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E-maintenance platform design for public infrastructure maintenance based on IFC ontology and Semantic Web services

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Summary

As an important kind of infrastructure, a tunnel's life is estimated to be 100 years or more. During its service life, an effective maintenance strategy plays an essential role in keeping its availability and safety. Maintenance work involves a set of participants, activities, and resources, and in this case, tunnel-related data are distributed to heterogeneous information management systems in varying formats, bringing difficulties to implement effective maintenance. This paper proposes an E-maintenance Framework for Public Infrastructure (EFPI), combining Building Information Modeling (BIM), Industry Foundation Classes (IFC), and Semantic Web technologies to help integrate heterogeneous data and expert knowledge, enable information sharing through the whole life cycle, and support maintenance managers to make effective maintenance decisions. A cost estimation case is provided in this paper to illustrate the implementation mechanism and validate the proposed approach.

KEYWORDS

BIM, e-maintenance, IFC, infrastructure, Semantic Web

1 | INTRODUCTION

Infrastructure plays an important role in sustainable development, and maintenance is of crucial importance to keep and improve system availability and safety. The actual maintenance work involves a great number of different and complex activities, associating various parties and requiring considerable resources. To support this work and reduce the potential security risks brought by the jumbled maintenance process, the concept of e-maintenance emerges.

The widespread concept of e-maintenance refers to the integration of information and communication technologies to meet needs for supporting maintenance strategies and plans.[1] E-maintenance provides some intelligent tools (such as a watchdog agent) for companies to monitor their assets through an Internet wireless communication system to prevent them from unexpected breakdown.[2] By dint of wireless and Internet technologies, any manager, operator, or expert is capable of remotely linking to a company's equipment diagnosis, fixing, performance monitoring, and data collection and analysis. Consequently, the lack of manpower problem can be solved.[3] It has almost unlimited potential to reduce the complexity of traditional maintenance guidance through online guidance based on the results of decision making and analysis of product condition.[4] The application of e-maintenance complies with the management requirements of Public-Private Partnership (PPP) projects.

Nevertheless, the establishment of e-maintenance also faces some challenges due to the large scale, big volume, and high diversity and complexity of infrastructure facilities and equipment. To begin with, an e-maintenance system involves a variety of cross-platform data, information, and knowledge integration issues,[3] which lead to the difficulty in information retrieval and tracking. In order to achieve a successful e-collaboration, the total information flow should be structured according to a common semantic terminology and frame, and all the relevant systems must be harmonized.[5] In addition, quantity take-off (QTO) and cost estimation (CE) should be efficient and accurate because of their

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high significance to a project's success. They require extracting information based on the knowledge of domain experts about the rules and processes throughout the project's life cycle.[6] Moreover, a successful e-maintenance process integration requires that the maintenance process must be stable and ontology based, ie, the structure does not change on a short-term perspective.[7] Heterogeneous models used by different designers also bring challenges in predicting and diagnosing failures and disturbances and estimating the remaining lifetime of components.[8]

To address these problems, this paper proposes an e-maintenance framework based on Industry Foundation Classes (IFC) and Semantic Web technologies, enabling information integration and retrieval through the whole project life cycle and providing support for maintenance decision making. The remainder of this paper is structured as follows. Section 2 reviews recent studies relevant to e-maintenance and building information integration and analysis. Section 3 illustrates the compositions of the proposed IFC-based framework and its working mechanism. The role of IFC in the platform and the development of the IFC ontology are explained in Section 4. A cost estimation case is provided in Section 5 to prove the operability of this platform.

2 | LITERATURE REVIEW

2.1 | E-maintenance

The term e-maintenance has emerged since early 2000 and is now a very common term in maintenance-related literature, and it can be considered as a maintenance strategy, a maintenance plan, a maintenance type, or maintenance support in different domains.[1] According to the work of Ucar and Qiu, e-maintenance can be seen as a maintenance plan to meet the needs of the future e-automation manufacturing world.[9] Zhang et al consider that e-maintenance is a combination of Web service technology and agent technology, which supports intelligent and cooperative features for the systems in an industrial automation system,[10] whereas Marquez and Gupta define e-maintenance as a distributed artificial intelligence environment.[11]

The need to integrate business performance and the appearance of e-technologies drive the emergence of e-maintenance. It helps realize remote maintenance, collaborative maintenance, and immediate maintenance with the real-time information pipeline.[1] Unlike the conventional maintenance, information transfer needs to get through a hierarchical reporting process, an e-maintenance platform introduces an unprecedented level of transparency and efficiency into the entire industry, and it can be adequate support of business process integration.[7] The integration of business processes significantly contributes to the acceleration of total processes, to an easier design, and to synchronize maintenance with production, maximizing process throughput and minimizing downtime costs.[1] According to the work of Lee, at an e-maintenance platform, goods are checked out from stores against a work order or a location, and the transaction is recorded in real time. Then, the massive data bottlenecks between the plant floor and business systems can be eliminated by converting the raw machine health data, product quality data, and process capability data into information and knowledge for dynamic decision making.[12]

Despite the perceived advantages of e-maintenance, there are also some challenges for the establishment of e-maintenance waiting to be responded through future research.[1] First of all, security and reliability concern arising from transactions over the Internet is a main restraining force,[13] and a reliable, scalable, and common informatics platform has to be developed in order to implement e-maintenance successfully.[14] The development of an e-maintenance system requires various information and business systems integration, which is inconsistent with the immanently lacking efficient interoperation among the plant software systems, and research on "highly integrated" e-maintenance systems is therefore a promising research area.[15] Holmberg et al put forward that the processing of data, information, and knowledge should be decentralized to a level as low as possible, eg, to the sensor level.[5] Since an effective and efficient predictive-based machine condition prognosis, which is necessary for modern plants, is not yet existent,[16] it is time to start focusing research on the prognosis and decision support modules.[17]

To support the objectives of e-maintenance, predictive intelligence (algorithms, software, and agents) and mapping of the relationship between product quality variation and machine and process degradation are required.[14] The success of this collaborative maintenance platform depends on having a multitasking and multiuser operating environment and a fast and easy-to-manage database for international experts to use to retrieve or store their aggregated knowledge and experiences.[18] One of the most urgent industrial problems is how to realize knowledge-based operation and maintenance of plants,[10] and therefore, there should be a knowledge-based system achieving intelligent conversion of data into information and information into knowledge.[12]

2.2 | BIM and IFC

Building Information Modeling (BIM) technology has been receiving an increasing attention in the Architecture, Engineering and Construction (AEC) industry.[19] Compared with the traditional Computer-Aided Design (CAD) technology, BIM is capable of restoring both geometric and rich semantic information of building models, as well as their relationships, to support life cycle data sharing.[20] Moreover, it is expected to facilitate the collaboration and interaction among different actors involved in different stages of a building project since decisions made by each expert working on a particular part have an impact on the overall project.[21] One of the major challenges to realize coordination is the interoperability problem due to data heterogeneity, modeling software diversity, and lack of common modeling standard.[20] Furthermore, it is hard to define a model to satisfy the particular needs of various experts involved because the model is not allowed to extract partially.[19] In order to overcome these problems, industry domains and software developers have been trying to change the ways to define, tailor, and manage the semantics of product models, which makes semantics of a building a research hotspot.[22]

