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RESEARCH ARTICLE

Qiufeng HE, Zezhou WU, Xiangsheng CHEN

An integrated framework for automatic green building evaluation: A case study of China

Abstract With the burgeoning emphasis on sustainable construction practices in China, the demand for green building assessment has significantly escalated. The overall evaluation process comprises two key components: The acquisition of evaluation data and the evaluation of green scores, both of which entail considerable time and effort. Previous research predominantly concentrated on automating the latter process, often neglecting the exploration of automating the former in accordance with the Chinese green building assessment system. Furthermore, there is a pressing requirement for more streamlined management of structured standard knowledge to facilitate broader dissemination. In response to these challenges, this paper presents a conceptual framework that integrates building information modeling, ontology, and web map services to augment the efficiency of the overall evaluation process and the management of standard knowledge. More specifically, in accordance with the *Assessment Standard for Green Building* (GB/T 50378-2019) in China, this study innovatively employs visual programming software, Dynamo in Autodesk Revit, and the application programming interface of web map services to expedite the acquisition of essential architectural data and geographic information for green building assessment. Subsequently, ontology technology is harnessed to visualize the management of standard knowledge related to green building assessment and to enable the derivation of green scores through logical reasoning. Ultimately, a residential building is employed as a case study to validate the theoretical and technical feasibility of the developed automated evaluation conceptual framework for green buildings. The research findings hold valuable utility in providing a self-assessment method for applicants in the field.

Keywords automatic evaluation, green building, BIM, web map service, ontology inference application

1 Introduction

The Paris Agreement calls for countries to endeavor to reach the peak of carbon dioxide emissions (Qi et al., 2020; Yu et al., 2022). The construction industry is recognized as bearing a primary responsibility for aiding countries in achieving this objective (Huo et al., 2022; Li et al., 2022). According to statistics, in 2020, the global construction industry's energy consumption accounted for 36% of total energy consumption and 37% of energy-related carbon dioxide emissions (United Nations Environment Programme, 2021). Green buildings are deemed pivotal in driving energy conservation and emissions reduction within the construction sector (Qiu and Kahn, 2019; Wang et al., 2019). Green buildings outperform their traditional counterparts in energy efficiency and environmental friendliness during the phases of design, construction, and operation (Bampou, 2017). By leveraging advanced energy-saving technologies or methods within the green building evaluation system, the construction industry can potentially reduce carbon emissions by 13% to 28% (Subramanyam et al., 2017; Qin

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Qiufeng HE, Zezhou WU (✉)
State Key Laboratory of Intelligent Geotechnics and Tunnelling, Shenzhen 518060, China; Key Laboratory for Resilient Infrastructures of Coastal Cities (Shenzhen University), Ministry of Education, Shenzhen 518060, China; Sino-Australia Joint Research Centre in BIM and Smart Construction, Shenzhen University, Shenzhen 518060, China; Shenzhen Key Laboratory of Green, Efficient and Intelligent Construction of Underground Metro Station, Shenzhen 518060, China
E-mail: wuzezhou@szu.edu.cn

Xiangsheng CHEN
State Key Laboratory of Intelligent Geotechnics and Tunnelling, Shenzhen 518060, China; Key Laboratory for Resilient Infrastructures of Coastal Cities (Shenzhen University), Ministry of Education, Shenzhen 518060, China; Shenzhen Key Laboratory of Green, Efficient and Intelligent Construction of Underground Metro Station, Shenzhen 518060, China

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et al., 2022). Consequently, countries worldwide are actively promoting the development of green buildings. The United States has completed 277 million m^2 of green buildings, while China has witnessed a substantial increase in newly constructed green buildings, rising from 4 million m^2 in 2012 to 2 billion m^2 in 2021 (YNET, 2022).

Determining whether a building qualifies as a green building necessitates certification through the green building evaluation system (Wu et al., 2021). This procedural step is known as green building evaluation. With the anticipated rapid expansion of green buildings in the future, green building evaluation faces significant market demand (Jalaei et al., 2020). Local governments have begun urging applicants to conduct self-evaluations of green buildings before seeking green building certification. This approach aims to alleviate the burden on experts responsible for conducting green building evaluations (JNMBHURD, 2021). However, as market demand for green building evaluation continues to surge, the limitations of manual evaluation become increasingly apparent, including its time-consuming nature, labor intensiveness, and heavy reliance on expert judgment (Jiang et al., 2018). Excessive dependence on expert judgment leads to additional expenses related to expert fees, potentially hindering the progress of green building (Li et al., 2020). Consequently, it becomes imperative to explore an automated evaluation methodology that can expedite the green building evaluation process while reducing reliance on expert judgment.

