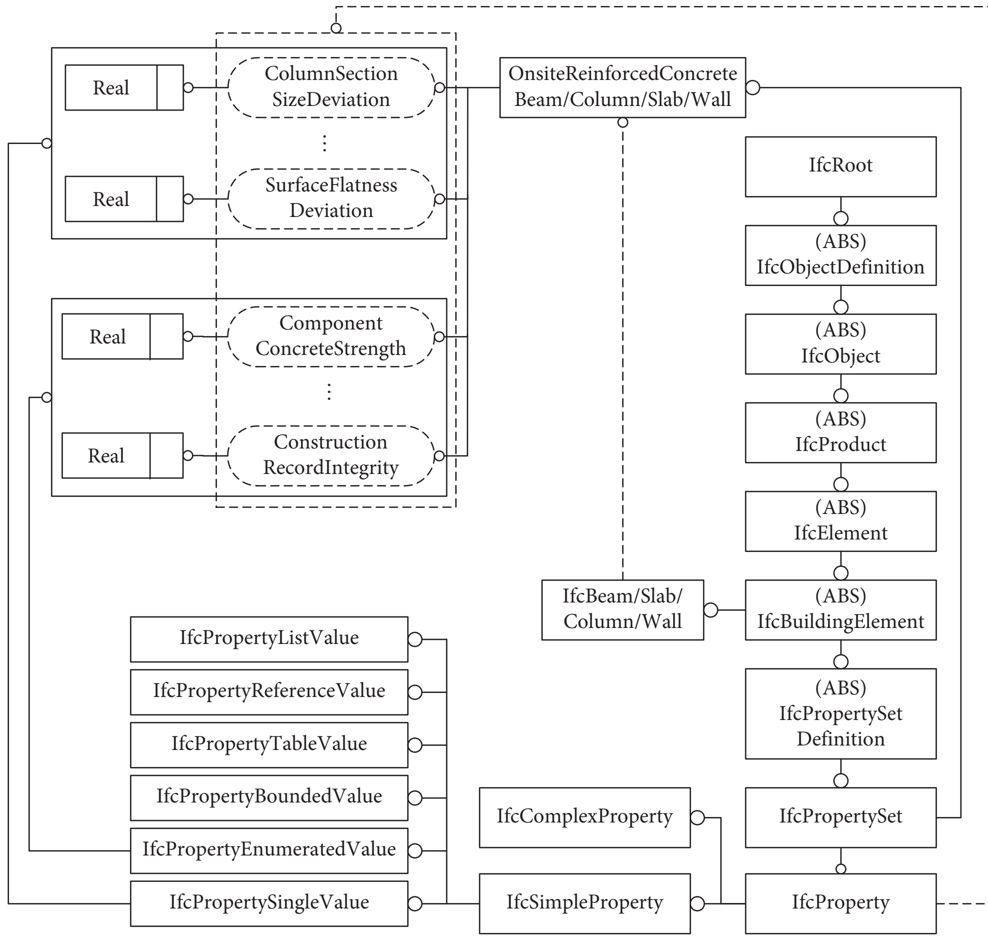


Figure 6: EXPRESS-G diagram for quality evaluation information.

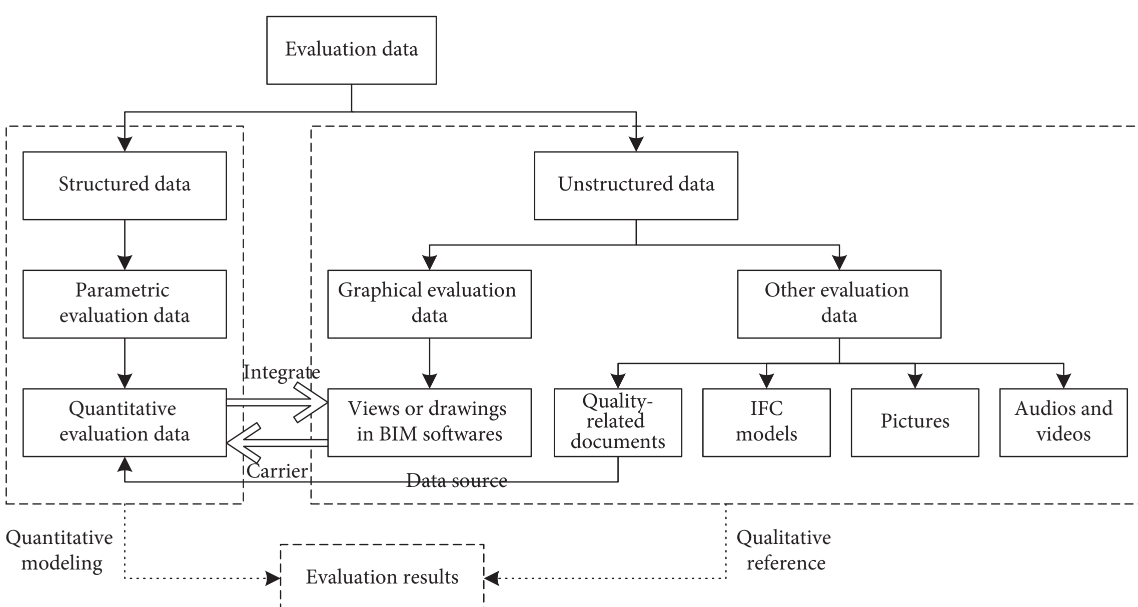


Figure 7: Data classification of quality evaluation.