As the most widely used data exchange standard for BIM, IFC developed by building SMART, which provides the commonly shared concepts, attributes, and relationships of BIM resources,[20] has been widely supported by the market-leading BIM software vendors in the AEC industry.[23] The IFC schema is based on a set of concepts, such as classes, attributes, relationships, property sets, and quantity definitions, to describe information of building models to be exchanged between different software applications so that BIM data can be extracted from proprietary software and be exchanged with other applications.[21] However, as a general-purpose data model that facilitates the exchange among different software applications, the IFC schema cannot anticipate the multiple ways of representing information of different BIM software. In addition, its ability to define the characteristics of a model in different ways might hinder its interpretation. Semantically validated IFC models can facilitate the exchange of information to members of the project team. However, the lack of mechanisms to restrict the way in which the constraints are defined in the model becomes a problem in keeping this semantic validation.[24] In this regard, it represents a big challenge to integrate all the existing modeling rules adopted by BIM vendors[21] and to reduce the ambiguity and unclearness of natural language in BIM documents.[20]

The use of semantic web technologies to address these problems in the AEC sector has been proposed by several authors.[20,21,25] Pauwels has suggested using the semantics and syntax of Resource Description Framework (RDF) graphs to combine models from different CAD/BIM applications.[26] Abdul-Ghafour et al have proposed an ontology-based approach based on Web Ontology Language (OWL) DL language for capturing, interpreting, and reusing the semantics of product information.[27] They point out that the definition of mapping rules is one of the real challenges to address in the future.

2.3 | Semantic Web technologies, IFC, and ontologies

Researchers started to propose the use of semantic web technologies in the AEC industries in the early 2000s. A basic tenet of semantic technologies is the separation of meaning from data. The purpose of Semantic Web is to apply these technologies to the Web of data. This way, applications can query data on the Web for different purposes such as integrating data or drawing inferences from the data available in the Web. To make this possible, the data on the Web should be available in the standard formats required by the tools developed by the Semantic Web, especially those data that concern the relationships between the data. The creation of these links between data on the Web enables people and machine to explore them. Pauwels et al conclude three main added value features brought by Semantic Web technologies, which are information exchange, data integration and complex search queries across several data sources, and construction document information management.[22]

The application of semantic technologies transforms the Web into a semantic network that is globally interconnected. Semantic Web technologies enable an explicit representation of the meanings of the information on the Web by means of ontologies.[21] According to Costa and Madrazo, an ontology can be described as "a formal and explicit specification of a shared conceptualization."[21] These specifications are defined by means of classes, attributes, values, relationships, roles, and rules. OWL is the most widely used language created by the World Wide Web Consortium to describe ontologies in a formal way.

Ontology is considered as a key element of Semantic Web technology. It can be roughly divided into two categories: general ontology and domain ontology.[20] The interest of general ontology is the whole world, whereas domain ontology focuses on the specification of particular domain conceptualization. Although some general ontologies contain a large number of general concepts, they are not designed for a specific domain, which may lead to an inaccurate description of concepts in the AEC domain. In contrast, domain ontology is a representation of semantics in a particular domain, which often consists of a hierarchical description of important concepts precisely defined in the domain, along with the description of properties of each concept.[28] In this paper, domain ontology is applied in the e-maintenance framework.

Recently, several IFC-based ontologies have been developed for particular application needs.[29-33] For instance, Pauwels et al[31] utilized an IFC ontology to semantic rule checking. Beetz et al[25] presented an approach for converting the IFC schema into the OWL format, which is a remarkable effort to lift the IFC specification onto the ontology level. Zhang and Issa[30] and Pauwels et al[31] used an IFC ontology to extract a partial model from a complete IFC model. In addition, several applications used IFC ontologies for querying spatial information within a building information model.[32,33] Most of the current IFC-based ontologies are developed for information query and sharing, aiming at improving the interoperability of multiple systems. The ontology in this paper focuses on the tunnel maintenance domain and defines the complex spatiotemporal relationship among elements in the complex maintenance process. In addition, expert knowledge is involved in using ontology representation, providing maintenance suggestions for users. The IFC-based domain ontology is created following the method proposed by Lee et al[34] and Liu et al.[35] Protégé and OntoGraph are used to edit the ontology and generate graphs, respectively.

3 | THE E-MAINTENANCE FRAMEWORK FOR PUBLIC INFRASTRUCTURE

3.1 | Framework overview

The E-maintenance Framework for Public Infrastructure (EFPI) proposed in this paper can be found in Figure 1, and it mainly includes two regions, six layers, and a bidirectional data stream.

Two regions: Support region and service region. The support region provides underlying information and knowledge support for the whole framework, whereas the service region aims to realize various functions, such as decision making, execution, and evaluation.

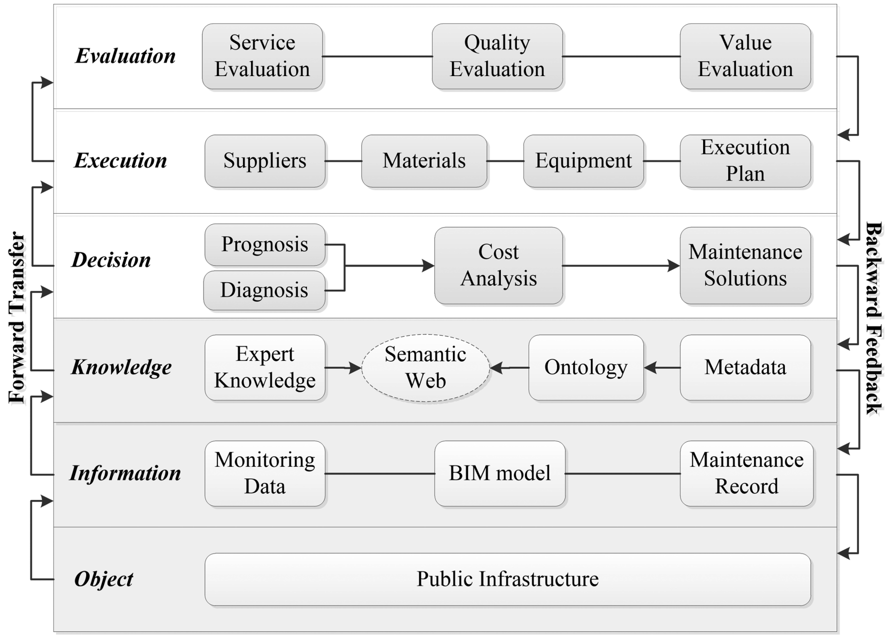

FIGURE 1 E-maintenance framework for public infrastructure

Six layers: The framework is divided into six layers according to the roles of the two regions, which consist of object, information, knowledge, decision, execution, and evaluation.

