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Research Article

Study on the Evaluation Method of Green Construction Based on Ontology and BIM

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Many problems and issues affect the green construction process. Inaccurate assessment is one of the important factors for green construction. The objective of this study is to propose a BIM and ontology-based approach that enables the evaluation information of green construction to be inferred from a knowledge base in order to achieve scheme optimization. To automate the inference, this study established the BIM ontology that consists of BIM shared ontology and BIM construction ontology. First, IFC extension is adopted in green construction assessment system to generate attribute sets. IFC-based parameters stored in BIM models are mapped to OWL and will be used as the data source of the evaluation indicators. Then, BIM-shared ontology and BIM construction ontology are defined. Protégé is employed to simulate the evaluation indicator system. Last, utilizing BIM knowledge base, through the construction of SWRL rule language and the Drools inference, the scores of evaluation indicators could be obtained. The experimental results demonstrated that BIM knowledge base for the evaluation of green construction could realize the sharing, maintenance, and acquisition of knowledge among different participants of the project and improve the management of green construction. The proposed ontological inference of evaluation item enables an automated search of the aspects needing improvements in green construction and assist project managers in using BIM data more easily and effectively.

1. Introduction

Sustainability in the AEC (architecture, engineering, and construction) industry has gained popular momentum over the past decades to enable all people to meet their basic needs and improve their quality of life while saving our natural resources and diversity [1]. By virtue of its size, the construction industry is one of the largest users of energy, material resources, and water, and it is a formidable polluter [2]. Construction and the environment are inextricably linked. Energy, materials, water, and land are all consumed in the construction stage of buildings and infrastructure.

Green construction is defined to ensure quality, safety, and other basic requirements and adopt scientific management and technological progress in the process to maximize the conservation of resources and reduce the construction activities which will bring negative impacts on the environment [3]. Green construction is the application of sustainable development idea in the AEC industry. The traditional construction method is to achieve the project quality, schedule, and cost as the basic goal [4]. The resource conservation and the environmental protection get less focus in the construction stage, while green construction emphasizes the efficient use of resources as the core and the environmental conservation as the priority principle in order to pursue the integrated construction method with the high efficiency, low consumption, and environmental protection [5]. Practitioners in construction industry have begun to pay attention to evaluating and controlling the environmental impacts due to their activities. Architects, designers, engineers, and others involved in the construction process have their opportunities to reduce environmental impacts through the implementation of sustainability objectives.

Over the last couple of years, BIM (Building Information Modeling) adoption has seen quite a significant growth in the AEC industry, and it has been impacting design and construction practices at the fundamental level. Seeing the value of BIM, more and more firms are migrating their practices to the BIM process. This approach enables stakeholders to participate in the construction process and maximizes the use of prefabrication, thereby optimizing the construction phase while staying within budget restraints. Through the digitalization of construction information, the BIM process gives us a great control in the construction stage. Having the data about all the construction products gives the possibility to check the impacts of construction activities on the environment.

As the green construction phenomenon continues to grow and gain popularity, many problems and issues cast doubts on the development of green construction. In one respect, green construction implementation on an integrated and comprehensive scale to satisfy the holistic perspective and collaboration has encountered many challenges [6]. The challenges need robust methods to tackle the complexity of green construction management and environmental treatments which involve better energy efficiency, improved environmental quality, and the minimization of resource usage in construction phase [1, 7, 8]. On the other hand, the inaccurate assessment of the green construction is a major obstacle to overcome [9, 10]. There is a need to better understand the pivotal attributes that participants should possess to manage green construction. Previous evaluation studies related to green construction are dependent on the subjective feedback from construction technicians, which are thought to be inefficient and unreliable. So as to make one step forward towards the development of green construction assisted by the improvements of information technologies, there is the need to integrate the process of green construction evaluation with BIM technology [11].

The challenge that this incorporation faces is the parameterized expression of the evaluation knowledge and BIM-related information synthesis of all the available elements in purpose of achieving optimized measurements. In recent years, information synthesis has turned out to be more complicated with the increased use of data mining and decision-making support [12]. It is noticed that semantic-based approaches using domain ontologies have been adapted for data modeling and information integration [13, 14]. In general, an ontology represents a shared, agreed, and detailed model (or set of concepts) of a certain problem domain [15]. Ontology-based information synthesis in evaluation process mainly aims at improving the interface between feature attributes and evaluation requests in order to bring the result sets closer to the users' requirements in practices.

The objective of this study is to propose a BIM and ontology-based approach that enables the evaluation information of green construction to be inferred from a knowledge base in order to achieve scheme optimization. To automate this inference, this study established the BIM ontology that consists of BIM-shared ontology and construction ontology. The basic attributes contained in the established BIM-shared ontology are identity, size, space, and material. BIM construction ontology is created to include principles of the green construction and evaluation indicators. According to the definition of ontological meanings based on the BIM data, specific evaluation results can be acquired. Also, the proposed ontological inference of evaluation items enables an automated search of the aspects needing improvements in green construction and assists project managers in using BIM data more easily and effectively.

In this paper, Section 2 briefly discusses the trends of research and system developed for green construction and BIM technology. Section 3 introduces the methodology suggested in this paper. Sections 4 and 5, in order to build BIM knowledge base, IFC (Industrial Foundation Classes) expression, and data mapping are presented to confirm that the proposed ontology can fully represent the content of green construction. Finally, the paper concludes by offering some final remarks in Section 6.

2. Related Works

Green construction aims to eliminate or reduce negative environmental effects on the construction phase. It is also known as sustainable construction. Construction is one of the largest contributors to greenhouse gas emissions. With the development of society, new requirements such as saving labor resources, selecting machinery, and building information platform are put forward and green construction emerges [16].

2.1. Green Construction. The adoption of green construction strategies is mainly driven by concerns about climate change and nonrenewable energy use and also economic and ergonomic reasons like to increase efficiency and improve the construction performance. Previous studies about green construction evaluation mainly focus on the indicator selection and the quantitative methods. Li et al. [17] developed a green construction evaluation system of mountain highway projects using gene analysis and fuzzy matter element method. Zhang and He [18] adopted fuzzy integrated method and AHP (Analytic Hierarchy Process) to set indicator in all levels for the evaluation system of green construction. Then, the weight of each indicator was calculated, and the evaluation model was established. In order to refine the quality management and evaluation, Gu and Li [19] discussed the common knowledge connotation on the compliance evaluation system of complex quality and proposed an ontology model of it with generic knowledge modeling method. Passornpakorn and Kamolphiwong [20] raised an ontology-based framework based on REST principles and SPARQL (SPARQL Protocol and RDF Query Language) rules to interactively self-assess e-health services. They also demonstrated its capability to maintain new data schema during run-time and support of IoT (Internet of Things). By analyzing semantic web technologies and the IFC standard, Pauwels and Terkaj [21] connected them with an agreed Web Ontology Language (OWL) ontology for IFC (termed ifcOWL) in order to support data interoperability, flexible data exchange, distributed data management, and the development of reusable tools. Yang et al. [22] applied the theory of the knowledge base and ontology to describe the four aspects of the telecommunications fraud cases and build a scalable case model. Through one example, the validity of the model in the analysis of telecommunications fraud cases is verified.

Internationally, many governments also make the efforts to develop different approaches in order to evaluate green construction. The first sustainability assessment method called BREEAM was developed in England in 1990. Besides, in America, LEED (Leadership in Energy and Environmental Design) raised the Green Building Rating System in 1995. In the same year, another green building assessment tool (GBtool) managed by the International Initiative for a Sustainable Built Environment (iiSBE) of Canada was released. Although their evaluation indicators vary from one standard to another, their goals are consistent to reduce the use of resources, protect the environment, and conform to the idea of sustainable development while meeting the standards in quality and safety. In China, according to the green construction guideline released by the Ministry of Housing and Urban-Rural Development, the aim of green construction is to conserve water, energy, land, material, and protect the environment through project management and advanced construction technology. With reference to these evaluation standards and their indicators, the Evaluation Standard for Green Building (ESGB) is developed by the China Academy of Building Research. The level of interior environment, operation management, and water, energy, land, material conservation are the main evaluation criteria of ESGB.

2.2. BIM and Green Construction Evaluation. It is indicated that the manual evaluation method, widely adopted now, relies on the experiences of the evaluators and is less efficient [23]. This complexity and need for reliable results claim for assistance of more integrated and intelligent tools, like BIM. BIM is an object-oriented, intelligent, and parameterized digital representation of building with rich semantic information. In order to manage the tremendous amount of information created in BIM and realize data exchange between different sectors, the information standards like IFC standard and its relevant EXPRESS language are developed. As a common adopted standard format for BIM data exchange and collaboration, IFC (Industry Foundation Classes), in which categories are called entities, is presented by object-oriented method. The architecture of IFC consists of four layers: resource layer, core layer, interoperability layer, and domain layer [24]. The information description module of each layer contains the definition of entities, types, and attribute sets, which can be modified by users to extend green construction information. The data modeling language of IFC schema is called EXPRESS, which is an international standard data modeling language for product data [25]. One of the advantages of using EXPRESS is its sufficient capability of describing data type, entity, algorithm, rules, etc. Through the definition of entities, physical, or conceptual objects in the real world, which share common characteristics, can be categorized and grouped together. Besides, the data content in these objects can be expressed by attributes in IFC and the behavior of these objects is represented by static constraints.

With the help of IFC schema and EXPRESS language, the green construction information can be connected to the BIM model. However, because the rich information from the real world is often implicit and do not have very logical schema, it is complicated for the computers to understand and digitalize it. To conquer the problem of relating target objects to the computer, the standardization would help a lot and facilitate model-based problem solving.

2.3. Ontology Method. Ontology method is introduced into the computation field from the 1980s to provide a basis of building models of all things in which computer science is interested; thus, it is intelligible both to computers and humans. Ontology is a domain and application-oriented method to assist in extracting knowledge that is specific to a particular domain and/or application [26, 27]. Besides, according to Moguillansky and Simari [28], an ontology model is not only formal and machine-understandable, but also available for knowledge sharing. Therefore, the ontology methodology is considered as a suitable method to model green construction evaluation indicators within BIM. An ontology can formally be specified using an ontology language. Because of the better expressive power, the OWL (Ontology Web Language) was recommended by the W3C (World Wide Web Consortium) as the ontology language [29]. The basic components of OWL are class, property, and instance. Class describes a set of instances which share common properties, while attribute connects instances with property values.