5.2.2. Inspection Lot. Inspection lot information was encoded using 11 random letters and numbers in four sections connected by short lines. The first section is a four-digit number whose first two and last two numbers, respectively, represent the starting number and ending number of an inspection lot. The second section is a four-digit number whose first two and last two numbers, respectively, represent the starting number and ending number of the vertical axis of an inspection lot. The third section is a two-digit capital letter that represents the starting number and ending number of the horizontal axis of an inspection lot. The fourth section is a capital letter, representing either *beam*, *plate*, *column*, *wall*, or *all* by B, S, C, W, and A, respectively, according to the actual acceptance of an inspection lot; see Figure 8 for the encoding form.

5.2.3. IFC Element (Structural Element and Evaluation Indicator). During database construction, every IFC object is encoded with a name and description about the concepts, and a globally unique ID (GUID), that is, a 16-byte (i.e., 128-bit number) commonly split up into several fields of varying lengths and written in groups of hexadecimal characters. Per the IFC standard, *IfcGloballyUniqueId* as an attribute defined in entity *IfcRoot* holds an encoded string identifier that uniquely identifies an IFC object. To recognize different indicators attached to one IFC object, unique serial numbers must be assigned to evaluation indicators as well. This task involves a combination of five random letters and numbers in the form of two sections connected by short lines. The first section consists of three capital letters, organized by the initial letter of each attribute name in Table 10. The two-digit number in the second section is set as 01, 02, and 03 sequentially to identify the same evaluation indicators applied in different inspection lots as shown in Table 10.

5.2.4. Quality-Related Files. This step adopts a two-section form of six capital letters and numbers connected by short lines. The first section is a group number consisting of four letters or an alphanumeric code representing a file name extension, supplemented with the letter "X" if the code has fewer than four digits. The second section is a two-digit number used to distinguish files in the same format, numbered sequentially with 01, 02, and 03 as shown in Table 11.

5.3. Design for Conceptual Entity Model of Construction Quality Database. With regard to the visual requirements of construction quality evaluation and data characteristics in the database, entities and attributes are categorized into the following five entities: fractional project, constituent project, inspection lot, IFC element, and quality-related files. The first four consist of structured data about construction components and the quality acceptance workflow. Entity attributes of a quality-related file are considered unstructured data, mainly including graphical evaluation data and other types (Table 12).

After categorizing the entities and their corresponding attributes, it is important to consider the relationship between the entities and adopt a bottom-up strategy to designing the conceptual entity model in the quality database. The global entity-relationship (E-R) diagram is illustrated in Figure 9. The rectangle, ellipse, and diamond box, respectively, represent an entity, attribute, and relationship between entities in the diagram.

(1) One fractional project entity could be divided into a constituent project, denoted as a $1:n$ (one-to-many) relationship between these two entities; that is, one fractional project can be connected to multiple constituent projects whereas one constituent project belongs only to a specific fractional project.

(2) A constituent project entity and inspection lot entity are also connected in a $1:n$ relationship; that is, the evaluation of a constituent project requires inspection and testing of multiple inspection lots while every inspection lot is assigned to exactly one constituent project.

(3) One fractional project entity includes multiple IFC element entities represented as a $1:\mathrm{n}$ relationship; that is, one fractional project consists of multiple structural elements with corresponding property attributes from the IFC model while each structural element belongs to only one fractional project entity.

(4) An inspection lot entity and IFC element entity are connected in an $\mathrm{m}:\mathrm{n}$ relation: one inspection lot must be examined using multiple evaluation indicators while one evaluation indicator will be used and inspected for multiple inspection lots.

(5) A fractional project (or constituent project, inspection lot, IFC element) entity and related files entity are connected in a $1:\mathrm{n}$ or $\mathrm{m}:\mathrm{n}$ relationship; that is, the quality status of each fractional project (or constituent project, inspection lot, structural element, or evaluation indicator) is recorded in one or multiple quality files while each file can reflect the quality status of one fractional project (or multiple constituent project, inspection lot, structural element, or evaluation indicator).

5.4. Transforming Conceptual Data Model to SQL. When designing relational databases of construction quality evaluation, transforming the conceptual data model to candidate tables and their definitions in SQL requires a specific step. As illustrated in Figure 10, a major part of designing a relational database for construction quality involves dividing construction data elements and entities into related tables. In the process of construction quality management using this kind of quality information system, relationships between the tables are necessary to connect data in meaningful ways. The entities and relations in the E-R diagram in this study can be transformed into five relational tables (see Table 13, subtables 1, 2, 3, 4, and 10) comprising the fractional project, constituent project, inspection lot, IFC element, and quality-related files with

Table 9: Part of data encoding of fractional project.