Nonetheless, achieving automated green building evaluation poses significant challenges. This endeavor requires the collection of multidisciplinary data from all phases of a green building's lifecycle, as well as a comprehensive understanding of the knowledge and scoring principles embedded in the evaluation system. Currently, some scholars have undertaken research on automated evaluation tools for green buildings. For example, Jalaei et al. (2020) developed a plug-in based on Autodesk Revit to conduct a comprehensive preevaluation of building sustainability according to the Leadership in Energy and Environmental Design (LEED). Jiang et al. (2018) manually obtained data from building information modeling (BIM) and subsequently inputted these data into an established ontology model to achieve automatic scoring based on specific elements of the *Assessment Standard for Green Building* (ASGB) (GB/T 50378-2014). In summary, existing studies have explored relatively comprehensive automated evaluation methods based on LEED, a prominent international green building evaluation system. However, concerning the ASGB in China, current research on automation is largely confined to scoring rationale, with a dearth of automation in data acquisition. Considering that the existing comprehensive automated evaluation methods may not align with China's domestic requirements, particularly given China's almost mandatory stipulation that all new buildings attain a minimum ASGB-based star rating, there is a pressing need to further investigate a more automated ASGB-based evaluation tool to meet the demands of the world's largest construction market (Zhu et al., 2023).

In response to the identified research gap, this study, in accordance with the ASGB, formulated a comprehensive approach that integrates BIM, ontology, and web map service (WMS) to establish a conceptual framework for automated acquisition of evaluation data and automated scoring reasoning. Among these components, BIM emerges as a potent tool for procuring diverse, profession-specific data pertaining to construction (Lu et al., 2017). Furthermore, researchers can manipulate visual programming language using Dynamo to directly extract building material and component attribute information necessary for evaluation from BIM, obviating the need for manual data collection (Guo et al., 2021).

Beyond assessing building performance, the ASGB also encompasses the evaluation of the accessibility of service facilities surrounding the building. Leveraging the capabilities of WMS as a robust geographic information repository, researchers can access these geographic data by invoking its open application programming interface (API) (Huang et al., 2022). The utilization of an ontology model represents an efficient knowledge management method (Zhang et al., 2020; Zheng et al., 2021) capable of housing the knowledge related to green building systems and facilitating hierarchical reasoning. Subsequently, the viability of the theoretical framework is validated through an illustrative engineering example. In essence, this study represents a significant advancement beyond prior research endeavors, offering a more user-friendly means for applicants to refine their green building design schemes and serving as a valuable reference for other countries exploring suitable automated evaluation tools.

The remainder of this paper is structured as follows. Section 2 provides an extensive review of the relevant literature and outlines the research gap. Section 3 elucidates the theoretical framework that integrates BIM, ontology, and WMS. Section 4 demonstrates the automated evaluation process through a selected green building case study. Section 5 discusses the findings and limitations of this study and presents concluding remarks.

2 Related studies

2.1 Green building evaluation systems

Green building evaluation systems serve as potent tools for assessing building sustainability and integrating the concept of sustainability into the construction and operation of buildings (Illankoon et al., 2017). In pursuit of enhanced environmental performance in building practices, numerous countries have developed their own green building evaluation systems tailored to their unique geomorphic characteristics, climate conditions, and technological advancement levels, as detailed in Table 1.

Table 1 Mainstream green building evaluation system in the world

Evaluation systems	Initial implementation time	Region of origin
BREEAM	1990	United Kingdom
LEED	1998	United States
CASBEE	2002	Japan
Green Star	2003	Australia
Green Mark	2005	Singapore
ASGB	2006	China
DGNB	2007	Germany
BSAM scheme	2019	sub-Saharan African countries

The Building Research Establishment Environmental Assessment Method (BREEAM) was the pioneering system established by the British Building Research Establishment in 1990 (Ding et al., 2018). It encompasses nine evaluation categories: Energy, waste, water, materials, health and wellbeing, transport, pollution, land use and ecology, and management. Over time, BREEAM has evolved into a leading evaluation system in Europe, with four distinct evaluation standards tailored to new buildings, renovated buildings, buildings in use, and community buildings (Guo et al., 2021). The LEED system, initiated by the United States Green Building Council in 1994, operates on a point-based evaluation framework (Ding et al., 2018; Uğur and Leblebici, 2018). It has progressed from LEED v1.0 to LEED v4.1, encompassing fundamental credit categories such as energy and atmosphere, materials and resources, sustainable sites, water efficiency, indoor environmental quality, innovation in design, and regional priority. China pioneered the ASGB in 2006 (Ye et al., 2015), subsequently revising it in 2014 and 2019. The latest iteration of ASGB incorporates five credit categories: Safety and durability, health and comfort, occupant convenience, resource saving, and environmental livability (MHURD of the PRC, 2019). Additionally, other nations have introduced their own green building evaluation systems, including the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan, Green Star in Australia, Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) in Germany (Yu et al., 2015), and the Building Sustainability Assessment Method (BSAM) in sub-Saharan Africa (Olawumi et al., 2020). While the specific indicators within these green building evaluation systems may vary from one country to another, they predominantly encompass aspects such as materials, energy, water, land, and occupant convenience (Zhang et al., 2017).

2.2 Automatic evaluation of green buildings

Given that BIM models and the simulation outcomes derived from BIM-related sustainability analysis software encompass a wealth of geometric, material, and energy consumption data, among other elements, most prior studies have employed BIM models as a foundational tool to explore automated evaluations in accordance with green building systems (Ilhan and Yaman, 2016; Ansah et al., 2019; Guo et al., 2021), as demonstrated in Table 2.