Data exploration helps us understand the investigated reality in a faster and better way. The data to be explored are domain knowledge bases with rules representation [30]. To best realize the power of ontology method in green construction evaluation and fit it in the task model, it is essential to construct a knowledge base with ontologies. As a technical basis, knowledge base is used to store complex structured and unstructured information that describes the target object in a computer system [31]. Furthermore, Liu and El-Gohary [32] suggested a way to extract the semantic features based on a bridge deterioration knowledge ontology. Warren et al. [33] suggested the advantage of knowledge base in facilitating information sharing, intelligent "query-ability" of data based on ontologies, and high reliability due to the standardized expression. Priya et al. [34] adopted knowledge reasoning method based on rules and utilize reasoning engine Drools to enhance the expressivity and richness of knowledge. Moreover, knowledge reuse plays also an important part in effective utilization of target objects in knowledge base.

In summary, there have been quite a number of studies on green construction evaluation over the last decade. Some of them deal with evaluation methods for green construction performances and others are for key technologies in green construction. Still others are for ontologies of the green construction knowledge. However, there seem to have limited studies specifically on the creation and utilization of BIM and ontologies to integrate the appropriate information for the purpose of green construction evaluation. Green construction evaluation is getting more and more complicated, and this is mainly due to the increased volume of the construction information and knowledge. This complexity and the need of reliable results claim for the utilization of existing tools, like BIM. The literature reviewed above identifies that BIM and evaluation methods are both necessary techniques that are used to facilitate the analysis and interpretation of green construction. Furthermore, evaluation indicator selection strategies offer limited integration of ontology and geometric data models. Related works lack a centralized knowledge database containing original data and solutions that can be used to determine problematic areas before finalizing optimization to green construction. Thus, developing an integrated evaluation system for green construction using existing experiences in ontology and BIM is key to effectively improve the sustainability of construction activities.

3. Methodology

The objective of this research is to establish an automatic green construction evaluation and optimization system. Hence, an ontology-based knowledge base from which the evaluation information of green construction could be inferred is proposed in consideration of four main steps: (1) five primary indicators and relevant attribute sets are defined based on previous studies and standards; (2) IFC expression is developed to describe the evaluation information and mapped to OWL as the data source; (3) combining BIM ontology and the evaluation indicator system of green construction, the framework of knowledge base is constructed; (4) the evaluation process is demonstrated using BIM knowledge base, and the results of the evaluation can be inferred from the collected data, as shown in Figure 1.

The proposed methodology, as the corresponding pseudocode shown in Algorithm 1, passes through the four steps to achieve the research objectives as follows. (1) After searching the existing standards and periodical articles concerning green construction evaluation, a green construction evaluation indicator system and the evaluation criteria are synthesized. (2) It further develops IFC extension which focuses on property sets P (p_1, $p_2, \ldots$) in order to express the indicators and attributes of green construction evaluation. Subsequently, the green construction evaluation indicator system is expressed as E (e_1, $e_2, \ldots$) by EXPRESS-G so that the relationships between entities can be graphically presented. Next, the IFC attributes of green construction evaluation are mapped into OWL language. The BIM model is used as the source data of green construction evaluation in the knowledge base. (3) BIM-shared ontology (BIMSO) and BIM Construction Ontology (BIMCO) are created. In parallel, Protégé Software is employed to simulate the green construction evaluation system. Since only formatted language could be understood and executed by computer, the model needs to be formatted by OWL. Combining BIM ontology and the evaluation model of green construction, the framework of knowledge base K is established in consideration of five aspects: BIM project, construction activities, green construction data, green construction evaluation, and optimization measures. (4) The proposed evaluation works by converting the knowledge of individual instance into Drools facts and converting SWRL (Semantic Web Rule Language) rules from the knowledge base, then running Drools inference based on rules, finally inferring new facts and updating the knowledge base. According to the calculation results, the unqualified indicators with scores lower than a limit t could be screened out by SPARQL inquiry. Afterwards, optimized measures could be inferred and the scheme of green construction could be modified. To demonstrate the evaluation process, a residential building is taken in this study as an example. Besides, based on the characters of knowledge reuse, the workflow to select the optimal scheme of green construction is suggested, which includes matching similar projects, modifying the green construction scheme, and updating the BIM database.

4. IFC Expression and Data Mapping

4.1. IFC Expression of the Evaluation Indicators. IFC is commonly adopted as the standard format for BIM data exchange and collaboration. This work develops a solution for the expression of the evaluation indicators of green construction, which could be used as the extended attribute sets of IFC entities. Because the extension is carried out based on the attribute set, considering beams, slabs, columns, and walls as entities in IFC standard, there is no need to define new entities and the original architecture of IFC standard remains unaffected. The process of IFC extension is shown in Figure 2. First, with reference to the characteristics of the evaluation indicator of green construction, corresponding entities and attributes in IFC standard are determined; second, the indicators are divided into attribute sets according to the properties of the evaluation; finally, the attributes and attribute sets are defined and the extension of IFC-based evaluation indicator of green construction is completed.

Over the last few decades, many management models have been adopted for the purpose of enhancing the performance of the construction projects. Some potential key performance indicators widely adopted can be used to evaluate and compare the performance of construction. With reference to previous studies by Nie et al. [35], Li et al. [17], and Zhang and He [18], there are five primary indicators, and their relevant attribute sets are defined in this work (as shown in Table 1).

The IFC4 standard has given definitions about generic attributes of beams, slabs, columns, and walls. Therefore, attributes and attribute sets mentioned above need to be specified. The specification of attributes includes attribute name, attribute type (IfcPropertySingleValue), and attribute value type (IfcReal). On the other hand, the attribute set

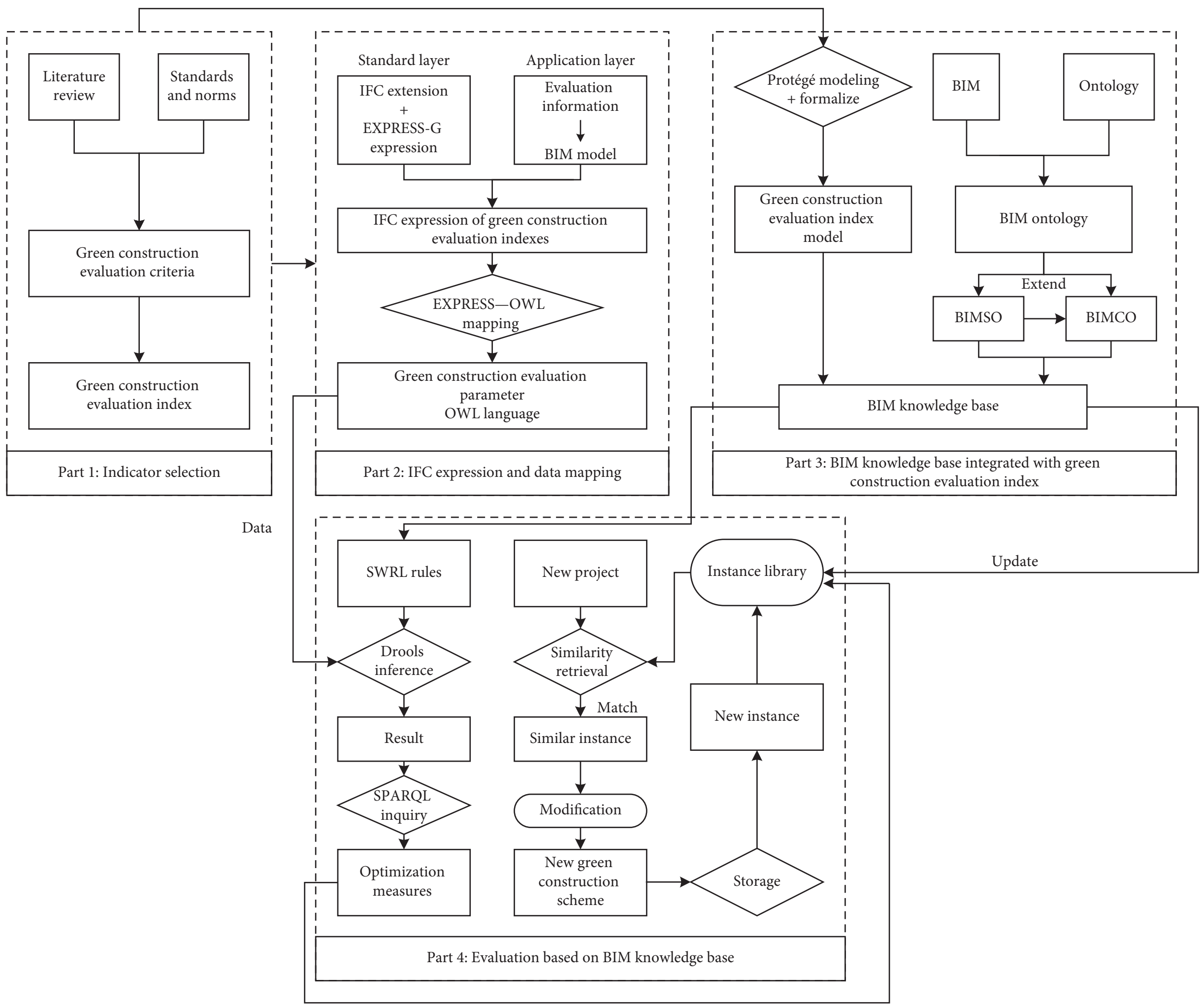

Figure 1: Overview of the implementation of proposed methodology.