(1) Object layer refers to the public infrastructure, including all series of facilities and equipment.
(2) Information layer covers monitoring data (status information), BIM data (structural information), and maintenance data (activity information).
(3) Knowledge layer includes metadata, ontology, and expert knowledge, as well as a semantic web linking ontologies and expert knowledge.
(4) Decision layer includes prognosis, diagnosis, cost analysis, and maintenance solutions determination process.
(5) Execution layer mainly focuses on the formulation of an execution plan, which consists of service supplier selection, materials, and equipment procurement.
(6) Evaluation layer evaluates the performance of maintenance, including service evaluation, quality evaluation, and value evaluation.

Bidirectional data stream: Forward transferring and backward feedback.

Basic idea of this framework

The main purpose of this framework is to retrieve infrastructure information in combination with the complexity of the components' relationship and to integrate the complex information to support maintenance decision making, improving maintenance efficiency and quality.

The information layer accurately describes three kinds of information: status information (real-time monitoring information), structural information (geometric features and spatial location), and activity information (maintenance data, traffic flow, equipment control, and emergency treatment). The core of the knowledge layer is to construct ontologies based on these discrete and independent data from a structural or spatial perspective and link them through a semantic web, taking expert knowledge into consideration. Based on the semantic web established in the knowledge layer, four engines are developed in the decision layer, which are prognosis, diagnosis, cost analysis, and maintenance solutions determination. The execution layer will generate an execution plan, including the selection of suppliers, materials, and equipment procurement to support the maintenance work planned in the maintenance solution. Finally, the evaluation layer can track the execution performance and generate a service evaluation report, quality evaluation report, and value evaluation report automatically. At the same time, the evaluation results will get back to the support region, and the maintenance solution can be adjusted to obtain better maintenance performance.

3.2 | Online-to-offline service model

The online-offline service model describes the implementation mechanism of decision making, plan execution, and maintenance evaluation, as illustrated in Figure 2. It consists of three modules: online activities, offline activities, and interaction mechanism. Online activities mainly focus on the generation process of maintenance solutions. Offline activities include the whole procurement process (materials, equipment, and services). The execution plan and evaluation results help realize the interaction of online and offline activities.

Online activities: The maintenance staff can retrieve various data about facilities and equipment stored in the information layer with the help of ontology and semantic web. Moreover, they can use these data to prognose and diagnose some potential defects. In addition, they can do a cost analysis about eliminating these defects according to some similar history records. After the cost analysis process, a final maintenance solution will be generated online.

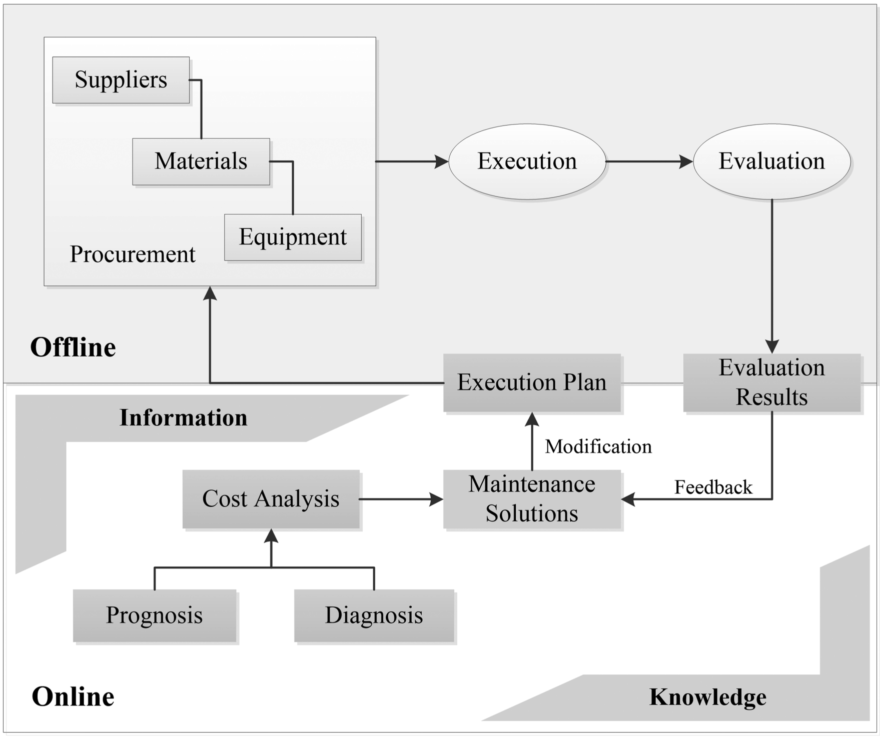

FIGURE 2 Online-offline service model

Offline activities: The execution plan includes the labor, materials, and equipment needed to perform the maintenance solution, managers can select the most suitable suppliers of materials, equipment, and services combined with the market price, company credit, and some other related factors.

Interaction mechanism: The execution plan generated online provides guidance to the offline procurement process. Moreover, the evaluation results generated offline need to be uploaded online to modify the maintenance solution.

4 | INFORMATION INTERCONNECTION BASED ON IFC

4.1 | Information expression of IFC

The IFC standard contains and manages all kinds of information through a hierarchical and modular framework, which is divided into four levels from bottom to top, namely, resource layer, framework layer, shared layer, and domain layer. Each level contains several modules consisting of a variety of entities, defining types, selecting types, enumerating types, rules, functions, and property sets. Entities are the main part to express building information through IFC. They are object-oriented components with the same common properties. Defining types, selecting types, enumerating types, rules, and functions serve for entities to constrain their properties and provide implementation methods. Entity instance is the carrier of data sharing and exchange. Property set is one of the ways of information diffusion in an IFC model. Some commonly used property sets have been defined in the IFC standard, that is, predefined property sets, which are used to describe the additional attributes of entities. In addition, users can customize property sets according to their own needs to expand IFC property sets.

The entities in the IFC standard can be divided into two categories. One class is the entity that can be used independently for data exchange; such entities are derived entities of entity *IfcRoot*, which are distributed in the framework layer, shared layer, and domain layer. They all have the *GlobalId* attribute, which enables the globally unique identification of entities. Another class is that of entities that do not exchange data independently at the resource layer. They are not derived from the entity *IfcRoot*, and they cannot identify themselves in the process of data exchange and usually exist in the form of attributes of *IfcRoot* derived entities.