Initially, Azhar et al. (2011) and Wong and Kuan (2014) embarked on investigations to ascertain whether BIM models could potentially serve as tools for assessing building sustainability. Their research revealed that documents generated using BIM sustainability analysis software could directly or indirectly contribute to the evaluation of certain credits within green building assessment systems. These credits encompassed, for instance, 5 credits and one prerequisite in LEED v2.2 and 26 credits in BEAM Plus (a green building evaluation system originated from Hong Kong, China). Subsequently, Nguyen et al. (2016) further advanced this approach by creating a plug-in named "LEED evaluator" based on Autodesk Revit Architecture 2013. This plug-in enabled automated scoring for building sustainability based on select credits within LEED. Olawumi and Chan (2021) developed a BIM-based tool for the automatic assessment of the sustainable performance of Nigerian buildings, addressing issues associated with time-consuming, labor-intensive, and cost-intensive manual evaluations. Additionally, Ilhan and Yaman (2016) not only achieved the automatic calculation of building green scores based on specific credits within BREEAM but also accomplished automated cost calculations associated with different green building technologies. In the context of China, Jiang et al. (2018), serving as pioneers in this domain, achieved automated evaluations based on three components within the ASGB (GB/T 50378-2014) by manually extracting evaluation data from BIM models and integrating it into their established ontology model.

However, the scope of automated building sustainability evaluation reliant on BIM models or sustainability analysis software has limitations. As discussed in Section 2.1, green building assessment systems typically include the credit category of "occupant convenience", which evaluation data cannot be directly extracted from BIM. Chen and Nguyen (2017) proposed a pioneering solution to this challenge by developing a plug-in within Autodesk Revit software that leveraged the API of Google Maps. This plug-in facilitated the automated collection of evaluation data for the "occupant convenience" credit category within LEED. More recently, Jalaei et al. (2020) introduced a more comprehensive and systematic framework for the automated assessment of green buildings. They created a

Table 2 Research on automatic evaluation for green buildings

Reference	Evaluation system and credit category	Country	Credit category for automatic evaluation
Nguyen et al. (2016)	**LEED v4** • Materials and resources • Location and transportation • Sustainable sites • Water efficiency • Energy and atmosphere • Indoor environmental quality • Innovation in design • Regional priority	United States	• Location and transportation
Abdelalim and Abo.elsaud (2019)	**LEED v4** • Materials and resources • Location and transportation • Sustainable sites • Water efficiency • Energy and atmosphere • Indoor environmental quality • Innovation in design • Regional priority	United States	• Location and transportation • Sustainable sites
Olawumi and Chan (2021)	**BSAM scheme** • Sustainable construction practices • Site and ecology • Energy • Water • Material and waste • Transportation • Indoor environmental quality • Building management	Nigeria	• Sustainable construction practices • Site and ecology • Energy
Ilhan and Yaman (2016)	**BREEAM Europe Commercial 2009** • Management • Health and wellbeing • Energy • Transport • Water • Materials • Waste • Land use and ecology • Pollution	United Kingdom	• Materials
Jiang et al. (2018)	**ASGB (GB/T 50378-2014)** • Land saving and land utilization • Energy saving and energy resource utilization • Water saving and water resource utilization • Material saving and material resource utilization • Indoor air quality • Construction management • Operation management	China	• Land saving and land utilization
Chen and Nguyen (2017)	**LEED for New Construction v2009** • Materials and resources • Location and transportation • Sustainable sites • Water efficiency • Energy and atmosphere • Indoor environmental quality • Innovation in design • Regional priority	United States	• Location and transportation
Jalaei et al. (2020)	**LEED v4** • Materials and resources • Location and transportation • Sustainable sites • Water efficiency • Energy and atmosphere • Indoor environmental quality • Innovation in design • Regional priority	United States	• Materials and resources • Location and transportation • Sustainable sites • Water efficiency • Energy and atmosphere • Indoor environmental quality • Innovation in design • Regional priority

plug-in capable of calculating and predicting potential cumulative LEED credits using the Autodesk Revit API, energy analysis tools, lighting simulation tools, Google Maps, and associated libraries. This plug-in employed the *K*-nearest neighbor data mining method to estimate missing scores that could not be directly computed from design specifications, ultimately presenting an innovative, comprehensive interface for the evaluation of green building projects.

In summary, considerable efforts have been invested in developing a relatively comprehensive automatic evaluation framework related to LEED. However, due to the variations in evaluation criteria and scoring regulations across different countries/regions, these well-established automatic evaluation methods do not align with China's specific evaluation requirements. Furthermore, many of these studies incorporate the evaluation system's content into the programming language, which can hinder users' comprehension of the system's knowledge. While Jiang et al. (2018) made notable strides in this regard by utilizing ontology technology and pioneering an automated scoring rationale applicable to China's ASGB (GB/T 50378-2014), their research lacked exploration of automated data acquisition.