Evaluation algorithm for green construction.
(1) **In:** Evaluation Indicator of green construction.
(2) **Out:** Evaluation scores and specific indicators needing improvements
(3) **Start**
//the first stage
(3) Synthesize the green construction evaluation indicators and criteria
//the second stage
(4) Develop Ifc-extended attributes P (p_1, p_2, ...) to represent the property sets.
(5) Develop Ontology-based parameter E (e_1, e_2, ...) to represent the evaluation indicators.
(6) Map (P/E, $\{p_1, p_2, \ldots\}/\{e_1, e_2, \ldots\}$)
//the third stage
(7) Build the knowledge base $K \supseteq E$
//the fourth stage
(8) Generate the evaluation score of all indicators E_i based on values from K
(9) Retrieve specific indicator with $e_i < t$ which needs to be improved and optimized//t is the lower limit for the evaluation result.
(10) **End**

Algorithm 1: Pseudocode description of the proposed methodology.

definition includes set name, applicable entity, applicable type, and set description. As an example, the attribute set of construction preparation indicator is defined in Table 2.

4.2. Indicator Expression in EXPRESS-G. After the green construction evaluation indicator is extended into IFC, the IFC expression needs to be realized. The data modeling

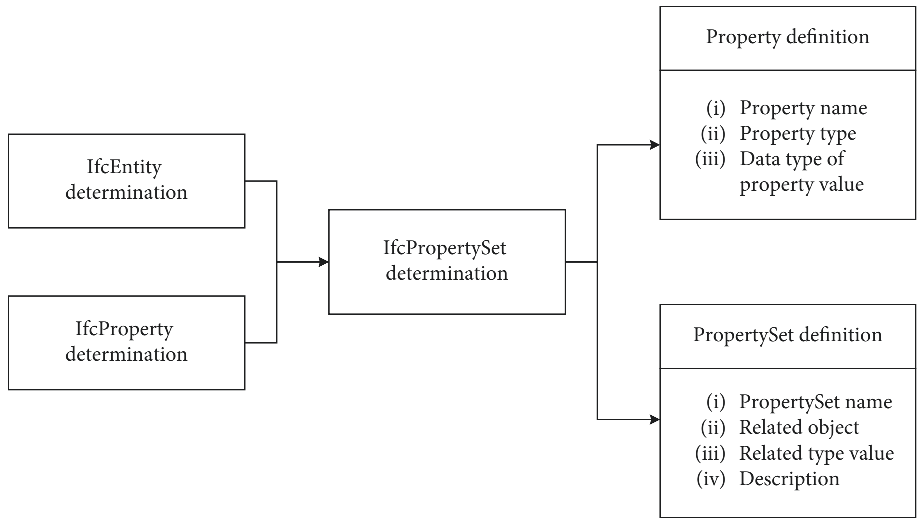

Figure 2: The process of IFC extension.

Table 1: Indicator attribute set.

Indicator	Attribute set
Construction Preparation	PSet_ Construction Preparation
Construction Site	PSet_ Construction Site
Ground and Foundation Engineering	PSet_ Ground and Foundation Engineering
Main Structure Engineering	PSet_ Main Structure Engineering
Decoration and Electromechanical Engineering	PSet_ Decoration and Electromechanical Engineering

Table 2: IFC construction preparation attribute set definition.

Attribute set name	PSet_ Construction preparation
Applicable entity	IfcEntity
Applicable type	Construction preparation
Set description	This property set describes indicators of construction preparation, aiming to conduct green construction evaluation

language of IFC schema is called EXPRESS, which is an international standard data modeling language for product data [22]. An EXPRESS data model can be described in two ways: the textual form of EXPRESS program and the tree-structured graphical notation called EXPRESS-G (a companion to the EXPRESS text, it is also called the graphical subset of the EXPRESS language). One of the advantages of EXPRESS-G is that the relationships between entities can be graphically presented in a more understandable manner. Therefore, EXPRESS-G notation is adopted as the method of expression in this work.

As shown in Figure 3, the EXPRESS-G diagram illustrates the IFC attributes with IfcRoot, IfcObjectDefinition, IfcObject, IfcProduct, IfcElement, IfcBuildingElement, IfcPropertySetDefinition, IfcPropertySet, and IfcProperty. The thick solid line represents the inheritance relationships between adjacent entities. The correlation between IfcPropertySet and IfcEntity is realized through IfcPropertySetDefinition. In this way, the status of IfcEntity can be represented by the evaluation indicator contained in IfcProperty. IfcProperty entity includes two subentities: IfcSimpleProperty and IfcComplexProperty. Moreover, IfcSimpleProperty consists of six subentities. The five attribute sets defined in this part are optional attribute sets of IfcBeam/Slab/Column/Wall (entities that inherits all the properties of IfcBuildingElement). The correlation between them is represented by dotted lines. All indicators are contained in the dotted box. The indicators can be displayed in the five attribute sets, and the relationships between them are represented by thin solid lines. The attribute value type of all the attributes is Real. "ABS" stands for abstract type. This study uses Revit to create specific BIM model in order to establish the correlation between the evaluation information of green construction and BIM model. The correlation process is comprised of four steps: ① setting up Revit family files, ② establishing the evaluation parameters of green construction and correlating them with family files, ③ loading family files into the project and inputting values of parameters, and ④ exporting IFC files.

4.3. Mapping IFC to the Evaluation Ontology. The evaluation information of green construction is stored in the BIM model in the form of IFC parameter. In this work, the IFC-based parameter is mapped to OWL and will be used as the data source of the evaluation indicators of green construction in BIM knowledge base.

4.3.1. EXPRESS—OWL Mapping Framework. By mapping the EXPRESS language of IFC standard to OWL, the information related to the BIM model and the ontology can be shared and integrated. The schema of IFC data conversion is illustrated in Figure 4. The conversion process obeys by the following principles: ① semantics described by EXPRESS before mapping is consistent with that described by OWL after mapping; ② if the definitions in IFC cannot be clarified with concepts or grammars in OWL, external grammar will

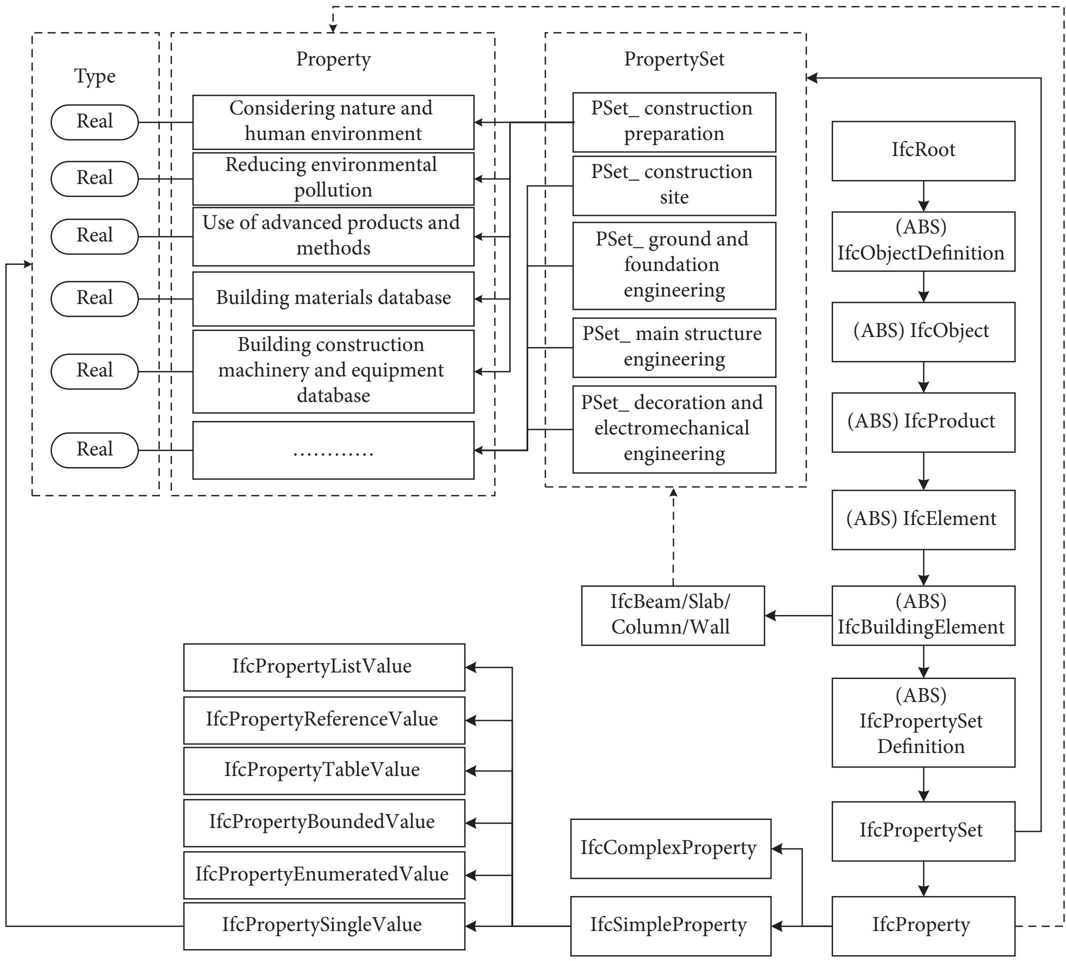

Figure 3: EXPRESS-G chart of the evaluation indicators on green construction.

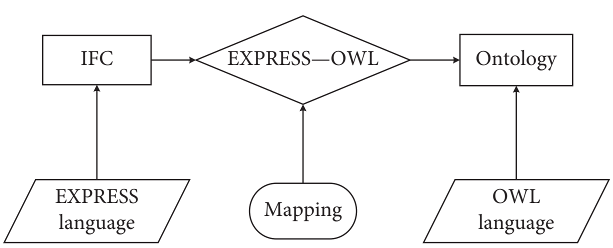

Figure 4: Diagram of IFC data mapping.

be adopted. Through the analysis of EXPRESS language based on the conversion mode between IFC and OWL, the EXPRESS-OWL mapping framework is developed, and therefore, the conversion of BIM data is realized (as shown in Table 3).

4.3.2. Mapping OWL to the Evaluation Indicator. The next step is to associate green construction evaluation information to the OWL parameter. Among all IFC-based parameters, "Dust control" is selected in this work as an example. Figure 5 shows the EXPRESS-OWL mapping of "Dust control," which is also applied to other parameters. The detailed illustration on the relationship between EXPRESS and OWL expression of "Dust control" is listed in Table 4. Through the mapping process, all indicators are converted into OWL format and the conversation of BIM data to OWL data is realized. The converted OWL data then will be used as the source data of green construction evaluation in the knowledge base.