The entity *IfcRoot* has a direct attribute named *GlobalId*, and the instances of its inherited entities have a globally unique identifier, which can be independently used for data exchange. Figure 3 shows the framework of *IfcRoot* and its main inheritances. The three main derived entities from *IfcRoot* are in the frame layer of the IFC model. *IfcObjectDefinition* and its derived entities are used to implement the definition of the object. *IfcPropertyDefinition* and its derived entities are used to define properties. *IfcRelationship* and its derived entities realize the definition of relationship. Through the definition of things, attributes, and relationships, the core framework of the IFC model is formed. Through these entities and their derived entities, the description of entities and attributes in the IFC model, the description of complex relationships between entities, and attributes or attribute sets can be realized.

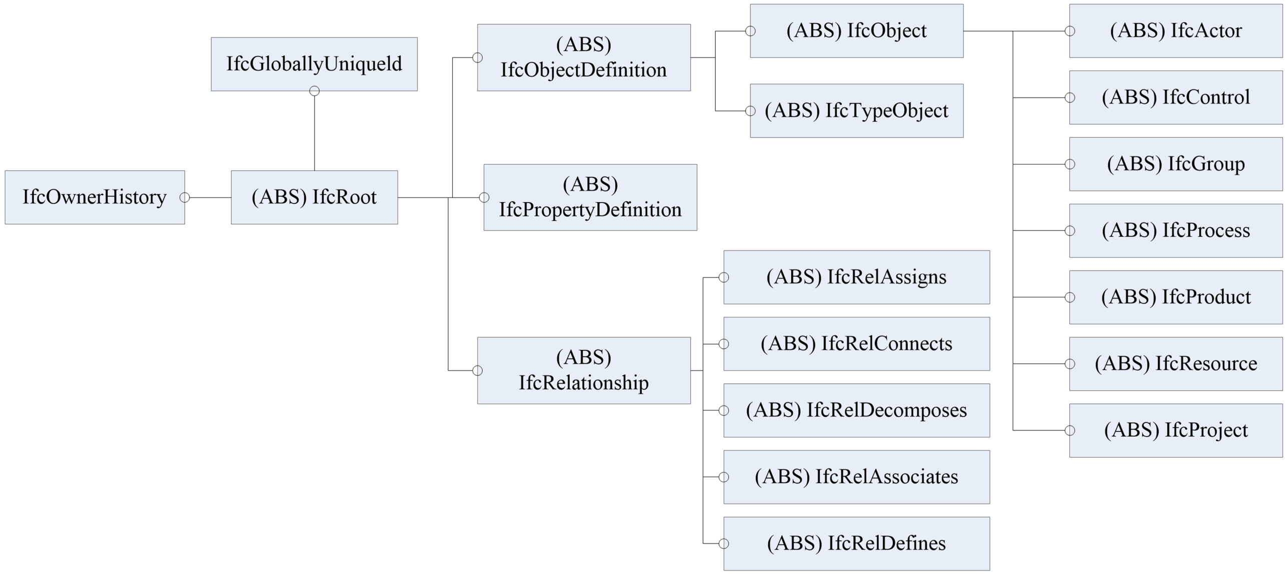

FIGURE 3 *IfcRoot* and its main inheritances

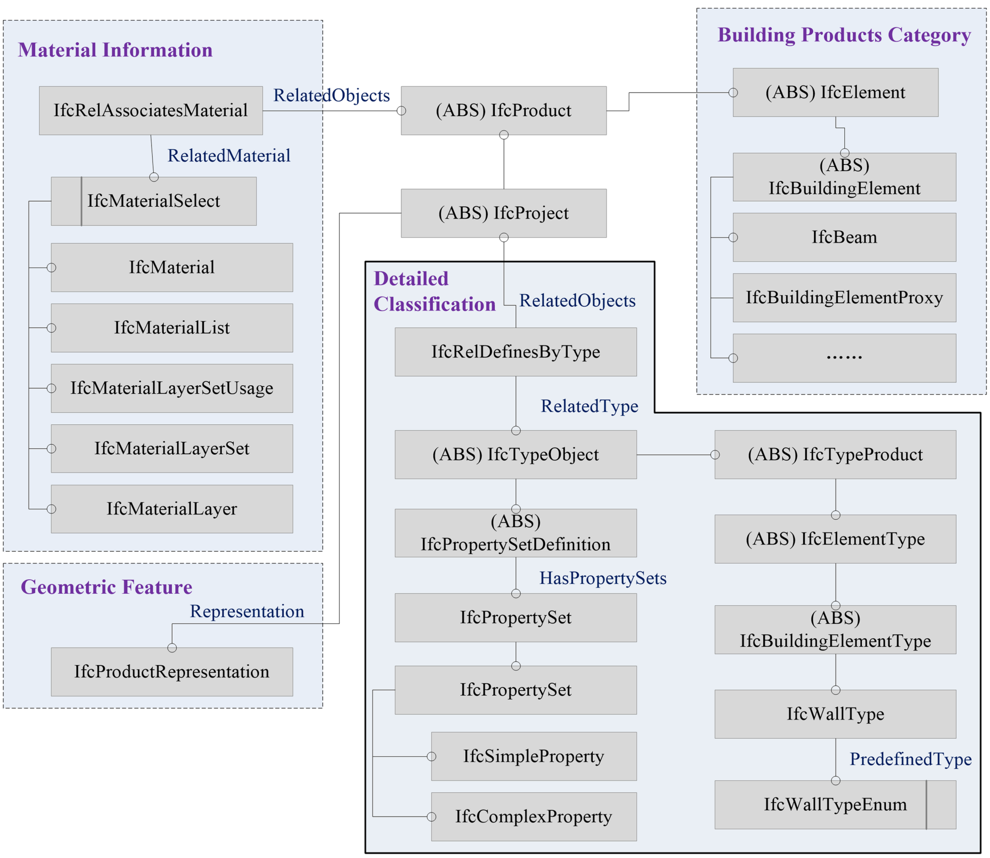

FIGURE 4 Building information interconnection

4.2 | Building information expression in IFC

To realize the automatic use of IFC data, we must first analyze what useful design information is contained in the IFC data obtained from the design stage and how this information is expressed using the IFC standard. Useful design information includes building product type, material information, building product classification, geometric features, and so on. Figure 4 demonstrates how the building information is interconnected through IFC.

In IFC standards, the expression of building products is realized through the entity *IfcProduct* and its derived entities. In addition, *IfcBuildingElementProxy* can also be used to express the undefined building products of the IFC standard. The geometric features are expressed by the *IfcProductRepresentation* entity corresponding to the Representation attribute of the *IfcProduct* entity. The derived entity defines a variety of geometric expressions, including SweepSolid, BoundingBox, Brep, etc, which can be used to describe the geometric features of a building product of various shapes. Material information is described by the selection of five material structures listed in the entity *IfcMaterialSelect*, which can be used to express the structure of the building products, material information, and then pass through. The relationship entity *IfcRelAssociatesMaterial* and the building product associated with the IFC standard for the refinement of the architectural product classification can be expressed in two ways: one is expressed by a refined classification entity derived from *IfcTypeObject*, such as *IfcWallType*, and the other is a side of the custom attribute set provided by the IFC standard. Expressions are expressed by defining the derived entity *IfcPropertySet* of the *IfcPropertySetDefinition* entity, whose attributes are expressed by the derived entities of the abstract entity *IfcProperty*, *IfcSimpleProperty*, and *IfcComplexProperty*, respectively, to express simple attributes and complex attributes.