With these considerations in mind, this study aims to make contributions in the following key areas: 1) developing an automatic evaluation framework tailored to China's ASGB (GB/T 50378-2019) to empower organizations to autonomously assess the environmental performance of target buildings; 2) leveraging ontology technology to visualize the knowledge embedded within the green building evaluation system, thereby enhancing users' grasp of the ASGB's intricacies; and 3) employing programming technology to autonomously extract the requisite evaluation data from WMS and BIM, thus expanding upon prior research pertaining to the automated acquisition of ASGB evaluation data.

3 Methodology

To accomplish the research objectives, this paper introduces a conceptual framework for the automated evaluation of green buildings, achieved through the integration of BIM, WMS, and ontology. Among these components, the BIM model serves as a pivotal document required for project bidding and project acceptance, a practice increasingly prevalent in China (BJMCHURD, 2022; DHUR-DHP, 2022; DHURDSZ, 2022). Autodesk Revit stands as a prominent modeling software currently in use (Shi and Xu, 2021). Within this study, the visual programming software Dynamo is employed to automatically extract evaluation data related to architectural geometry and construction information from Autodesk Revit. ASGB also encompasses the need for evaluation data pertaining to the accessibility of service facilities surrounding buildings, information not available within the BIM model. Consequently, Baidu Map, a widely used WMS, is utilized to gather evaluation data within the "occupant convenience" category by obtaining point of interests (POI). Ontology, functioning as the rationale for determining green scores, obviates the need to encode the evaluation system's content into programming code. Instead, it stores the content in a structured and visual format within the ontology model (El-Gohary and El-Diraby, 2010). This attribute simplifies knowledge storage and comprehension for users, particularly those with limited experience. Moreover, users can intuitively modify instances within the ontology model to accommodate updates in the evaluation system's content when new versions are released (Zhang et al., 2019). Currently, ontology finds widespread application within the construction industry for knowledge storage and standards-based reasoning, encompassing areas such as building cost calculations (Lee et al., 2014), environmental quality monitoring (Zhong et al., 2018), and construction safety (Zhang et al., 2015; Shen et al., 2022b).

With the provision of the target building's longitude and latitude, along with access to the BIM model, the proposed approach can directly compute the green scores for the target building. This capability streamlines the process for design and construction units to self-evaluate whether their building design scheme attains the desired star rating. The conceptual framework is composed of two distinct modules, as illustrated in Fig. 1.

To execute this process, three experts well-versed in BIM, ontology, and the Baidu Map API have been enlisted to meticulously sift through the content of ASGB. Initially, all ASGB items are categorized into two groups: BIM items, which acquire evaluation data from the BIM model, and WMS items, which rely on WMS for data acquisition. Subsequently, the evaluation objects, evaluation indicators, and evaluation rules contained within these items are subject to in-depth analysis. For instance, distinct items entail specific evaluation objects, such as indoor fitness areas, elevators, and distances between the building and kindergarten. Evaluation indicators establish criteria for these evaluation objects, specifying requirements such as a minimum indoor fitness area of 60 m^2 or the necessity for elevators to be wheelchair-accessible and capable of accommodating stretchers. Evaluation rules delineate the points to be awarded if the evaluation indicators within the items are met and the points to be deducted if they are not.

To obtain the performance assessment of the target building across various items, a detailed procedure for acquiring evaluation data, either through BIM or Baidu Map, must be outlined. For instance, specific attributes of the elevator in the BIM model can be accessed by establishing nodes in Dynamo.

Building upon the ASGB content analysis, the evaluation data acquisition module is developed using Autodesk Revit and Baidu Map. For BIM items, Dynamo customizes nodes to extract the required evaluation data from the BIM model. Dynamo serves as a solution for addressing the limitations of Autodesk Revit, which can only export data in a fixed format that does not align with the personalized requirements of ASGB. Additionally,