5. BIM Knowledge Base Integrated with the Evaluation Indicators of Green Construction

5.1. BIM Ontology

5.1.1. BIM-Shared Ontology (BIMSO). A BIM model consists of numerous building elements, which are the basic composition units of the BIM model. Therefore, by specifying the basic attributes of every building elements, the model can be defined exactly. According to the basic attributes of building elements, a basic BIM-shared ontology is constructed in this work. The shared ontology can be applied to the construction field by supplementing corresponding attributes. The basic attributes in the form of the building elements, which are contained in the established BIM shared ontology (BIMSO), are identity, size, space, and material. The detailed BIM-shared ontology is illustrated in Figure 6. BIMSO:Building stands for building element; BIMSO:

Table 3: Mapping between EXPRESS language and OWL language.

			EXPRESS expression	OWL expression
Patterns and interface specifications			(i) Pattern (ii) User interface specifications (iii) Reference interface specifications	(i) Ontology (ii) rdf:about (iii) owl:import
Data type	Simple data types		Data type: (i) Boolean (ii) Integer (iii) String (iv) Real (v) Binary (vi) Number	owl: Datatypeproperty: (i) xsd:boolean (ii) xsd:integer (iii) xsd:string (iv) xsd:real (v) hexBinary/base64Binary (vi) Methods to customize axiom
	Aggregation types		LOGICAL	Expressed by union in XML schema
			ARRAY BAG SET	Expressed by user-defined data types in XML schema
			LIST	rdf:Lists
	Constructed types		ENUMERATION SELECT	owl:one of rdfs:subclasses owl:unionOf
	Defined data types		Defined data	Expressed by user-defined data types in XML schema
	Entity data types		Entity data	Add prefix information when defining entity properties
Entity type	Entity—classes		Entity + entity name	<owl:Class rdf:ID = "entity name">
	Entity—instances		Entity + instance name	<owl: individual = "instance name">
	Entity attribute	Explicit attribute	Mandatory	<owl:ObjectProperty rdf: ID = "EntityName_PropertyName"><owl: DatatypeProperty rdf: ID = "EntityName_PropertyName">
			Optional	OPT_
		Derive attribute	Derive	Specific owl:Class
		Inverse attribute	Inverse	ObjectInverseOf declaration of a property as inverse property InverseObjectProperties declaration of two properties as mutual inverse properties
	Local rules	Domain rule	Where	swrl:equal
		Unique rule	Unique	Expression key hasKey of axion hasKey
	Supertype&Subtype		Supertype&Subtype	rdfs:superClassOf rdfs:subClassOf

hasIdentity, BIMSO:hasSize, BIMSO:hasSpace, and BIMSO: hasMaterial stand for the four basic attributes that are contained in the building elements.

(i) Identity: it includes description, ID value, Manufacturer, etc.

(ii) Size: it includes length, height, thickness, volume, etc.

(iii) Space: it includes associated floor number and room position

(iv) Material: it includes qualitative properties of the materials like the grade and color of the cement and quantitative properties of the materials like density and compression strength.

(v) fc: ConstructionAndBuildingMaterials is designed based on the existing Free Class OWL ontology (FC) and represents the building material; qudt_schema: Unit is designed based on the existing QUDT ontology and stands for unit.

5.1.2. BIM Construction Ontology (BIMCO). By extending BIM shared ontology, the BIM construction ontology (BIMCO) can be constructed. BIMCO will be utilized as the foundation of the BIM knowledge base. The details of BIM construction ontology are shown in Figure 7. By supplying relevant information about green construction extension (BIMSO:hasGreenConstruction) into BIMSO:Building, BIMCO: Element is created and consists of two parts.

(1) Principles of Green Construction. According to the green construction specification, there are five principles: BIMCO: EnergyConservation, BIMCO:WaterConservation, BIMCO: LandConservation, BIMCO:MaterialConservation, and BIMCO: EnvironmentalProtection.

(2) First Level Indicators of Green Construction Evaluation (BIMCO:FirstIndicator). The first level of green construction evaluation information consists of five indicators which are extended into BIM model ontology: BIMCO:ConstructionPreparation, BIMCO:ConstructionSite, BIMCO:

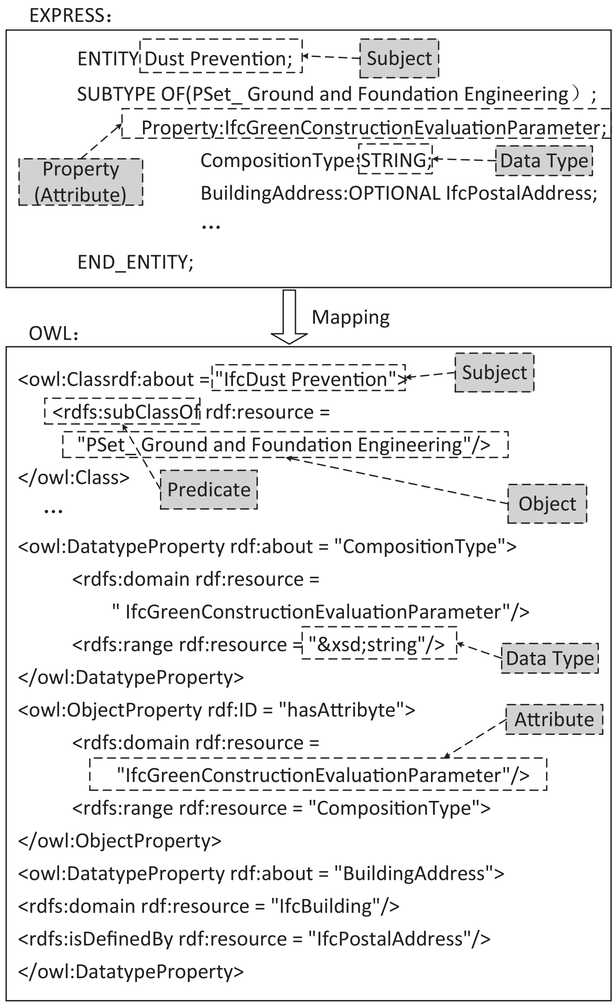

Figure 5: EXPRESS-OWL mapping of dust control parameter.

GroundAndFoundation, BIMCO:MainStructure, and BIMCO: DecorationAndElectromechanicalEngineering.

5.2. BIM Knowledge Base Framework. In this study, Protégé is applied to model the evaluation indicator system of green construction, which could support the integration of evaluation indicator system and BIM knowledge base. Protégé is always viewed as a professional tool especially in ontology modeling and knowledge acquiring based on Java environment. It is an open source software application and is widely used for ontology modeling in semantic network. Since only formatted language could be understood and executed by computers, after the evaluation indicator framework is constructed, its expression needs to be formatted. In this paper, OWL is used to formalize expressions, and classes need to be defined and declared. Their subordination relations are then determined before OWL code is programmed.

By combining BIM ontology and the evaluation indicator system of green construction, the framework of knowledge base is determined in consideration of five aspects: BIM project, construction activities, green construction data, green construction evaluation, and optimized measures. An instance of the framework is represented in Figure 8. As shown in this example, after the BIM project is created, the next step is to collect data from construction activities. The "construction activities" is divided into five first-level indicators: construction preparations, construction site, ground and foundation engineering, main structural engineering, and decoration and electromechanical installation engineering. "Construction activities" generates "green construction data," which is viewed as the second-level indicator. After collecting green construction data, the evaluation process is to be conducted, and optimized measures can be suggested. Finally, based on the evaluation indicator framework of green construction and the composition of the BIM model, the BIM knowledge base is established. BIM knowledge base mainly consists of the relationships between classes, object properties, data properties, and instance creation.

5.2.1. Relationship between Classes. Class is the basic element in the knowledge base. The five basic aspects, including BIM project, construction activities, green construction data, evaluation of green construction, and optimization measures, are defined by class as shown in Table 5.

5.2.2. Object Properties. To describe the nonhierarchical relationships between classes, numerous object properties could be defined in the knowledge base. "BIM project" includes "construction activities," and their relationships can be expressed by "hasConstruction;" "Construction activities" produces large amounts of "green construction data," and their relationships are represented by "produceInformation;" the property of "Evaluation of green construction" is conducted based on "green construction data," and this step is called "conductEvaluation;" "optimization measures" is developed according to "evaluation of green construction" and described based on "raiseOptimization."

Name, domain, range, and function properties are defined as the four object properties mentioned above (as shown in Table 6). The definition of domain is the origin of the attribute relations, and the definition of range is the ending of the attribute relations. In other words, domain and range are linked by attribute relationships. "Functional" means that the attribute could only connect one entity and "inverse functional" means that the inverse property of the attribute has the functional property. According to the analysis, all four attributes have inverse functional properties. Although there always have been several construction activities in one project, each specific construction activity belongs to only one project.

5.2.3. Data Properties. Data property represents the relationship between class and data, which is simpler than object property. Data is linked to class by data properties, and data properties exist depending on class. Data properties of five basic classes are analyzed, and the detailed results are listed in Table 7.

Table 4: EXPRESS-OWL mapping of dust control parameters.