Fractional project		Constituent project	
Name	Encoding	Name	Encoding
Ground foundation engineering	Fd	Reinforced constituent project	Rb
Structural engineering	St	Template constituent project	Tp
Decoration engineering	De	Concrete constituent project	Rc
Roofing project	Rf	Cast-in-place structure constituent project	Cs
Installation project	In		

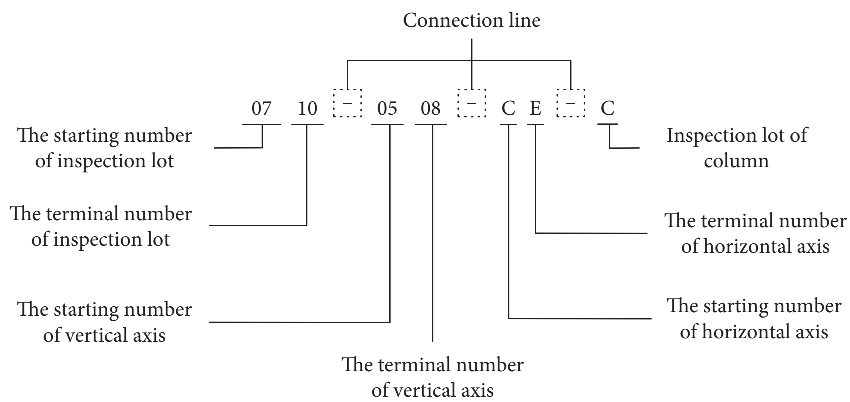


Figure 8: Example encoding of inspection lot of Column.

Table 10: Encoding of valuation indicator.

No.	Evaluation indicator name	Encoding	No.	Evaluation indicator name	Encoding
1	Concrete strength	CCS-01	10	Axis deviation	APD-01
2	Reinforcement cover thickness deviation	PLD-01	11	Elevation deviation	LED-01
3	Column cross section dimension deviation	CSD-01	12	Verticality deviation	LVD-01
4	Wall thickness deviation	WTD-01	13	Planeness deviation	SFD-01
5	Beam depth/width deviation	BHD-01	14	Crack	CXX-01
6	Plate thickness deviation	STD-01	15	Joint reliability	CRX-01
7	Completeness of raw material record	MRI-01	16	Exposed reinforcing steel	RBE-01
8	Completeness of construction record	CRI-01	17	Overall appraisal	SQS-01
9	Completeness of test record	TRI-01			

Table 11: Encoding of files.

File format	Encoding	File format	Encoding
PDF	PDFX-01	WAV	WAVX-01
DOC	DOCX-01	MP3	MP3X-01
PPT	PPTX-01	WMA	WMAX-01
TXT	TXTX-01	RMVB	RMVB-01
BMP	BMPX-01	MP4	MP4X-01
JPEG	JPEG-01	RFA	RFAX-01
JPG	JPGX-01	RVT	RVTX-01
GIF	GIFX-01	IFC	IFCX-01

associations that are either $m:n$ or $1:n$ on the "one" (i.e., parent) side. For example, fractional project entities stored in the information sheet shown in Figure 9 should be converted into a separate relational model with four attributes corresponding to the fractional project features. In subtable 1 of Table 13, the reference number of an entity is the primary key that can be uniquely identified to represent an individual row field in the table. Constituent project entities stored in an information sheet as shown in Figure 9 should be converted into a separate relational model with

Table 12: Classification of entities and attributes.

Entity	Attribute	Data source
Fractional project	Reference number	Table 9
	Name	Real name of specific fractional project
	Construction units	Contract document
	Construction quality score	Parameter information obtained from BIM models
Constituent project	Reference number	Table 9
	Name	Real name of specific constituent project
	Inspection result	Acceptance records for constituent quality
	Acceptance decisions	Acceptance records for constituent quality
	Professional technical director	Acceptance records for constituent quality
	Supervision engineer	Acceptance records for constituent quality
	Reference number of fractional project	Table 9
Inspection lot	Reference number	Figure 9
	Name	Real name of inspection lot
	Inspection data	Acceptance record for inspection lot quality
	Acceptance date	Acceptance record for inspection lot quality
	Construction standard and specification	Standards, specifications, design documents
	Inspection results of construction units	Acceptance record for inspection lot quality
	Acceptance decision of supervision unit	Acceptance record for inspection lot quality
	Reference number of inspection lot	Table 9
IFC element	Reference number of structural element	IfcGloballyUniqueId (entity IfcBuildingElement)
	Element name	IfcLabel (in entity IfcBuildingElement)
	Detailed description	IfcText (in entity IfcBuildingElement)
	Reference number of fractional project	Table 9
	Reference number of indicator	Table 1
	Indicator name	Indicator name in Table 1
	Evaluation standards and requirements	Standards, specifications, design documents
	Evaluation results	PSet_OnsiteReinforcedConcreteWall/Column/ Slab/Beam (in entity IfcWall as in Figure 6)
Quality-related files	Reference number	Table 11
	Name	File name
	Creation date	Time records of file creation
	Reference number of fractional project	Table 9
	Storage path	Storage position in system

seven attributes corresponding to the features of the constituent project. Meanwhile, by attaching a $1:n$ relation to this model, the reference number of the fractional project can also be viewed as an attribute reflecting the affiliative relationship between the fractional project and constituent project. The value of the reference number of the fractional project as a primary key in subtable 2 of Table 13 is considered a foreign key in the relational table of the constituent project.

The database system relies on matching values found in both tables to form relationships. In the relational table, an attribute can be designated as either a primary or foreign key. A primary key is used to uniquely identify a table or a row within a given table; a foreign key is a column that was formerly a primary key in a parent table that migrated to the child table and now identifies the relationship between the tables. The foreign key can participate as a key or non-key column within the child table. In subtable 10 of Table 13, the composite primary key refers to cases where more than one attribute is used to specify the primary key of the table. In such cases, GUID in IfcBuildingElement and the serial number of the evaluation indicators are used to uniquely identify a structural element with a particular evaluation. All foreign keys also include all attributes in the composite key, which can be different data types. For example, the foreign key of the *related_files* subtable, F_ComponentID and F_IndicatorID, references the composite primary key F_ComponentID and F_IndicatorID in the *IFC_element* subtable. During an insertion or update, if users try to insert a row into the *related_files* subtable whose values for F_ComponentID and F_IndicatorID do not correspond exactly to those of F_ComponentID and F_IndicatorID in an existing row in the *IFC_element* subtable, the database server will return an error.