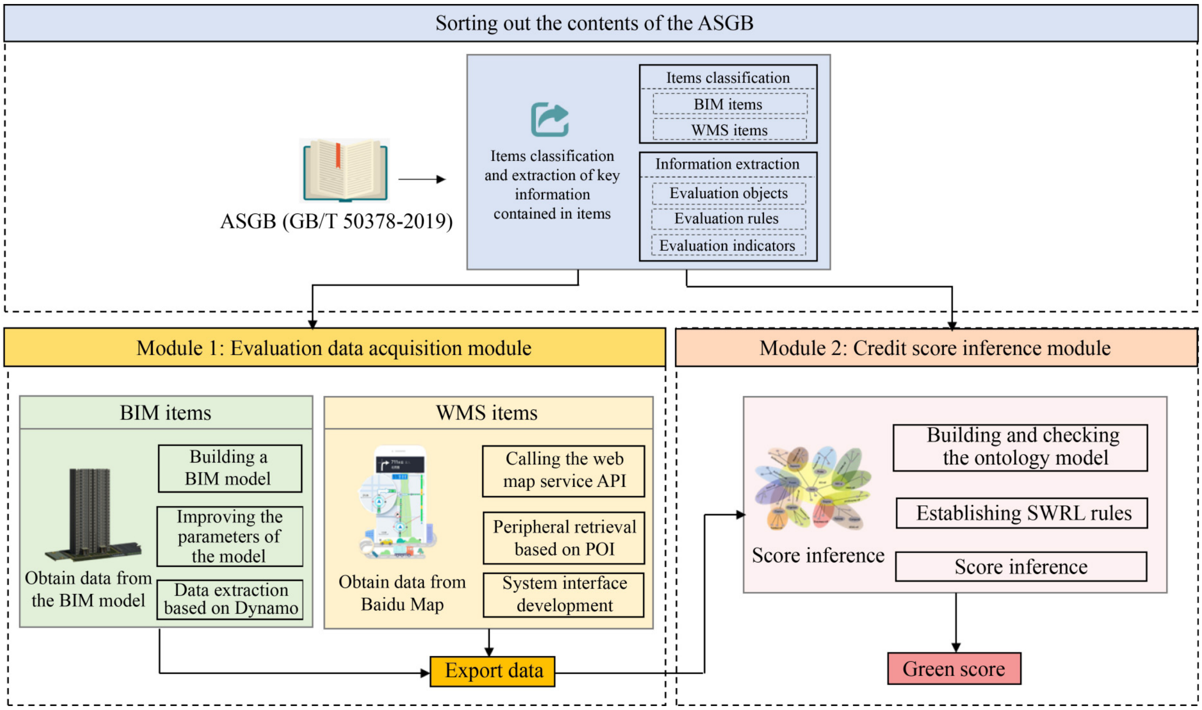

Fig. 1 The conceptual framework for the automatic evaluation of green buildings.

Dynamo facilitates real-time data export by interfacing with external software.

For WMS items, the Java programming language is employed to invoke the open API offered by Baidu Map. By utilizing code packages, including peripheral data retrieval and walking distance calculations, the evaluation data relevant to the accessibility of service facilities around the building are swiftly acquired.

Drawing from the ASGB content analysis, an ontology model and Semantic Web Rule Language (SWRL) rules are established within Protégé to create the scoring reasoning module. Initially, instances, data attributes, object attributes, and classes are defined to construct an ontology model that stores the knowledge of the green building evaluation system. Subsequently, SWRL rules are authored in accordance with ASGB scoring regulations. Finally, the Pellet inference engine is employed to convert the ontology and rules into a compatible format, enabling the storage, management, and application of the green building evaluation standard knowledge.

3.1 Evaluation data acquisition

3.1.1 BIM-based evaluation data acquisition

The BIM encapsulates an extensive reservoir of building geometry, material specifics, and construction attribute information, spanning multiple professional domains such as civil engineering, materials, and construction scheduling. The utilization of the BIM model for acquiring green building evaluation data can significantly streamline the evaluation process, enhancing its efficiency.

First, a manual analysis of pivotal information within the BIM items is essential. This analysis encompasses the evaluation object, evaluation criteria, data acquisition method, and precision requirements for the model. The evaluation object should align with the family within the BIM model, encompassing elements such as external walls, rooms, and casement windows. The evaluation criteria correspond to the attribute details of these families within the BIM model, which may either be inherent to the software family itself or necessitate manual addition, such as the length of inspection railings. Users can access the requisite parameter information for evaluation through visual inspection, Dynamo-based development, and similar methods. It is crucial to note that the model's accuracy level of development (LOD) is paramount for the reliability of data acquisition. A higher LOD implies a more detailed and accurate model, but it also entails increased time and human resources for modeling. Thus, it is imperative to explicitly outline the model's accuracy requirements within various BIM items. LOD 100 signifies that the model's accuracy is sufficient to depict the building's shape, area, and orientation. LOD 200 incorporates more precisely positioned building components compared to previous models. LOD 300 stipulates requirements for the attribute information attached to the family, including not only its inherent attributes but also more intricate parameter details. LOD 400 denotes that the model should meticulously illustrate the component or device's performance, encompassing manufacturer information, and more. LOD 500 dictates that the model should encompass all pertinent information about the family to support the operational management of the building.

Once the crucial information within the BIM items has been elucidated, Dynamo is employed in this study to expediently extract the evaluation data. Dynamo, as a visual programming software, facilitates various essential programming functions, such as extraction, integration, modification, and calculation, for the Autodesk Revit database. The data extraction process using Dynamo within this study is depicted in Fig. 2. Initially, "String" and "Category. ByName" are employed to extract categories by name from the BIM model, followed by the use of "All Elements of Category" to obtain all primitives belonging to the specified categories. Subsequently, "Element. GetParameterValueByName" is employed to extract parameter information from the element, with a connection to "String" indicating the parameter type to be retrieved, such as length, area, or volume. Additionally, "Element. ElementType" is accessed before "Element. GetParameterValueByName" to acquire the family type of the selected element. The type parameters of elements can be extracted by connecting "Element. ElementType" to "All Elements of Category". Finally, "List. Create" is utilized to organize the extracted parameters into a list, which is then transposed using "List. Transpose". The BIM data are subsequently exported to Excel through "Excel. WriteToFile". The generated visualization program can be further saved on a local server. In instances where it is necessary to obtain relevant evaluation data from a new BIM model, the visualization script can be directly executed to extract the data.