EXPRESS expression	OWL expression
Dust prevention is an entity called dust prevention	Correspondence: OWL subject—owl:class rdf:about = "IfcDust Prevention"
Relationship: SUBTYPE OF	Correspondence: OWL predicate—rdfs:subClassOf
Property set that it belongs to: PSet_Ground and Foundation Engineering	Correspondence: OWL object—rdf:resource = "PSet_Ground and Foundation Engineering"
IfcGreenConstructionEvaluationParameter Property: IfcGreenConstructionEvaluationParameter	Correspondence: OWL ObjectProperty, its domain is rdfs:domain rdf: resource = "IfcGreenConstructionEvaluationParameter"
Composition type: Data type STRING	Correspondence: OWL DataTypeProperty, its domain is rdfs:range rdf: resource = "&xsd:string"

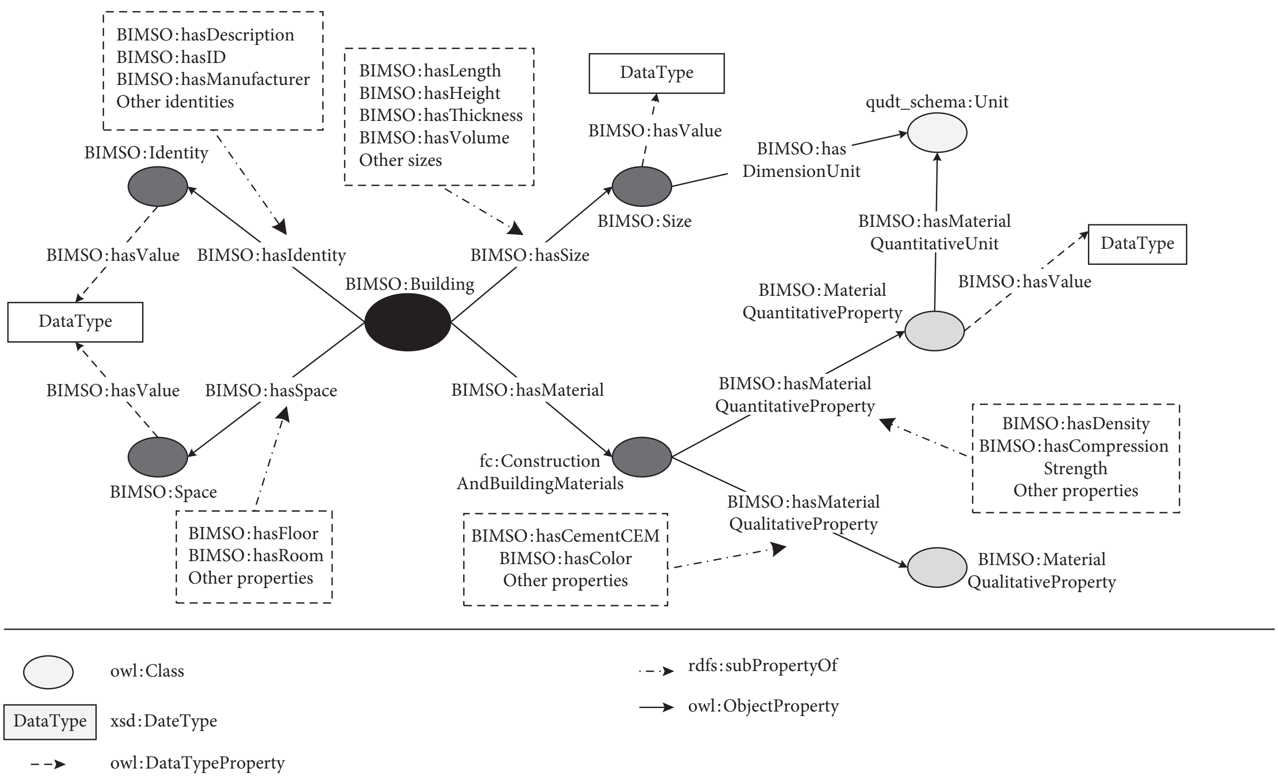

Figure 6: Concept of BIM ontology.

5.2.4. Instances Creation. After establishing classes and properties, the next step is to create instances according to classes. In comparison with the class which is an abstract concept, the instance represents the specific entity. The establishment of instances is of great significance for the application of the knowledge base. For example, a specific BIM project is an instance and the construction activities generated are corresponding specific instances. Considering the instance of "decoration and electromechanical installation" as an example, the environmental pollutant concentration indicator, which is one of the indicators of green construction information, is selected to help evaluate green construction and develop optimized measures. This whole process is named as "instances creation."

Through the establishment of instances, corresponding links are formed between BIM projects, construction activities, green construction data, evaluation of green construction, and optimized measures (as shown in Figure 9). Instances are added and linked to the former ones through the addition of object properties which point to another instance. The complete link of BIM knowledge base contains the following parts. "Residential Building BIM project" has the construction activity of "indoor decoration," which generates the "data of indoor pollutant concentration" as part of the green concentration data. With reference to the "data of indoor pollutant concentration," the evaluation of green construction is conducted and the result "indoor pollutant concentration is high" is obtained. To solve the detected problem, optimized measure "low-pollution materials should be used for decoration" is raised.

6. Evaluation Based on BIM Knowledge Base

To demonstrate the evaluation process, a BIM project of a residential building is taken in this work as an example, from which some indicators of green construction are collected

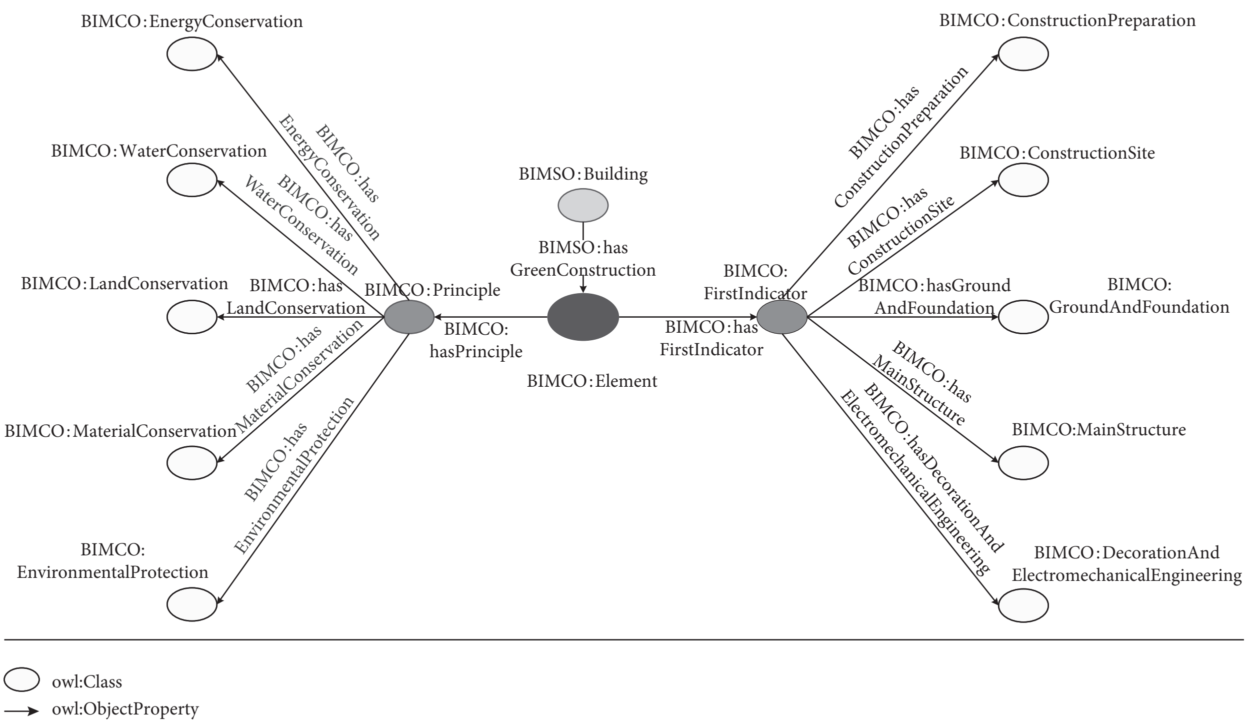

Figure 7: Concept of BIM construction ontology.

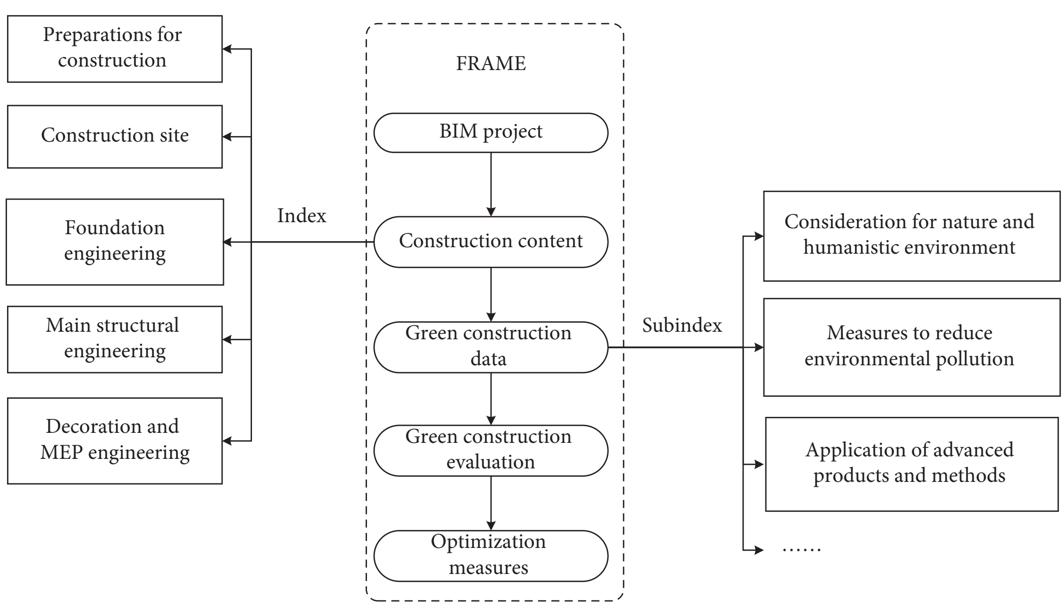

Figure 8: Framework of BIM knowledge base.

and the evaluation of green construction is conducted accordingly. Firstly, the standards for evaluation indicators are developed and described by SWRL before it is input BIM knowledge base; secondly, the values of green construction indicators are determined, which are derived from the extension of BIM model and have been converted to OWL language format; lastly, with the help of SWRL rule base, the evaluation results can be inferred from the collected data of the indicators.

(1) Establishment of property rules

According to the link diagram of BIM knowledge base, the relationships between BIM projects, construction activities, green construction data, evaluation of the green construction, and optimized measures are simulated as follows: BIM project and construction activities are connected by "hasConstruction" property; construction activities and green construction data are connected by "produceInformation" property;

Table 5: Definitions of basic classes.