Two basic relationships emerged when modeling the database: identifying (i.e., mandatory) and nonidentifying (i.e., optional). When both entities are mandatory, each entity becomes a table, and the key of either entity can appear in the other entity's table as a foreign key. One of the entities in an optional relationship should contain the foreign key of the other entity in its transformed table. When both entities are optional, either entity can contain the embedded foreign key of the other entity, with nulls allowed in the foreign keys. The $1:n$ relationship can appear as either mandatory or optional on the "many" side without affecting the transformation. On the "one" side, the relationship may be either mandatory ((a) in Table 14) or optional ((b) in Table 14). In all cases, the foreign key must appear on the "many" side, representing the child entity, with nulls allowed

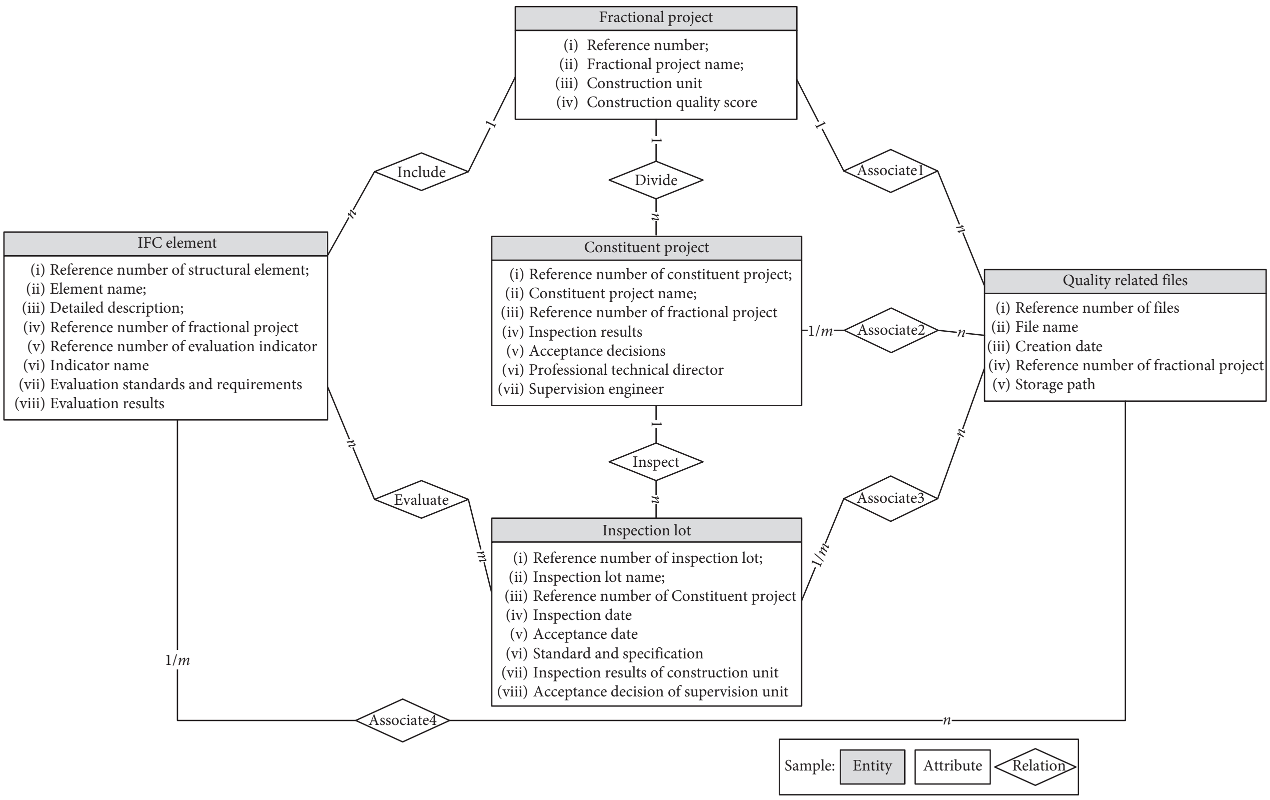


Figure 9: The workflow of quality database operation.