3.1.2 WMS-based evaluation data acquisition

Manually gathering evaluation data associated with geographic information is a labor-intensive and time-consuming endeavor. In this study, we employ the Java programming language to construct an efficient geographic data collection platform. This platform is created by invoking the Baidu Map API and incorporating WMS components into the algorithm using Android Studio 4.3 development software. The architectural layout of the geographic data collection platform is elucidated in Fig. 3.

The platform primarily encompasses two modules: The user module and the geographic data retrieval module. Here is a detailed account of the development process for each module.

(1) User module

This module comprises two main components. The first segment enables users to input the latitude and longitude of the building. Once users enter these coordinates and initiate the search, the APP client transmits the query to the server. The second component handles the presentation of retrieval results. It is responsible for showcasing the retrieved target values, result values, and reference data associated with each WMS item. Target values pertain to the requirements specified by the WMS items. The resulting values are the actual outcomes obtained. By comparing target values with result values, users can determine if the item's requirements have been met. When results cannot be retrieved within the established limits, the server continues to extend the distance limit up to 2000 m to retrieve reference data. In addition to the aforementioned results, this segment also provides more detailed information, such as the retrieved building name, address, and specific distance from the target building.

(2) Geographic data retrieval module

Developing this module involves three key steps. The initial step entails incorporating crucial information such as evaluation objects and evaluation parameters from the WMS items into the code. The second step involves data retrieval. This is achieved by leveraging the Baidu Map API and utilizing its peripheral retrieval function to ascertain the number of service facilities surrounding the target building or the direct linear distance to these facilities. If

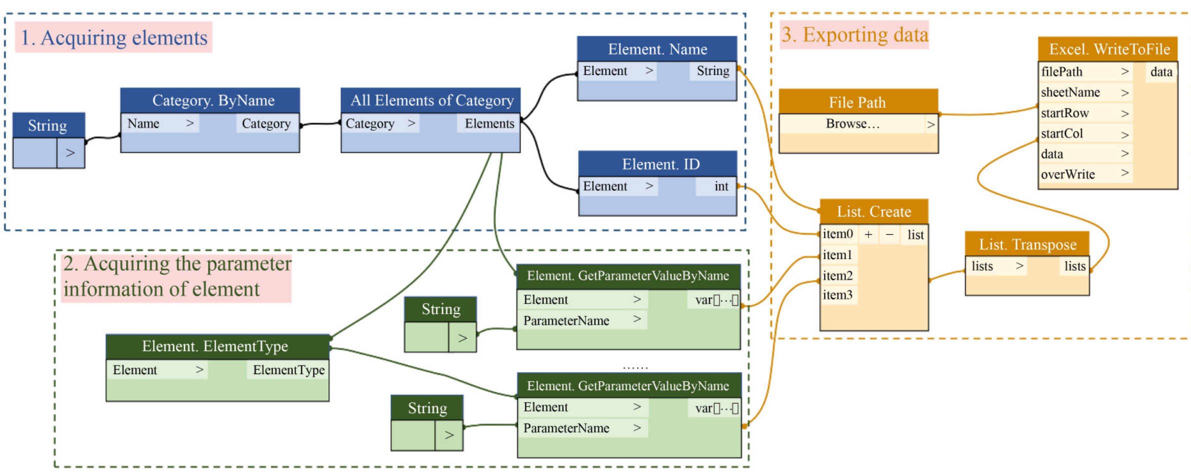

Fig. 2 BIM model parameter data extraction process based on Dynamo.

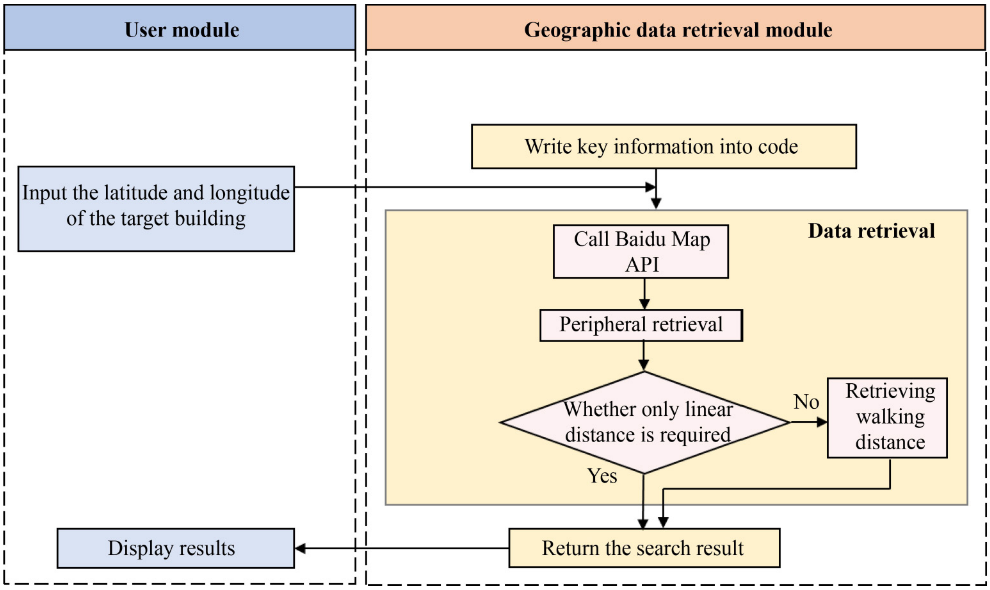

Fig. 3 Design structure for the geographic data collection platform.