Class name	Abbreviation in English	Description
BIM project	BIM	BIM model of the project
Construction activity	Construction	Construction activities of the project, mainly the first-grade indicators of the indicator system
Green construction data	Information	Relevant green construction data, mainly the second-grade indicators of the indicator system
Green construction evaluation	Evaluation	Green construction evaluation according to green construction indicator values
Optimization measure	Optimization	Optimization measures according to green construction evaluation result

Table 6: Definitions of object properties.

Property name	Domain	Range	Function characteristic
hasConstruction	BIM project	Construction activity	Inverse functional
produceInformation	Construction activity	Green construction data	Inverse functional
conductEvaluation	Green construction data	Green construction evaluation	Inverse functional
raiseOptimization	Green construction evaluation	Optimization measures	Inverse functional

Table 7: The definition of data properties.

	BIM project	Construction activity	Green construction data	Green construction evaluation	Optimization measure
Data property	(i) Project number (ii) Project name (iii) Project address (iv) Project description (v) Contract price (vi) Owner unit (vii) Design unit (viii) Construction unit (ix) Supervision unit (x) Starting date (xi) Construction period	(i) Serial number of construction activity (ii) Name of construction activity (iii) Construction phase (iv) Relevant project (v) Description of construction activity (vi) Builders (vii) Construction material (viii) Construction machinery (ix) Construction environment	(i) Relevant construction activity (ii) Relevant project (iii) Indicator name (iv) Green construction description (v) Constructor (vi) Construction material (vii) Construction machinery (viii) Construction environment	(i) Relevant construction activity (ii) Relevant project (iii) Indicator name (iv) Energy conservation (v) Water conservation (vi) Land conservation (vii) Material conservation (viii) Environmental protection (ix) Score (x) Evaluation result	(i) Relevant construction activity (ii) Relevant project (iii) Evaluation result (iv) Scores of indicators (v) Optimization measure
Value type	int or string	int or string	int or string	int or string	int or string
Function type	Functional	Functional	Functional	Functional	Functional

green construction data and evaluation of green construction are connected by "conductEvaluation" property; and evaluation of green construction and optimization measures are connected by "raiseOptimization" property, and the inference rules of property of the relationship between nodes are as follows:

Rule-A: assume that $X \in$ BIM project, $Y \in$ Construction, $Z \in$ green construction data, $\mathrm{A} \in$ green construction evaluation, $\mathrm{B} \in$ optimization measures, and X (hasConstruction) Y, Y (produceInformation) Z, Z (conductEvaluation) A, A (raiseOptimization) B; then, X (produceInformation) Z, X (conductEvaluation) A, X (raiseOptimization) B.

Rule-B: assume that $X \in$ BIM project, $Y \in$ Construction, $Z \in$ green construction evaluation, $\mathrm{A} \in$ optimization measures, and X (produceInformation) Y, Y (conductEvaluation) Z, Z (raiseOptimization) A; then, X (conductEvaluation) Z, X (raiseOptimization) A.

Rule-C: assume that $X \in$ green construction data, $Y \in$ green construction evaluation, $Z \in$ optimization measures, and X (conductEvaluation) Y, Y (raiseOptimization) Z; then, X (raiseOptimization) Z.

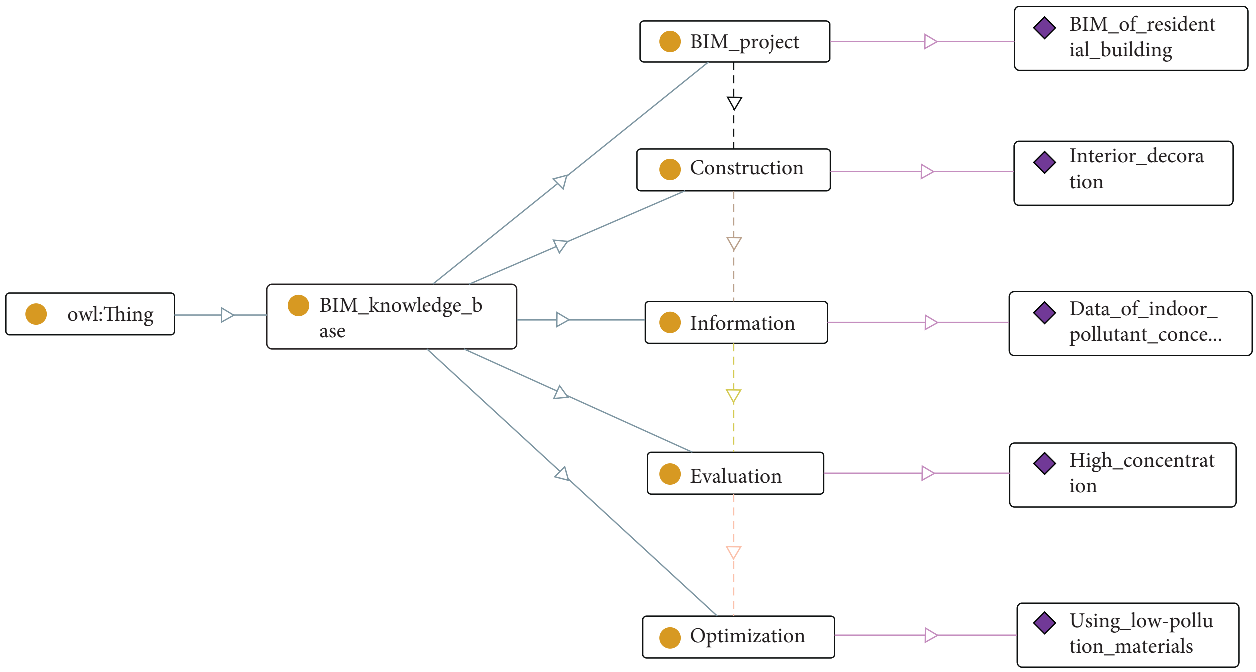

Figure 9: Link relationship of BIM knowledge base.

The rules above can be represented directly by Figure 10. The solid lines stand for the known relationships, while dotted lines stand for the implicit relationships inferred by SWRL rules.

According to the three rules mentioned above and taking indicator "dust control" as an instance, its expression in SWRL rule language is summarized as follows. First, Protégé system identifies the value of indicator "dust control" with a score 1.5, which confirms to Rule-1.1 $(1.3 < X \leq 1.5)$ and infers the result conductEvaluation (?x, 1), i.e., the score is 1 point. The result of induction is shown in Figure 11. Then, optimized measures are derived from raiseOptimization.

(2) Establishment of Instance rules

With reference to four evaluation standards and norms for green construction, including Guidelines for Green Construction (2007), Evaluation standard for Green *Construction of Building (GB/T50640-2010)*, *Code for Green Construction of Building (GB/T50905-2014)*, and *Assessment Standard for Green Buildings (GB/T50378-2014)*, as well as specific standards *Emission Standard of Environmental Noise for Boundary of Construction Site (GB12523-2011)* and *Integrated Wastewater Discharge Standard (GB8978-1996)*, the evaluation indicator and scoring criteria of one specific residential building project is created in order to establish instance rules.

6.1. Green Construction Evaluation Based on Drools Inference. Based on the actual data of indicators collected and the evaluation criteria, the results of evaluation will be inferred in Drools. When Drools is provided with certain domain rules and data, it can process a variety of inference tasks. Through the conversion of the corresponding format, the knowledge presented in ontology form and rules expressed in SWRL could be transformed into facts and rules that can be understood and supported by Drools. Afterwards, the inference engine of Drools is able to infer issues in the field of domains and generate new facts. The inference engine of Drools has been integrated into software Protégé. It can transform ontology instances and SWRL rules into Drools facts and Drools rule in order to obtain the fact and rule basis. The inference is comprised of four steps: ① converting the knowledge of individual instance into Drools facts; ② converting SWRL rules to Drools rules; ③ running Drools inference based on facts and rules; ④ inferring new facts and updating the knowledge base with them. The inferring process of Drools based on BIM knowledge base is shown in Figure 12.

The indicator values in Table 8 are derived from the data of BIM model and have been converted into OWL language before stored in BIM knowledge base. Here, "dust control" is taken as a sample to conduct Drools inference.

Figure 13 shows the instance of "Dust control." The value of indicator 1.5 has been already stored in the knowledge base. Inference is then conducted upon the value of indicator. Rule-1.1, Rule-1.2, and Rule-1.3, SWRL rule language specifically written in previous section for dust control, are edited in SWRL Tab before the Drools inference. First OWL + SWRL -> Drools is run, in which system converts ontology knowledge (indicator value 1.5) and SWRL rules into knowledge and rules that Drools can understand and support. Then, Run Drools is executed for inference. The system identifies that the indicator value 1.5 is within the range of Rule-1.1 $(1.3 < X < 1.5)$ and then

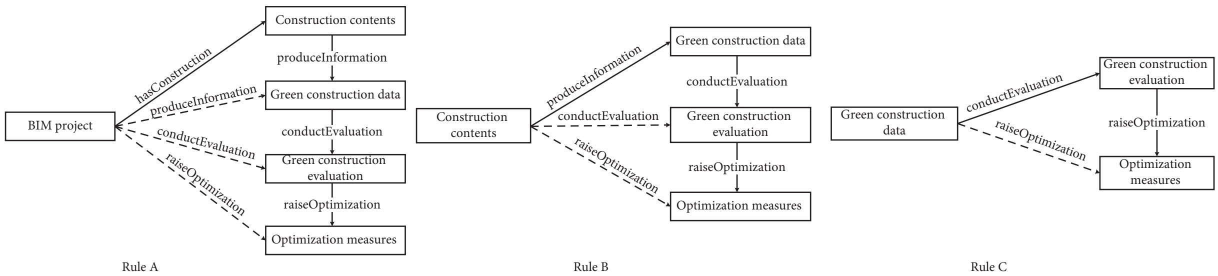

Figure 10: Illustration of SWRL rules.