5 | SYSTEM APPLICATION

In order to demonstrate how the proposed e-maintenance framework works to solve problems and provide maintenance support, an automated cost estimation process combining with different maintenance strategies will be explained in the following sections.

Cost estimation is one of the most critical tasks for building construction project management, and it requires information from various sources, such as labor, materials, and equipment. Traditional cost estimation is performed manually, and it is time consuming, low efficient, and prone to error. In order to solve the problem of subjectivity of cost estimators, several studies have explored the method to combine BIM and semantic web technologies. Lee et al put forward an ontological inference process to output appropriate work items from the BIM model.[34] Liu et al established a cost estimation model based on ontology representation and reasoning rules to generate specific construction conditions and work items.[35] Under the Chinese context specifically, Ma et al created a discrimination model for Bill of Quantity items generation based on Chinese standards.[36] These research studies provided some technical bases for the e-maintenance implementation, but they mainly focused on work items generation without consideration of maintenance strategies. The proposed method in this paper can improve the accuracy of cost estimation regarding different maintenance strategies. The original automated cost estimation process can be seen in Section 5.1, and the modification of cost estimation results based on different maintenance strategies can be found in Section 5.2.

5.1 | Cost estimation process

The general process of cost estimation is shown in Figure 5, including five main steps.

(1) Identify "work conditions"

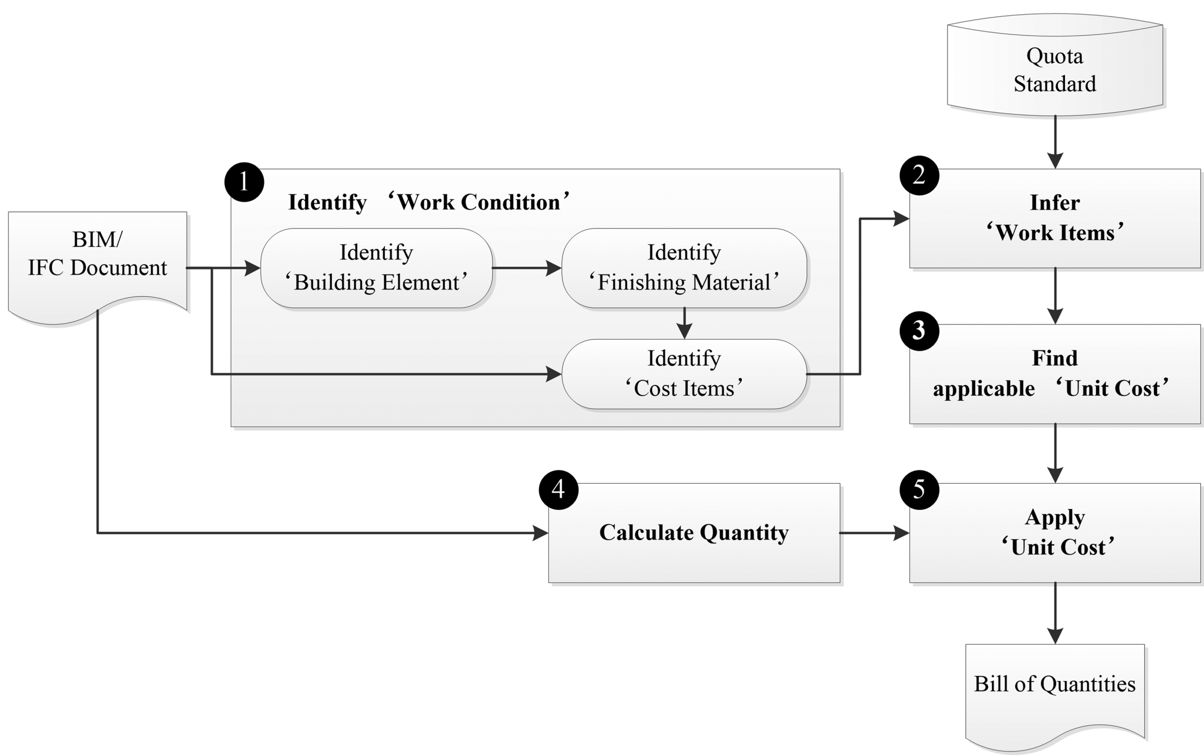

FIGURE 5 General process of cost estimation

Element Code	Element	Work Item	Cost Item	Cost Item Code	Cost Item Name	Unit	Unit Price	Quantity
Y030101	Sheild tunnel middle section	Y3-6-10	Labor	100200	human	work day	125	5.75
Y030101	Sheild tunnel middle section	Y3-6-10	Material	213270	thoxyline resin	kg	32	1
Y030101	Sheild tunnel middle section	Y3-6-10	Material	222076	flexane	kg	40	3
Y030101	Sheild tunnel middle section	Y3-6-10	Material	217721	curing agent （T-31)	kg	46	0.5
Y030101	Sheild tunnel middle section	Y3-6-10	Material	222052	waterproof slurry	kg	25	2.4
Y030101	Sheild tunnel middle section	Y3-6-10	Material	219020	concrete	kg	0.29	0.03
Y030101	Sheild tunnel middle section	Y3-6-10	Material	212360	grouting pipe	kg	4	1
Y030101	Sheild tunnel middle section	Y3-6-10	Material	222060	industrial alcohol	kg	6	0.5
Y030101	Sheild tunnel middle section	Y3-6-10	Material	222027	glass cloth (0.2 thick)	m^2	2	1.2
Y030101	Sheild tunnel middle section	Y3-6-10	Material	218001	other material	%	1	5
Y030101	Sheild tunnel middle section	Y3-6-10	Equipment	314058	manual slurry pump	per	211.12	0.38
Y030101	Sheild tunnel middle section	Y3-6-10	Equipment	314023	aerial lift vehicle	per	880.88	0.38
Y030101	Sheild tunnel middle section	Y3-6-10	Equipment	304010	4t motorlorry	per	455.73	0.38
Y030101	Sheild tunnel middle section	Y3-6-10	Equipment	JX2030	other equipment	%	0	1
Y030101	Sheild tunnel middle section	Y3-1-3	Labor	100200	human	work day	125	1.65
Y030101	Sheild tunnel middle section	Y3-1-3	Material	213270	thoxyline resin	kg	32	15.33
Y030101	Sheild tunnel middle section	Y3-1-3	Material	217721	curing agent(T-31)	kg	46	1.25
Y030101	Sheild tunnel middle section	Y3-1-3	Material	209480	quartz sand	kg	0.49	31.65
Y030101	Sheild tunnel middle section	Y3-1-3	Material	217701	cetone	kg	10.5	1.8
Y030101	Sheild tunnel middle section	Y3-1-3	Equipment	304010	4t motorlorry	per	455.73	0.51

FIGURE 6 Example of quota standard items

First, "work conditions" such as building elements, finishing materials, and cost items like required labor and equipment will be identified automatically through IFC entities and properties, instead of estimators identifying this series of information manually.