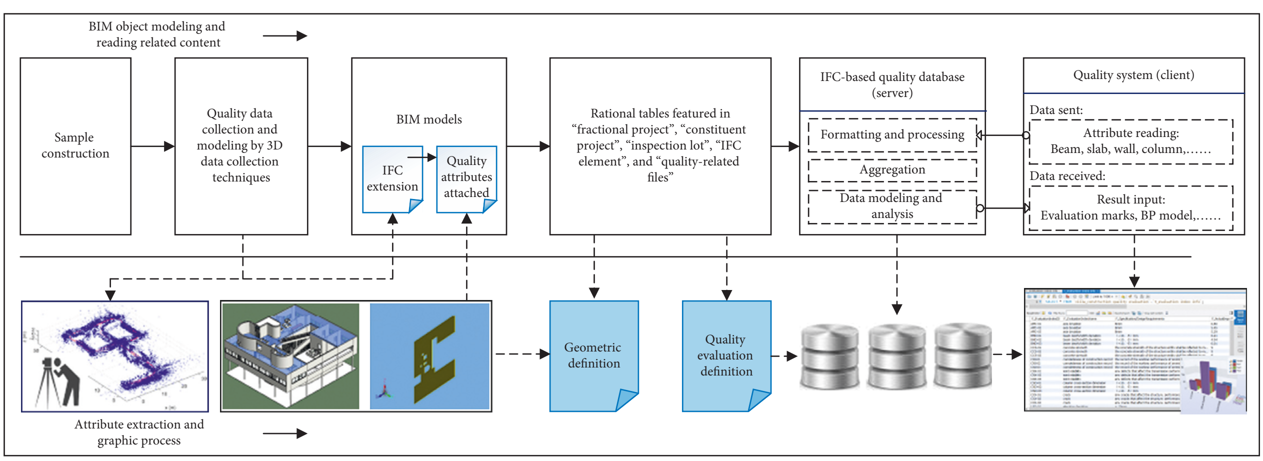


Figure 10: E-R diagram for quality evaluation database.

for foreign keys only in the optional “one” case. Foreign key constraints are set according to the specific meaning of the relationship and may vary from one relationship to another. The $m:n$ relationship, depicted in (c) and (d) in Table 14 as optional and mandatory for both entities, requires a new table containing the primary keys of both entities. The same transformation applies to either the optional or mandatory case, including that the “not null” clause must appear for the foreign keys in both cases. An optional entity means that the corresponding SQL table derived may have zero rows for that particular relationship, which would have no effect on “null” or “not null” in the table definition.

6. Operating the IFC-Based Database

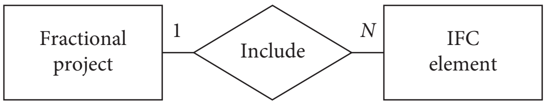
6.1. Workflow of the Proposed Method. Considering the complexity of large construction projects, it is crucial to establish a construction quality management system that

Table 13: Relational tables of the database.

Relational tables			
Name	Attribute	Data type	Constraint
Subtable 1—fractional project			
F_BranchWorkID	Reference number	Char(2)	Primary key
F_BranchWorkName	Name	Varchar(12)	Required
F_ConstructionU	Construction units	Varchar(40)	Required
F_ConstructureQS	Construction quality score	Decimal(4,2)	Required
Subtable 2—constituent project			
F_ConstituentPID	Reference number	Char(2)	Primary key
F_ConstituentPName	Name	Varchar(12)	Required
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPIR	Inspection result	Varchar(100)	Optional
F_ConstituentPAD	Acceptance decisions	Varchar(100)	Required
F_ConstituentPTD	Professional technical director	Varchar(10)	Required
F_ConstituentPSE	Supervision engineer	Varchar(10)	Required
Subtable 3—inspection lot			
F_InspectionLotID	Reference number	Char (14)	Primary key
F_InspectionLotName	Name	Varchar(50)	Required
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotDate	Inspection date	Date()	Required
F_InspectionLotAD	Acceptance date	Date()	Optional
F_InspectionLotS	Construction standard and specification	Varchar(50)	Required
F_InspectionLotIR	Inspection results of construction units	Varchar(100)	Required
F_InspectionLot SU	Acceptance decision from supervision unit	Varchar(100)	Required
Subtable 4–files			
F_DocumentID	Reference number	Char(7)	Primary key
F_DocumentName	File names	Varchar(40)	Required
F_CreateTime	Creation date	Date()	Optional
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_StoragePath	Storage path	Varchar(40)	Required
Subtable 5—evaluate			
F_InspectionLotID	Reference number	Char (14)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 6—include			
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 7—divide			
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPID	Reference number	Char(2)	Foreign key
Subtable 8—associate			
F_DocumentID	Reference number	Char(7)	Primary key
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotID	Reference number	Char (14)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 9—inspect			
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotID	Reference number	Char (14)	Foreign key
Subtable 10—IFC element			
F_ComponentID	Reference number/GUID in IfcBuildingElement	Varchar(100)	Composite key
F_ComponentName	Ifc element name	Varchar(20)	Required
F_ComponentDetail	Detailed description	Varchar(20)	Required
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6)	Composite key
F_IndicatorName	Indicator name	Varchar(20)	Required
F_EvaluationSR	Evaluation standards and requirements	Varchar(200)	Required
F_EvaluationResult	IfcPropertySet on Wall/Column/Slab/Beam	Varchar(5)	Required

Table 14: Relationship between two entities.

(a) $1:n$, both entities mandatory



Every structural element belongs to exactly one fractional project, and each fractional project has at least one structural element

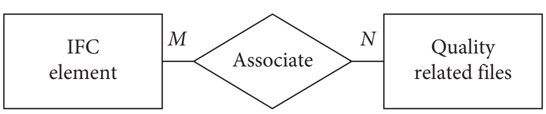
```
Create table fractionalproject
    (F_BranchWorkID char(2),
    F_BranchWorkName varchar(12),
    F_ConstructionU varchar(40),
    F_ConstructureQS decimal(4,2),
    Primary key (F_BranchWorkID));
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2) not null,
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
    Foreign key ((F_BranchWorkID) references
fractionalproject
    On delete set default on update cascade),
```