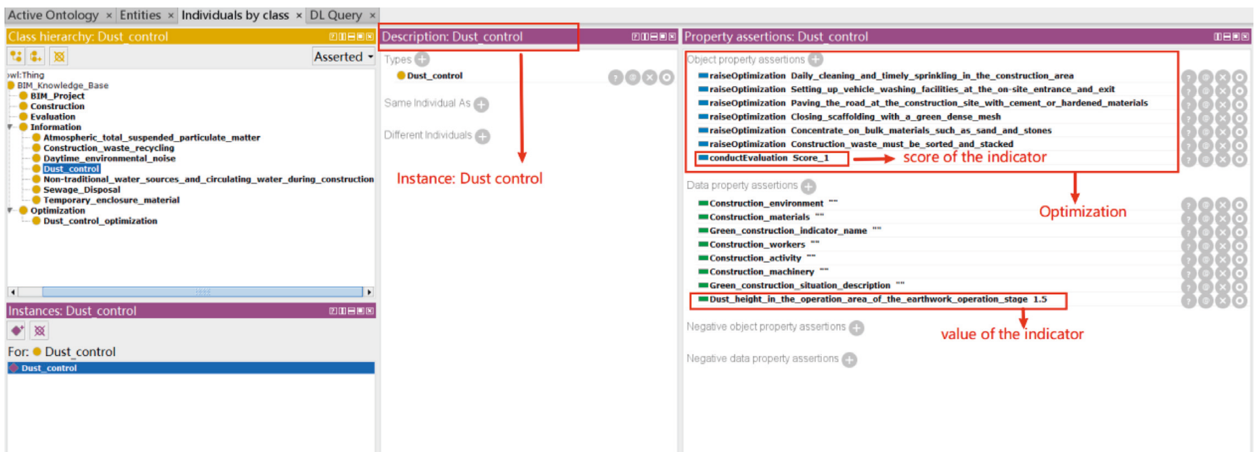

Figure 11: Induction instance of “dust control.”

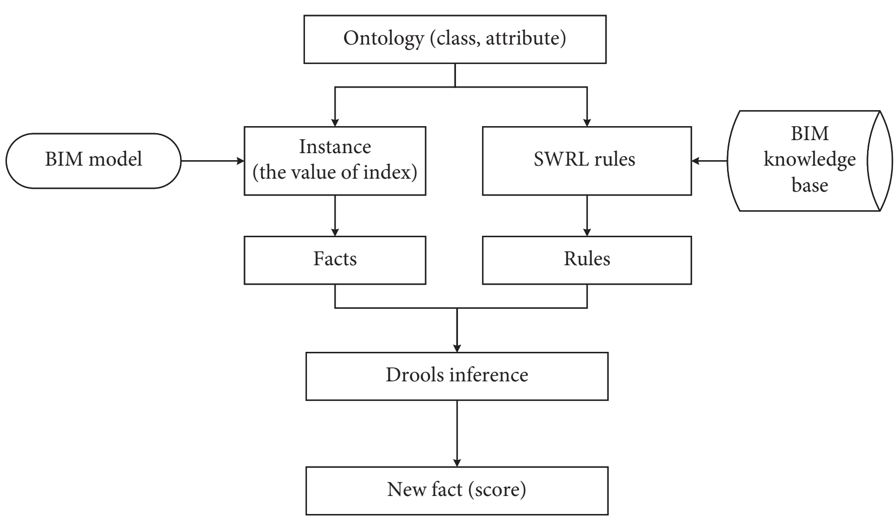

Figure 12: Flow chart of Drools inference.

indicates the result conductEvaluation (? X, 1), i.e., the score is 1.

In the same way, 16 indicators in SWRL rule language are listed and entered into the knowledge base. Drools inference is conducted upon 16 indicator values stored in BIM knowledge base, and the scores of evaluations are obtained as shown in Table 9.

6.2. SPARQL Inquiry-Integrated Green Construction Optimization. In view of the result, the specific indicators could be identified which do not conform to the requirements and also lead to the results of disqualification; then, optimized measures need to be put forward. In this paper, the evaluation of indicators is completed in BIM knowledge base, and a way to inquire is proposed. SPARQL

Table 8: Indicator results.

Number	Specific indicator content	Indicator values
1	Dust control: visual inspection of the fugitive dust height in the earthwork area (m)	1.5
2	Ambient noise at daytime (dB)	65
3	Suspended solid content in sewage water (mg/L)	300
4	Difference between monthly average total suspend particulate (TSP) on site and the city back ground value (mg/m^3)	0.065
5	Recycle and recovery ratio of construction wastes (%)	15
6	Reuse ratio of field temporary housing and retaining wall material (%)	40
7	Reuse ratio of unconventional water and recycled water (%)	45
8	Illumination should not exceed the percentage of the minimum illumination (%)	20
9	Equip ratio of water-saving devices in administrative area and living quarters on site (%)	80
10	Ratio of energy-saving lightings (%)	95
11	Ratio of reusable partition walls (%)	60
12	Ratio of prefabricated parts (%)	35
13	Ratio of premixed mortar to building mortar (%)	65
14	Ratio of ordinary rebar with higher grades than 400 MPa (%)	45
15	Lost rate of reinforcement field processing (%)	3
16	Usage of tool type combination formwork (%)	80

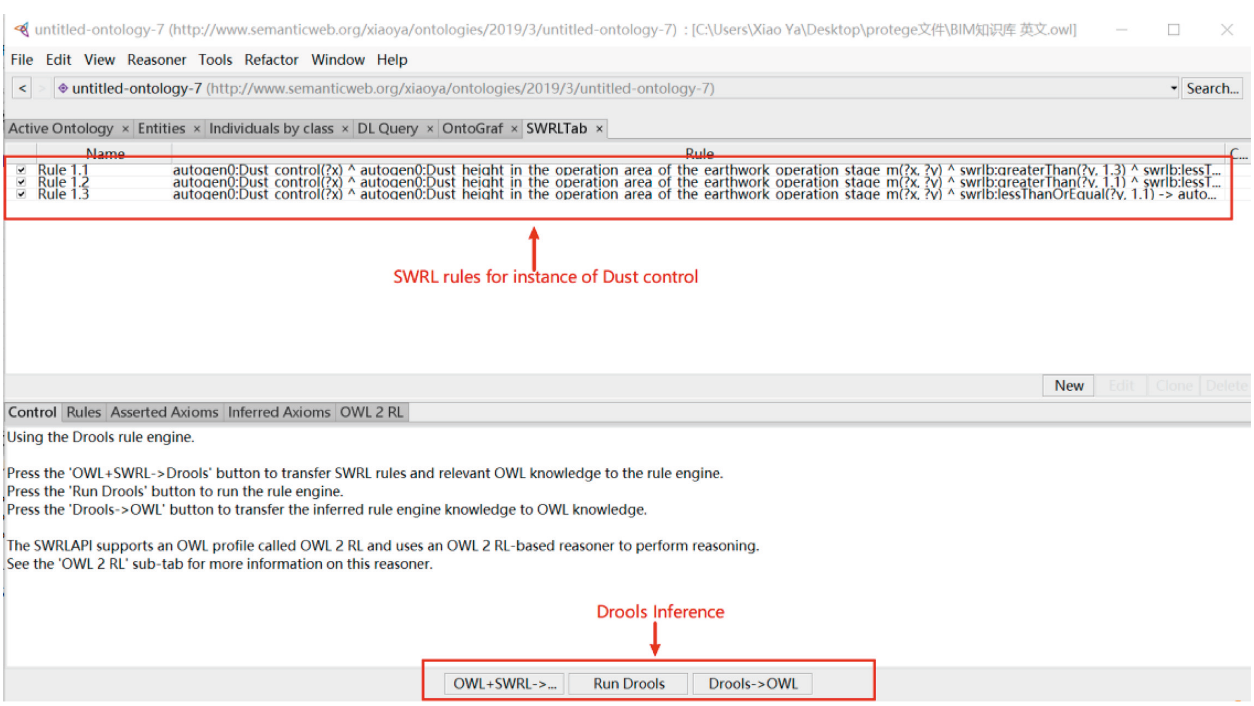

Figure 13: Induction instance of “dust control.”

is chosen as the language to inquire BIM knowledge base. SPARQL, as the inquiry language for semantic network developed and recommended by W3C, could be used to retrieve the information in BIM knowledge base. Programming code is input into the editing block of SPARQL inquiry. SPARQL inquiry is a command inquiry tool from Protégé, which is used to search for information in the knowledge base. SPARQL inquiry coding is run and the indicators with scores less than 2 points are shown in the following Table 10.

Considering the 9 indicators with scores less than 2 points, with the help of knowledge inference, optimized

Table 9: Evaluation result.

Number	Specific indicator content	Indicator values	Scores
1	Dust control: visual inspection of the fugitive dust height in the earthwork area (m)	1.5	1
2	Ambient noise at daytime (dB)	65	1
3	Suspended solid content in sewage water (mg/L)	300	1
4	Difference between monthly average total suspend particulate (TSP) on site and the city back ground value (mg/m^3)	0.065	2
5	Recycle and recovery ratio of construction wastes (%)	15	0
6	Reuse ratio of field temporary housing and retaining wall material (%)	40	1
7	Reuse ratio of unconventional water and recycled water (%)	45	2
8	Illumination should not exceed the percentage of the minimum illumination (%)	20	1
9	Equip ratio of water-saving devices in administrative area and living quarters on site (%)	80	1
10	Ratio of energy-saving lightings (%)	95	3
11	Ratio of reusable partition walls (%)	60	2
12	Ratio of prefabricated parts (%)	35	2
13	Ratio of premixed mortar to building mortar (%)	65	1
14	Ratio of ordinary rebar with higher grades than 400 MPa (%)	45	1
15	Lost rate of reinforcement field processing (%)	3	2
16	Usage of tool type combination formwork (%)	80	2

Table 10: SPARQL query on indicators with scores less than 2 points.