(2) Infer "work items"

Second, work items will be generated based on an external unit cost database, and herein, we take quota standard as an example because it is applied as the mainstream of cost estimation. The list items in quota standard include type of resources, quantities of resources, and unit cost of resources for each work item (see Figure 6). This step requires an in-depth experience and, thus, involves expert knowledge. The automatic mapping between BIM items and quota items is the key role of e-maintenance in the cost estimation process. The implementation mechanism mainly includes three parts: the rule base of quota item discrimination, the discriminant model of quota item, and the algorithm of automatically generating quota item list based on IFC.

According to practical experience and data analysis, as long as the following four aspects of information are available, that is, the type of building product, geometric characteristics, material information, and detailed classification, the quota item of a construction product can be determined only. This information is called quota item discriminant information, which can be extracted by IFC, and the mapping relation between quota item and quota item discriminant information can be expressed and stored in a database. Then, form the quota item discriminant rule base.

Based on the discriminant model of quota items and the analysis of IFC data, an intelligent algorithm for applying quota items is established, as shown in Figure 7. The algorithm consists of three key steps.

(1) Extracting the subdivision attributes contained in the IFC design information for each IFC entity of a construction product, and mentioning the subdivision attribute contained therein. After that, the extracted attributes are processed by semantic standardization with the design information semantic library, and the standardized sub-attributes are obtained.

(2) Establishing the attribute mapping relationship by using the standardized subdivision attribute. By traversing the standardized subdivision attributes, it is determined whether the subdivision attributes are sufficient to match and establish the mapping relation of attribute sets for the detailed classification of construction products. If the match is successful, an attribute set mapping relationship is automatically established. Otherwise, it is necessary to manually set up the detailed classification of building products before a building attribute set mapping relationship can be established.

(3) Determining the quota items to be applied to the construction products by using the complete subdivision attributes. Based on the detailed classification, the detailed content of the attribute set of the detailed classification mapping is automatically set by using the standardized subdivision information. If the attribute set is set up automatically, the corresponding quota items are applied to the rule base of quota items automatically. Otherwise, it is necessary to manually set the attribute set to complete and then apply the corresponding quota items to the rule base of quota items.

(3) Find applicable "unit cost"

Third, applicable unit costs can be calculated from the quota standard to prepare an estimate.

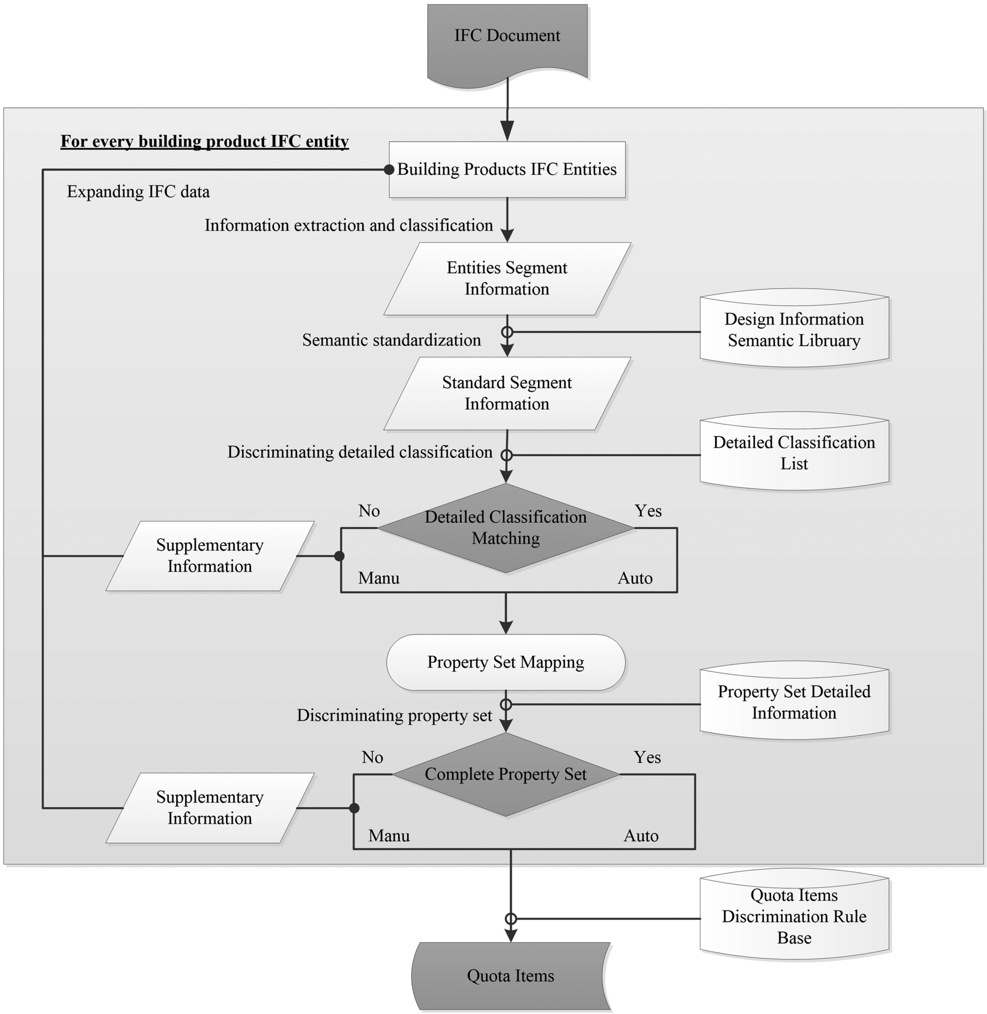

FIGURE 7 Intelligent algorithm for obtaining quota items

(4) Calculate quantity

Fourth, the quantities for each of the work items can be extracted from BIM/IFC documents and transformed into RDF formats (see technical details in the work of Liu et al[35]).

(5) Apply "unit cost"

Finally, unit cost is assigned applicable work items by multiplying quantity by unit cost. Moreover, bill of quantities can be calculated by multiplying unit cost and work item quantities.

Usually, the total estimated cost based on quota standard is higher than real costs. This is because the work items in quota standard basically follow a time-based maintenance strategy, which is different from the real situation. Maintenance work of different facilities and equipment may follow varying strategies according to their level of importance, spatial or systematical relationships, etc. In this case, quantities of each work item need to be modified to obtain accurate cost estimation results.