(b) $1:n$, one entity mandatory, one entity optional

Each fractional project is evaluated in one or more related file. A given quality-related file may not necessarily belong to a fractional project

```
Create table fractionalproject
    (F_BranchWorkID char(2),
    F_BranchWorkName varchar(12),
    F_ConstructionU varchar(40),
    F_ConstructureQS decimal(4,2),
    Primary key (F_BranchWorkID));
Create table relatedfiles
    (F_DocumentID char(7),
    F_DocumentName varchar(40),
    F_CreateTime date(),
    F_BranchWorkID char(2),
    F_StoragePath varchar(40),
    Primary key (F_DocumentID),
    Foreign key (F_BranchWorkID) references fractionalproject
    On delete set default on update cascade);
```

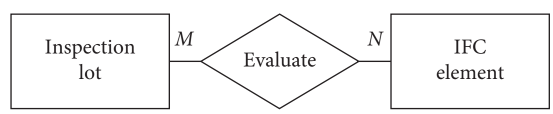
(c) $m:n$, one entity mandatory, one entity optional



Each evaluation property attached in IFC elements is applied in one or more quality-related files. A given quality-related file may not necessarily include a structural element with quality attributes

```
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2),
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
Create table relatedfiles
    (F_DocumentID char(7),
    F_DocumentName varchar(40),
    F_CreateTime date(),
    F_BranchWorkID char(2),
    F_StoragePath varchar(40),
    Primary key (F_DocumentID),
Create table associate4
    (F_DocumentID char(7),
    F_ComponentID Varchar(100),
    F_IndicatorID Char(6),
    Primary key (F_DocumentID, F_ComponentID,
F_IndicatorID);
```

(d) $m:n$, both entities mandatory



Each structural element is evaluated in one or more inspection lot. And one inspection lot consists of one or more structural elements

```
Create table Inpectionlot
    (F_InspectionLotID char(14),
    F_InspectionLotName varchar(20),
    F_ConstituentPID char(2),
    F_InspectionLotDate date(),
    F_InspectionLotAD date(),
    F_InspectionLotS varchar(50),
    F_InspectionLotIR varchar(100),
    F_InspectionLot SU varchar(100),
    Primary key (F_InspectionLotID);
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2),
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
Create table evaluate
    (F_ComponentID Varchar(100) not null,
    F_IndicatorID Char(6),
```

Table 14: Continued.

Foreign key (F_DocumentID) references **relatedfiles** on delete set default on update cascade),	F_InspectionLotID char(14),
	Primary key (F_InspectionLotID, F_ComponentID, F_IndicatorID),
Foreign key (F_ComponentID, F_IndicatorID) references **IFCelement**(F_ComponentID, F_IndicatorID) on delete set default on update cascade);	Foreign key (F_InspectionLotID) references **Inspectionlot** on delete set default on update cascade), Foreign key (F_ComponentID, F_IndicatorID) references **IFCelement** (F_ComponentID, F_IndicatorID) on delete set default on update cascade);

acts as distributed data storage for BIM data. Like other BIM applications, the IFC-based construction quality management system tends to be influenced by project organizational structure, working relationships, or even social networks, all of which are influenced by a specific evaluation database. Quality database operations cannot be disconnected from the model with which construction information is organized and illustrated according to a standard like IFC. As shown in Figure 9, the prototypical framework was developed based on an IFC extension and mathematical method (i.e., neural network model) for predicting overall appraisal, whereby indicator selection and database table design are normally organized sequentially. In the workflow, the quality data of structural elements are collected to compute the value of quality content, and it is important to establish an evaluation indicator system that accounts for performance testing, quality records, allowable deviation, and appearance quality. Then, the evaluation information is aligned with open international standards of IFC according to which the BP neural network model can be trained and tested as expected, and then the approved model can be used to predict the construction quality score. A formalization structure is suggested for database tables to facilitate the exchange of IFC-based evaluation indicator information via the information provider and information receiver, which maintains the information exchange between the IFC model and database tables. With regard to the visual requirements of construction quality evaluation and data characteristics in the database, entities and attributes of structural elements are categorized into the following five database tables as quality information server: fractional project, constituent project, inspection lot, IFC element, and quality-related files. Lastly, to design the relational databases of quality evaluation system as the information client, the conceptual data model is transformed and defined in SQL.

Ideally, several 3D data collection techniques including scanning, photogrammetry, virtual modeling, 3D printing, and rapid prototyping can be employed to capture quality information about construction projects. In the design stage, the IFC extension is developed to synthesize various evaluation modes and derives an optimal expression in a geometric and evaluation definition, thus constructing an entire BIM to be shared with the database as a server. Furthermore, MySQL Workbench as client is suggested to extract attributes from the database server and to migrate complex database systems. According to the logic structure design described above, relevant evaluation data were obtained and then imported directly into the corresponding field manually to create the database tables (Figure 11) and realize the preliminary establishment of a construction quality evaluation database. Users can access the quality database as a server through data sent by the quality system client, which is also fed back to the evaluation results stored in the IFC model.

6.2. Implementation of the Case. The proposed IFC-based quality database of this paper was applied to the case study of cast-in-place steel-concrete structure which is evaluated by 16 quality indicators in four categories (i.e., performance testing, quality records, allowable deviation, and appearance quality). When the inspection request for “cast-in-place steel-concrete” structural elements (beam, slab, column, and wall) was confirmed; the corresponding quality evaluation template and predicted results from BP network were identified based on inspection data collection and structured data from BIM model. The professional quality inspector completes the checklist with construction information and inspection data obtained from the construction site. Any data with a deviation beyond tolerated variance will be identified and recorded in the relevant attributes of the BIM model. Then, an acceptance rate for each evaluation indicator will be generated in the IFC-based quality database developed in SQL. Lastly, the overall quality appraisal of the case of cast-in-place steel-concrete structure is rated as “Good”. According to the average value of each evaluation indicator, in terms of performance testing, quality records, allowable deviation, and appearance quality, and the construction quality of the four aspects remained equivalent and demonstrated no significant differences. From these four aspects, the concrete strength in the testing project was found to be relatively superior while the wall thickness deviation was somewhat large.