Number	Specific indicator content	Indicator values	Scores
1	Dust control: visual inspection of the fugitive dust height in the earthwork area (m)	1.5	1
2	Ambient noise at daytime (dB)	65	1
3	Suspended solid content in sewage water (mg/L)	300	1
4	Recycle and recovery ratio of construction wastes (%)	15	0
5	Reuse ratio of field temporary housing and retaining wall material	40	1
6	Illumination should not exceed the percentage of the minimum illumination (%)	20	1
7	Equip ratio of water-saving devices in administrative area and living quarters on site (%)	80	1
8	Ratio of premixed mortar to building mortar (%)	65	1
9	Ratio of ordinary rebar with higher grades than 400 MPa (%)	45	1

measures for these indicators are given. Firstly, SWRL rule language for optimized measures is constructed. Based on the 16 indicators constructed in SWRL rule language above, SWRL rules corresponding to optimized measures of indicators are designed. The next step is the Drools inference. The indicator "Dust control" is taken as an instance and six optimized measures are proposed from raiseOptimization: ① vehicle rinsing facilities are to be established at the entrance and exit of construction site; ② roads on construction site are to be paved; ③ granular materials such as sand, gravel, and cement are to be stockpiled and covered; ④ construction area is to be cleaned and sprinkled regularly daily; ⑤ waste classification must be in place for construction waste; and ⑥ scaffolding must be enwrapped by green closely knitted safety net. The method is used to infer the other eight indicators and optimization measures are suggested. The optimized measures are listed in Table 11.

7. Limitation and Future Work

Two main limitations of this work are acknowledged. First, the proposed evaluation methodology only considers a selected evaluation indicator system defined by previous studies and related standards. A larger indicator system could better capture the needed attributes to evaluate green construction in practice. Further research is needed to study systematically the ontology for semantic interpretation of green construction indicators. It is necessary to explore the

Table 11: Optimization method.

NO.	Specific indicator content	Values	Scores	Optimized measures
1	Dust control: visual inspection of the fugitive dust height in the earthwork area (m)	1.5	1	(i) Establish vehicle rinsing facilities at the entrance and exit of construction site (ii) Pave the roads on construction site (iii) Stockpile and cover granular materials such as sand, gravel and cement (iv) Clean and sprinkle construction area regularly daily (v) Waste classification must be in place for construction waste (vi) Enwrap scaffolding with green closely knitted safety net
2	Ambient noise at daytime (dB)	65	1	(i) Reduce the noise of concrete vibrators, use low-frequency vibrators instead of high-frequency vibrators (ii) Isolate inevitable noise sources
3	Suspended solid content in sewage water (mg/L)	300	1	(iii) Equip effective sewage treatment facilities (iv) Build settling ponds, oil interceptors, and septic tanks
4	Recycle and recovery ratio of construction wastes (%)	15	0	(v) Improve the recovery and reutilization of construction wastes
5	Reuse ratio of field temporary housing and retaining wall material (%)	40	1	(vi) Improve the reutilization of temporary housing and retaining wall material
6	Illumination should not exceed the percentage of the minimum illumination (%)	20	1	(vii) Properly reduce the number of lightings
7	Equip ratio of water-saving devices in administrative area and living quarters on site (%)	80	1	(viii) Increase the equip ratio of water-saving devices
8	Ratio of premixed mortar to building mortar (%)	65	1	(ix) Increase the ratio of premixed mortar
9	Ratio of ordinary rebar with higher grades than 400 MPa (%)	45	1	(x) Increase the use of ordinary rebar with higher grade than 400 Mpa

various types of green construction information and identify which types of data can be extracted in a BIM-based quantitative way and which would require subjective evaluation and verification. Even for the type of subjective evaluation on green construction, the proposed approach in this study could be useful in acting as a possible way to construct the knowledge base of subjective opinions, and ensure the alignment with the concept representations of the green construction information. Second, the process of the proposed evaluation approach is not totally automatic, which would require some level of human involvement. It is essential to achieve high performance in extracting green construction information and generating corresponding IFC attributes to support the functional requirements in evaluation tools. In future work, in order to study possible ways for further performance improvement, further research could be conducted to explore different methods for integrating BIM software and evaluation tools.

8. Conclusion

BIM-based construction management has begun to expand [36]. Since the number of practices that use BIM-based information management has significantly increased, the construction industry has augmented its use of BIM model and knowledge base during construction projects. However, although the BIM tool may supply geometric attributes extraction, it cannot provide directly and automatically any information on the evaluation items on green construction. Theoretically, the information needed for managing green construction can be automatically obtained from BIM. Practically, however, the information that can be obtained from BIM will remain very limited unless BIM contains full information and knowledge. Therefore, although BIM tools are used for construction simulation, the corresponding optimization measures on green construction cannot be linked to BIM model directly.

In this paper, it is demonstrated that in BIM knowledge base, through the construction of SWRL rule language of indicators and the Drools inference, the scores of indicators could be obtained. By analyzing the scores, green construction could be evaluated. According to the results of the evaluation, unqualified indicators could be screened out by SPARQL inquiry. Afterwards, corresponding optimized measures could be inferred and the scheme of green construction could be modified. In comparison to existing evaluation methods' efforts in the green construction domain, this work contributes to the body of knowledge in two main ways. First, the proposed method integrates the evaluation indicators of green construction with IFC expression. The integration allows for extracting evaluation information directly from BIM models, which avoids both

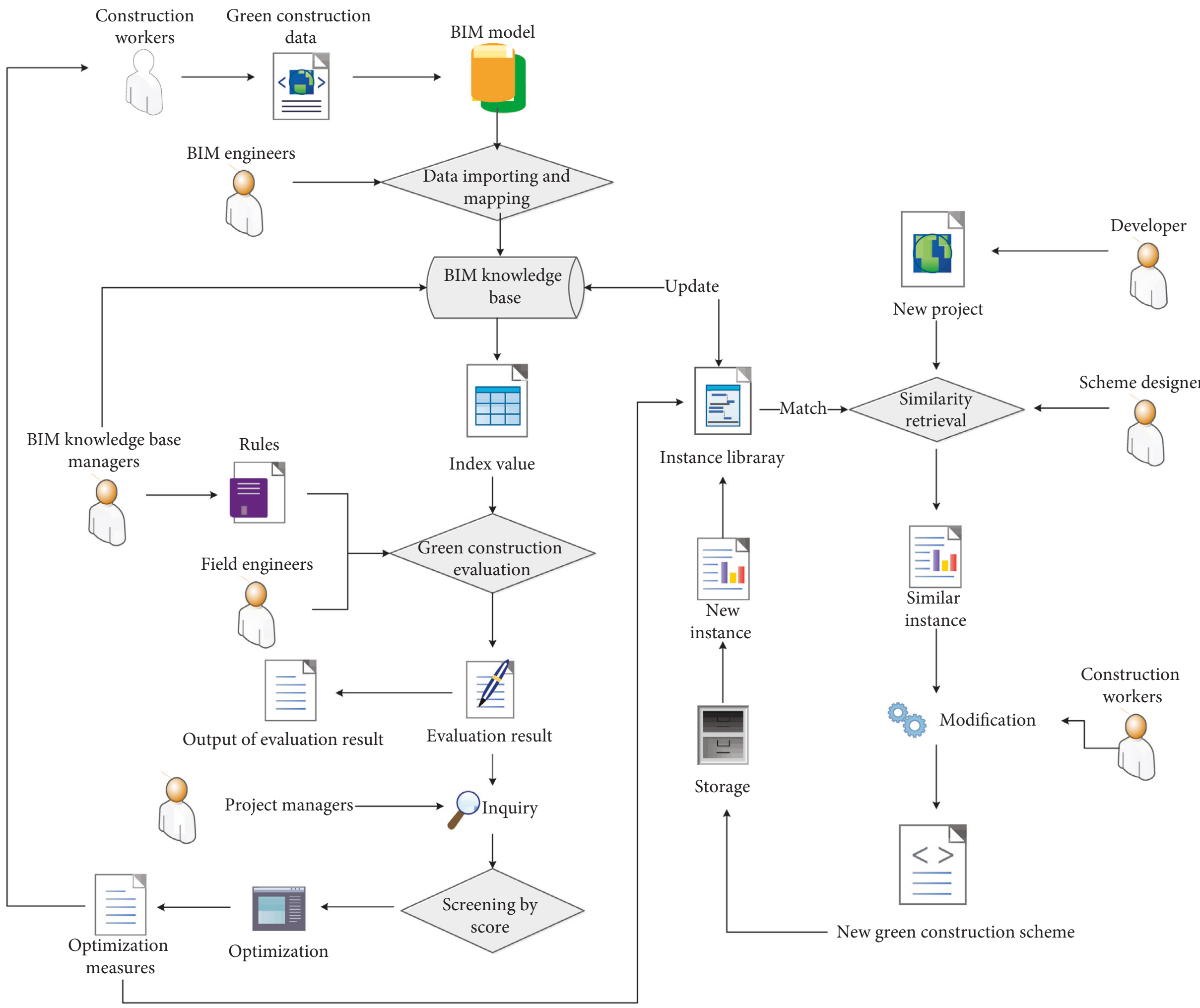

Figure 14: Flow chart of BIM knowledge base application.

errors and computational effort resulting from processing large amounts of construction data. Second, this work proposes to use the ontology for green construction to build a conceptual knowledge base for the evaluation information and proposes a SPARQL inquiry-integrated evaluation method. The experimental results show that the use of the proposed approach was effective in designing optimized measures in green construction.

Knowledge base can facilitate knowledge sharing. Therefore, BIM knowledge base for the evaluation of green construction could realize the sharing, maintenance, and acquisition of knowledge among different participants of the project and improve the management of green construction. Through the analysis of the BIM knowledge base, the workflow of the system is determined (as shown in Figure 14). First, construction site personnel collect relevant green construction data from the site and input into BIM model. Second, the BIM engineer maps and transforms the input data into BIM knowledge base to derive the value of the evaluation indicator of green construction. Then, managers of BIM knowledge base establish the rules of evaluation. Afterwards, site engineers can utilize BIM knowledge base to evaluate green construction in order to obtain and output results. Next, project managers inquire the results of evaluation, screen scores, optimize green construction, put forward optimization measures, and deliver these measures to constructors as feedback. In the meantime, project and its optimization measure plan are saved in BIM knowledge base as an instance. When the contractor plans for a new project and need to determine green construction scheme, engineers can conduct a similarity retrieval of project cases from the base of project cases in BIM knowledge base to find the matching case and make improvements to suit the new one. The new project and its scheme of green construction will also be stored as a new instance in the base of project cases, which will be regularly updated and maintained by managers.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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