the item specifies that the evaluation value pertains to walking distance, the platform further utilizes Baidu Map's route planning function to calculate the walking distance between the target building and the service facilities. The final step revolves around constructing the platform to display the retrieved results. This is accomplished by employing Android Studio to design the platform's interface and using Java to integrate the retrieved results into the corresponding interface elements. Subsequently, the computer terminal and mobile device terminal are connected via a universal serial bus data cable, allowing for performance verification and debugging within Android Studio until the feedback results align with the expected outcomes.

3.2 Credit score inference

3.2.1 Ontology-based knowledge storage

The establishment of an ontology model typically follows a seven-step method (Gao et al., 2022). In this study, an improved approach is employed to build the ontology model, which consists of five steps. The software for building ontology models and inference applications is selected as Protégé 5.2.0.

(1) Determining the domain and scope of the ontology

In this study, the ontology being developed pertains to the domain of green buildings. Its primary focus is to encompass knowledge related to China's green building evaluation system and to facilitate the reasoning of green scores for target buildings.

(2) Defining classes and class hierarchies

This study adopts a top-down approach to systematically enumerate and define classes. To store the knowledge of the ASGB systematically and comprehensively, the ontology class structure predominantly consists of three categories: "EvaluatedBuildingType", "EvaluationProvision", and "EvaluationType". Each of these classes encompasses various subclasses, establishing a hierarchical relationship between the parent class and its subclasses. The specific details are outlined in Table 3.

(3) Defining the data attributes and object attributes of the class

Object properties serve to define the relationships between classes. As per the predefined settings in Protégé software, "is_a" functions as the default object attribute (Shen et al., 2022a). It signifies the ownership relationship between a class and the encompassing class. For example, "ResidentialBuilding" is categorized under the broader class "EvaluatedBuildingType". Data attributes, on the other hand, establish connections between a class and data. In this study, data attributes are employed to represent the evaluation data corresponding to instances. These data attributes encompass various types, such as integers, strings, floating points, and more. This means that the input evaluation data can encompass diverse information types and are not constrained by format. For instance, the area of an indoor fitness venue is categorized as a floating-point type, while elevator accessibility attributes are classified as string type, and so forth.

(4) Creating an instance

An instance represents a more concrete object and is essential for enabling automatic reasoning. The process of instance creation involves selecting a class and then constructing an instance based on the specific evaluation object and evaluation indicator of the corresponding items. For example, Clause 6.2.1.1 has the evaluation object of the walking distance from the entrance to the

Table 3 Established classes for ASGB

Class	Definition for class	Subclass	Definition for subclasses
EvaluatedBuildingType	Type of building evaluated	PublicBuilding	The type of building evaluated is a public building
		ResidentialBuilding	The type of building evaluated is a residential building
EvaluationProvision	Evaluation items of ASGB	EvaluationControl	Prerequisite items
		EvaluationScore	Scoring items
EvaluationType	Evaluation at different stages of construction	PreAssessment	Evaluate prior to construction
		PostAssessment	Evaluate the building after one year of operation

bus station, with the evaluation indicator being the walking distance. Consequently, an instance established under the class "EvaluationScore6_2_1_1" incorporates the aforementioned evaluation object and evaluation indicator. Finally, the established attribute is linked to the corresponding instance.

(5) Verifying the ontology

Given that the ontology model serves as a concrete abstract representation of domain knowledge encompassing various hierarchical relationships, its construction's reasonableness is assessed by examining the ontology's consistency. This verification process is conducted using the Pellet reasoner (Zhang et al., 2015).

3.2.2 Ontology-based knowledge inference

To enable the application reasoning of the ontology, it is necessary to establish SWRL rules based on the established ontology model. SWRL is a language capable of expressing rules and logic that is compatible with classes, relationships, and instances within ontology models. Each SWRL rule established in this study comprises three essential components: The data attribute of the instance, the judgment condition, and the judgment result. The data attribute of an instance becomes comparable once it is assigned a specific value. Utilizing the comparison logic within the SWRL rules, the data attributes of instances are compared, ultimately yielding the score for the target building under each clause.

The SWRLTab plug-in in Protégé software seamlessly bridges the SWRL rule environment and the ontology editing environment (Shen et al., 2022a), significantly enhancing the convenience of creating SWRL rules. Via the visual interface, users can select the relevant data attributes and comparison logics to construct the ASGB rule base. This rule base streamlines the process, eliminating the need for laborious manual specification searches and score calculations. Finally, the Ontology Web Language (OWL) and SWRL rules are transformed into Drools rules. The Rete algorithm is employed to match Drools rules for reasoning, automatically updating the green score within the ontology model, thereby accomplishing the automatic reasoning of the green building score.