5.2 | Cost modification based on maintenance strategy

Various types of complex failure processes may occur due to the complexity of infrastructure facilities and equipment. Degradation-based failure (due to wear, fatigue, and corrosion) and sudden failure are two representative failure modes observed in building construction projects.[37] Common stochastic processes characterizing degradation behaviors include Gamma process, Wiener process, general path model, and so on,[37] and arrival processes of sudden failure are generally characterized by Poisson processes.[38] It is worth noting that the Wiener process has achieved satisfactory results in modeling the gradually evolving degradation with many actual applications.[39] Furthermore, the increment of degradation is different under different states, as shown in Figure 8. In this case, taking distinguishing maintenance measures according to the infrastructure state is necessary.

Preventive maintenance (PM) activities, including inspections, repairs, replacements, and routine services, are of great importance for a majority of industrial systems. Among the PM activities, time-based maintenance (TBM) and condition-based maintenance (CBM) are two of the most

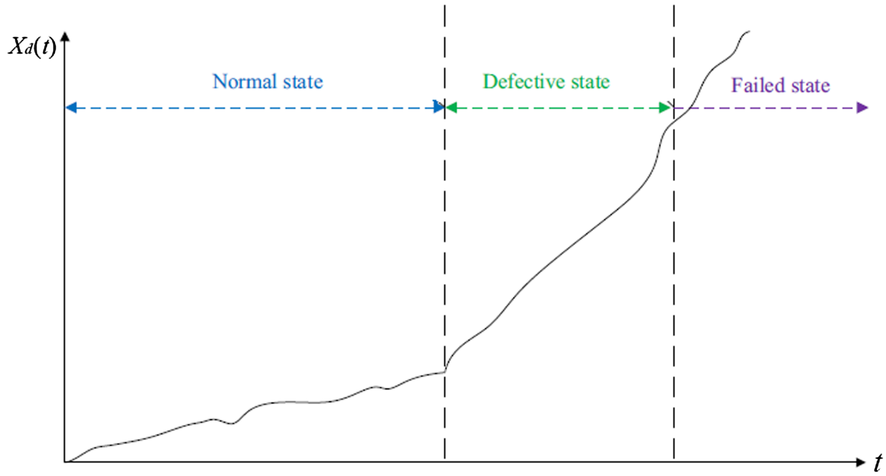

FIGURE 8 The degradation behavior of the system under different states

TABLE 1 Maintenance strategy specifications

Maintenance Strategy	Target Failure/Components	Maintenance Action
Time-based maintenance	Sudden failure, general components with low importance	Taking maintenance actions with a certain interval based on a predetermined age and taking immediate repair actions once sudden failure occurs
Condition-based maintenance	Degradation-based failure, large-scale components with high importance	Based on the facility condition, taking repair actions when the degradation level reaches a certain threshold
Group maintenance	Components in the same system or space operating with collaboration	Taking repair actions based on the optimal system maintenance cost strategy

extensively reviewed strategies.[40] The former is schemed at a predetermined age, which is a common strategy for sudden failures. The latter is schemed based on the degradation information, which is provided by condition monitoring or manual inspection. A single maintenance strategy is obviously easy for implementation but is unable to capture the characteristics of both degradation-based and sudden failures. Applying hybrid maintenance strategies ensures more flexible allocations of maintenance resources and less operation losses.[40]

In addition, each failing machine may be repaired at any time and is considered as good as new once it is repaired. A repair cost is assumed to have both a constant term C_0 reflecting the overhead cost of repair (eg, the cost of bringing a special instrument or a skilled personnel) and a cost of repair per machine C_1. Thus, the cost of repairing n machines is $C_0 + nC_1$. It is assumed that repairs are performed instantaneously. A second type of cost is the cost incurred due to failing machines. This cost is the same for all machines and proportional to the elapsed time between the failure of a machine and its time of repair. Thus, denoting the proportion factor by C_2, the cost of production loss for n failing machines during a time interval of length h is nhC_2. It is shown that an optimal policy is either never to repair (a necessary and sufficient condition for this is provided) or to repair all failing machines as soon as their number exceeds a certain threshold.[41] Following an inspection, we may alternatively decide (not) to repair the failed machines and inspect again at some later time (which may depend on the number of failed machines found in the current inspection). In this case, if a failing machine cannot make the whole operation system to stop working, we can wait until the cost-optimal repair timing comes to perform a group maintenance.

Different maintenance strategy specifications can be found in Table 1, and this maintenance strategy specification process mainly relies on expert knowledge in the e-maintenance platform. Afterward, the corresponding cost estimation results will be modified according to the designated strategy.

6 | APPLICATION CASE: QIANJIANG TUNNEL IN HANGZHOU

6.1 | Qianjiang tunnel in Hangzhou

To validate the effectiveness of the proposed approach, we applied it to the cost estimation process of the Qianjiang tunnel in Hangzhou. The Qianjiang tunnel is one of the most important channels connecting Jiaxing, Hangzhou, and Shaoxing, playing a significant role in road networks. It is composed of two bidirectional six-lane tunnels with an overall length of 4450 m (from K11 + 400 to K15 + 850). It is a type of cross-river tunnel where there are a series of interconnected facilities and equipment. Figure 9 shows the basic civil structure of the Qianjiang tunnel, and the

FIGURE 9 Qianjiang Tunnel in Hangzhou

electromechanical system can be divided into five divisions: power system, lighting system, ventilation system, drainage system, and monitoring system. The description of space and facilities, the partition of objects, and the measurement modes in the Qianjiang tunnel are pretty different from that in quota standard, bringing difficulties in effective cost estimation.

The maintenance strategy of the Qianjiang tunnel is based on the scope of the whole life cycle. The interrelationship among various components, tasks, and factors from design, to construction, and to maintenance is taken into consideration. In this case, the overall maintenance strategy follows the principle of cost minimization and comprehensive benefit maximization.

6.2 | Principles of cost estimation

Compared with a traditional maintenance strategy (corrective maintenance), the life cycle–based maintenance strategy follows the idea of predictive maintenance. Under corrective maintenance, defects or failures are found through daily inspection, whereas potential threats can be predicted through predictive maintenance based on real-time monitoring data. Therefore, under traditional maintenance, a maintenance action is usually taken after defects are discovered, which is opposed to that in life cycle–based maintenance. By fully considering the interrelationship between components and items through the whole life cycle, preventive maintenance is able to enhance system reliability and safety; reduce maintenance manpower, spares, and repair costs; eliminate scheduled inspections; and maximize lead time for maintenance and parts procurement.

The majority of cost in life cycle–based maintenance is generated from predictive maintenance measures, and a limited part of the cost is generated from daily maintenance and major repairs. The principles of cost estimation for the Qianjiang tunnel in terms of differentiated maintenance strategies are as follows.