Therefore, the following points for further improvement in follow-up construction warrant attention. First, the technology and attitude of construction personnel and quality of construction equipment should be improved. Second, records of raw materials in quality records should be complete, true, and valid, and procedures should be complete and well documented. Third, testing records and construction records must be enhanced. Fourth, the construction quality status reflected by each indicator in terms of allowable deviation should align with that of appearance quality. Finally, the quality of template installation and cleanliness of the internal surface should be strictly controlled to reduce size deviation and improve appearance quality.

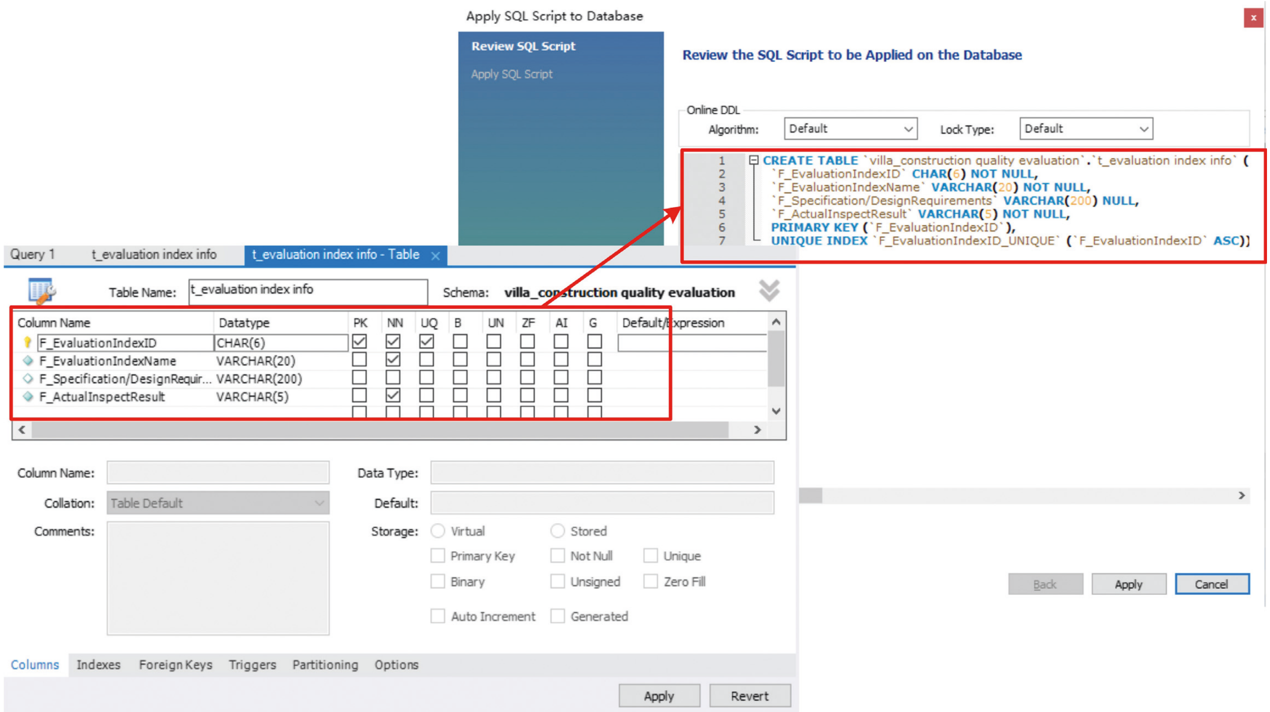


Figure 11: Create a new evaluation index information table.

Based on the discussion above, the IFC standard can be used to describe construction quality information as a whole. However, the current version of the IFC standard could not yet directly support the expression of the construction quality evaluation. Therefore, it needs to be extended in order to support the direct data exchange with the relevant quality database. The BIM model for quality evaluation established in this paper is used to realize the logical association among structural elements, evaluation items, quality indicators, and attribute sets. The research not only lays a sound foundation for developing the BIM-based application software for construction quality evaluation but also shows a feasible approach to extending the IFC standard to satisfy the requirements for quality management.

7. Evaluation of Proposed Method

The objective of evaluating the proposed model is to understand the effectiveness of IFC-based database if implemented in real practice. In order to take the opinion of construction firm and design institutes about identified factors, a questionnaire was developed. To make questionnaire simple and easy to understand, it was divided into three sections. The first section represents the composition of respondents. The second section includes statistical graphs of the means of survey results and the categorical weights of survey factors. In the third section, weights were assigned by respondents to factors in relation to quality for interpretation of data. Weights are in the range of 1 to 10. Zero to two is in poor range, two to four is in fair range, four to six is in average range, six to eight is in good range, and eight to ten is excellent range.

The survey was conducted by distributing a developed questionnaire to different construction practitioners. A total of 117 construction professionals including construction managers and structural designers participated in the survey. In this study, surveys were used to evaluate the four primary objectives of proposed method: (1) to increase the ability of construction managers to use BIM technology for quality control; (2) to involve structural designers in parametric-oriented quality control activities including the use of BIM software; (3) to expose key quality information to model builders and users; and (4) to provide complete quality database to develop management platform as well as information storage system. The results of the survey filled out by 64 participants in construction management and 19 participants in structural design are summarized in Table 15.

There are several points of note in the table. BIM technology and related data are considered very effective in increasing participants' awareness in design and management process (means across both groups reached 6.77 out of 10 in "Good" and 5.98 close to "Good"), benefiting users with the integration, utilization, and visualization of construction quality information related to IFC model (means across survey results fell in "Good"). This is also revealed that survey participants saw significant value of IFC-based quality database which could offer them an advantage in their work. However, the IFC-based method was not as enough effective in improving work efficiency both for construction managers and structural designers (both means were located in "Average" level). Actually BIM helps not just in constructing "buildings" but also in building a new sort of quality management mode. It is an integrated process built on coordinated and reliable information about a project

Table 15: Evaluation of the proposed method.

Evaluation questions	Participant		Mean	Poor (0~2)	Fair (2~4)	Average (4~6)	Good (6~8)	Excellent (8~10)
1. How familiar were you with BIM?	Construction Manager ($n = 64$)		6.77	0	0	19	33	12
	Structural designer ($n = 53$)		5.98	0	2	27	19	5
2. To what extent can IFC-based quality database improve information integration of construction quality?	Construction Manager ($n = 64$)		7.55	0	0	17	37	10
	Structural designer ($n = 53$)		6.99	0	0	31	18	4
3. To what extent can IFC-based quality database improve information utilization of construction quality?	Construction Manager ($n = 64$)		7.27	0	1	15	22	26
	Structural designer ($n = 53$)		6.5	0	0	20	25	8
4. To what extent can IFC-based quality database improve the visualization of quality management?	Construction Manager ($n = 64$)		7.73	0	0	7	21	36
	Structural designer ($n = 53$)		7.18	0	0	13	20	20
5. To what extent can IFC-based quality database improve work efficiency of quality management?	Construction Manager ($n = 64$)		5.34	0	12	29	20	3
	Structural designer ($n = 53$)		5.02	0	15	20	18	0
6. To what extent can IFC-based quality database improve understanding of construction quality control?	Construction Manager ($n = 64$)		6.82	0	0	21	24	19
	Structural designer ($n = 53$)		6.12	0	5	17	21	10
7. How useful do you consider the overall method proposed?	Construction Manager ($n = 64$)		5.88	0	7	22	30	5
	Structural designer ($n = 53$)		5.01	0	6	16	28	3

from design through construction which give users more time to adapt it. Another question worthy of deep conversation on quality control reveals that this may be due in large part that the primary reason why participants would like to use IFC-based database was because BIM can be considered a thought process that improves the understanding of construction quality through various stages of the project in the shape of information that stays digital, consistent, and coordinated; for example, a large part of participants' responses to the survey indicated this was one of the primary reasons (means of the two groups reached "Good" level), while more than 50% of these participants stated that they think highly of the effect of the overall method utilized in quality evaluation.

8. Conclusion

The presented findings contribute to the understanding of the potential use of BIM in construction quality evaluation and fill an existing gap in data integration on the use of relational database. This paper explored the implementation of BIM in quality management and proposed integrated solutions to improve current quality management processes with assistance of an IFC-based working environment. In order to better utilize the performance of the BIM model and database on construction quality control, a variety of BIM-based evaluation frameworks have been proposed. Also, this paper discusses how these IFC and neutral network models will work together to facilitate construction quality management. It helps the project participants to better understand the quality progress and to collaborate more effectively, thanks to a visualized data format.

In this way, the IFC-based construction quality model is effective and reliable for participants to understand quality problems and track the corrective action. The benefits of the construction quality database proposed in this paper lie in the aspects as follows: first, the utilization of the IFC data mapping in construction quality domains ensures information consistency and predicated results. Furthermore, the quality data and structured construction codes are integrated to provide clear quality definition requirements for evaluation. Typical errors caused by misunderstanding of cross-reference codes can be avoided. Lastly, IFC-based quality database ensures a source of information for quality management techniques to identify useful evaluation attributes in data to inform users, which helps the project participants to better understand the quality requirements acceptance and to collaborate in a visualized manner.

It can be concluded that BIM and database technology-integrated construction quality evaluation method is suitable and helpful in quality compliance management. A quality system based on this approach proposed in this study could allow us to automate data acquirement and extraction from the BIM model and produce evaluation information that can also be used by users of the quality system platform. Whilst there is a significant amount of time for us to implement the mapping of the IFC element against evaluation results, the benefits to users are they do not need to manually seek corresponding data which are attached to a BIM model as a database. The effort invested to create the mapping will allow us to ultimately move to being able to produce reliable IFC-based quality database. Like any new feature, there is always room for improvement, the requirement of more automation, and new functionality generated with the development of quality system platform is a giant step towards massive open-structured and unstructured data-related construction quality.

There are some limitations for the proposed method as follows: (1) the IFC extension model designed for quality evaluation does not contain unstructured data related to construction quality, such as outward appearance and historical inspection records. Therefore, unstructured data should be considered in the quality-oriented BIM model. (2) The use of IFC-based database is not convenient and automatic at this time with the proposed method due to the manual input of the evaluation results. Related evaluation software application should be developed in the future for improvement in recording field data and direct data transfer to BIM.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Related work on this study has been presented in the International Conference on Construction Engineering and Project Management 2017

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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