(1) Significance level–based maintenance

Defects or failures occurred on critical facilities or equipment are more likely to have a significant impact on the operation of the tunnel. There is no reasonable emphasis on the maintenance of these critical components under a traditional maintenance strategy, and all the components are treated equally. Repair is implemented after defect or failure detection, and daily maintenance is executed with the same time interval. Under the life cycle–based maintenance strategy, the maintenance frequency will be modified in terms of the significance level, not just following the maintenance standard or quota.

(2) Condition-based maintenance

For those components with a high level of significance, a health status prediction model is developed based on the real-time monitoring data with the help of sensing technologies, RFID, and data analysis tools. An early warning benchmark is predefined by experts, and maintenance frequency will be modified accordingly.

Taking inspection frequency modification as an example, Table 2 shows the comparison of maintenance frequency between the traditional way and the life cycle maintenance strategy.

6.3 | Cost estimation results

A work item mapping example is shown in Tables 3 and 4. Table 3 shows the mapping information (discriminant information), which can be extracted from IFC, and Table 4 shows a certain quota item's property set. In this case, the property set can be matched between a specific work item and the discriminant rule, and it is determined as the work item "Y3-6-4" Tunnel segment joint.

The cost items in quota standard include five cost categories, namely, structure maintenance, equipment maintenance, facility cleaning, check and inspection, and operation management. We compared the cost estimation results in terms of three different schemes: (1) cost calculation

TABLE 2 Modification of inspection frequency

Inspection Item	Traditional Method	Life Cycle Method	Sig. Level	Traditional Frequency	Life Cycle Frequency
Ice opening	Human	Camera	I	Every winter	Real-time monitoring
Smoothness detection	Test vehicle	Lightweight detection	II	Twice a year	Once a week
Damage detection	Human	Lightweight detection	II	Twice a week	Daily
Skid resistance test	Test vehicle	Lightweight detection	II	Twice a year	Once a week
Segment leakage	Human	Fiber grating	I	Once a month	Real-time monitoring
Tunnel settlement	Human	Sensor	I	Once a quarter	Real-time monitoring
Tunnel convergence	Human	Displacement	I	Once a quarter	Real-time monitoring
PH detection	Human	Sensor	I	Once a month	Real-time monitoring

TABLE 3 Examples of quota items and mapping information

Work Item Code	Work Item Name	Property Set			
		Product Category	Geometric Feature	Material Information	Detailed Classification
Y3-6-4	Tunnel segment joint	joint	line	concrete	Segment joint
Y3-6-7	Structure joint	joint	line	concrete	Structure joint
Y3-1-11	Reinforcement installation	joint	line	reinforcement	Steel expansion joint

TABLE 4 Property set of tunnel segment joint

No.	Property	Property Value	Setting
1	Product category	Joint	Auto
2	Geometric feature	Line	Auto
3	Material information	Concrete	Auto
4	Detailed classification	Segment joint	Auto

based on quota quantity (see Table 4), (2) cost calculation based on modified quantity (see Table 6), and (3) cost calculation with labor special based on modified quantity (see Table 7). The different schemes' output can be generated by manually setting calculation parameters in a cost analysis module.

It can be found (Tables 5 and 6) that there is a big gap between the results of calculation based on quota quantity and that based on modified quantity. After calculating the total cost based on quota standard, the results would be transferred to decision makers, and they are also accessible to all the authorized experts. Since the cost is way out of budget, maintenance management would develop differentiated maintenance strategies in accordance with the experts' suggestions. Therefore, real quantities of each work item would be modified according to the specific maintenance solutions, and the total cost can be reduced significantly.

Another notable issue is that the labor cost in quota standard is distributed to each work item, whereas in a real situation, labor cost is relatively fixed because of the certain number of employees and their standard salary level. In this case, it seems unreasonable to calculate the total labor cost through quota standard. With regarding labor cost (as well as the overhead) as a special case, the total cost is recalculated, and it is found that there is another drop in total cost (Table 7).

By applying this e-maintenance platform, decision makers can refer to the calculation results based on quota and develop more cost-effective maintenance solutions with the help of experts. These maintenance solutions have fully taken consideration of facility state, a predetermined age, and the spatial/systematic relationship among components. In this case, both the maintenance efficiency and cost estimation accuracy can be improved significantly. In addition, through the e-maintenance implementation, both internal and external resources are well involved in the decision-making process. Infrastructure information can be tracked through the whole life cycle, and all participants can get access to an overview of related data from other phases.

TABLE 5 Cost calculation based on quota quantity (in 10 thousand)

Category	Labor	Material	Machine	Overhead	Total Cost
Structure	565.0519	354.8708	550.1427	316.1429	**1786.2082**
Equipment	273.6547	154.0858	283.9294	204.7081	**916.3779**
Cleaning	47.8578	36.2577	77.3369	34.7209	**196.1732**
Inspection	133.0612	2.1307	144.9734	60.2506	**340.4159**
Operation	154.1341	21.4317	145.6017	69.1442	**390.3117**
Total cost	**1173.7597**	**568.7766**	**1201.9841**	**684.9665**	**3629.4869**

TABLE 6 Cost calculation based on modified quantity (in 10 thousand)

Category	Labor	Material	Machine	Overhead	Total Cost
Structure	33.2856	5.3032	16.7377	11.8982	**67.2247**
Equipment	115.2070	29.7737	234.9495	89.0002	**468.9304**
Cleaning	18.2228	23.4784	52.2905	20.2133	**114.2050**
Inspection	56.7812	0.2394	82.2564	29.9520	**169.2291**
Operation	99.5416	19.6197	54.3343	37.3519	**210.8475**
Total cost	**323.0382**	**78.4144**	**440.5685**	**188.4155**	**1030.4366**

TABLE 7 Cost calculation with labor special based on modified quantity (in 10 thousand)

Category	Material	Machine	Total Cost
Structure	5.4343	20.5206	25.9549
Equipment	16.0997	137.9788	154.0785
Cleaning	35.6230	76.8383	112.4613
Inspection	0.2394	91.0923	91.3317
Operation	16.5597	53.7343	70.2941
Labor cost			441.0000
Overhead			73.7832
Total cost	**73.9562**	**380.1644**	**968.9037**

7 | CONCLUSION

In this paper, we have proposed an e-maintenance framework for public infrastructure based on IFC and semantic web technologies to deal with the interoperability problem in the AEC industry. It is able to gather and process heterogeneous information and output particular information for particular users, supporting more effective maintenance work. Taking tunnel projects as an example, this paper implemented the method into a tunnel maintenance cost analysis process based on quota standard, providing more detailed information about the automatic implementation mechanism of the proposed e-maintenance framework. It is proved that both the maintenance efficiency and cost estimation accuracy can be improved by applying this approach. This idea can also be applied to other infrastructure domains to improve maintenance efficiency.

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