4 Case study

4.1 Project description

To validate the proposed framework, a residential building was chosen as a case study. The theoretical framework presented in this study was applied to conduct a preevaluation of its green score within the credit category of occupant convenience, following the ASGB guidelines. By comparing the evaluation results with those obtained from green building evaluation experts, the feasibility and validity of this theoretical framework can be confirmed.

The geographical coordinates of the building are 106.696757 for longitude and 29.519323 for latitude. It comprises 33 floors above ground and 2 underground levels. Figure 4 depicts both the civil engineering BIM model and the electromechanical engineering BIM model of the case building. Based on the previous analysis of BIM model accuracy, the BIM models employed in this study fulfill the requirements for automated preevaluation.

4.2 Evaluation data acquisition for the residential building

The sixth chapter of China's ASGB, specifically the occupant convenience credit category, was chosen to validate the conceptual framework introduced in this study. This credit category comprises one prerequisite item and four scoring items. The scoring items within the occupant convenience credit category encompass the following: 1) transit and accessibility; 2) service facility; 3) intelligent operation; and 4) property management (PM). Given that the conceptual framework proposed in this study is designed for use during the building design stage and that the PM scoring item pertains to the operational stage, this study focuses on the prerequisite item and the first three scoring items within the occupant convenience credit category. To elaborate, the data acquisition process using the proposed conceptual framework unfolds as follows.

4.2.1 BIM-based evaluation data acquisition for the residential building

The items within the occupant convenience credit category

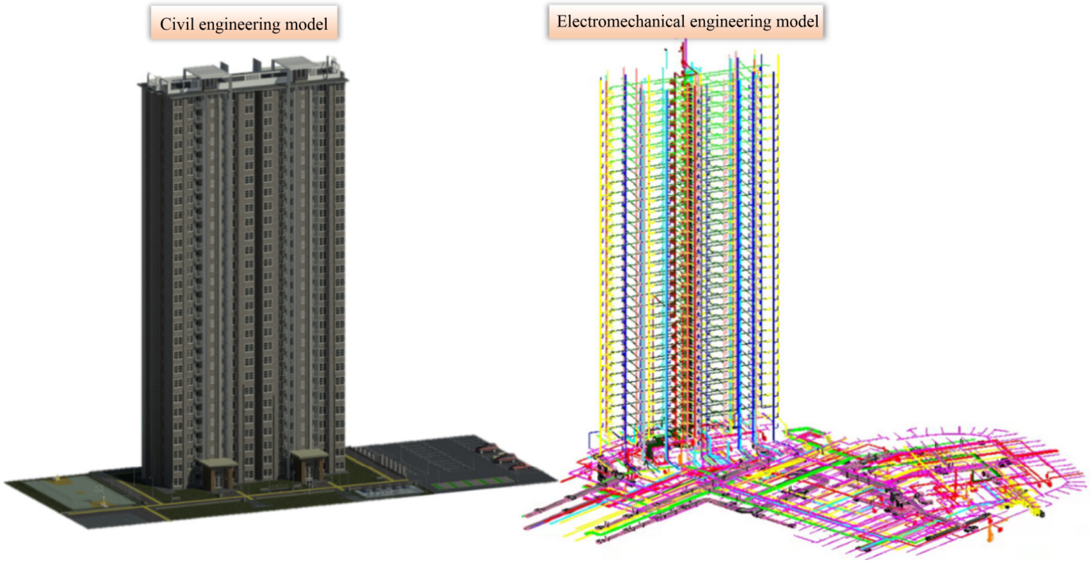

Fig. 4 BIM models of the case building.

are divided into BIM items and WMS items. Table A1 in Appendix A provides an analysis of the key information present in all BIM items, along with specifying the accuracy requirements for each item in relation to the BIM model. Notably, BIM items allow for the acquisition of evaluation data through visual inspection of the BIM model or by utilizing Dynamo for development. In cases where visual inspection of the BIM model aligns with the evaluation criteria for a given item, the evaluation data are assigned a value of 1; otherwise, they are assigned a value of 0. This rule is exemplified in the evaluation data results for the case building based on the visual BIM model, as presented in Fig. 5.

For instance, Clause 6.1.1 stipulates that accessible ramps and pathways for the visually impaired must be provided for the height difference of the site, the outdoor site of the building, the main entrance and exit of the building, and the junction of the public road on the site. By inspecting the barrier-free facility configurations in the three-dimensional BIM model, it becomes evident that the case building complies with this requirement, resulting in an evaluation data assignment of 1.

For the remaining BIM items, specific element parameters can be programmatically selected within the Dynamo platform, facilitating the automatic extraction of evaluated data. As an example, Clause 6.2.5.4 mandates that the distance between the building stairs and the main entrance should not exceed 15 m. To meet this requirement, the “Category. ByName” function is employed to extract the “building stairs” element from the BIM model. Subsequently, “All Elements of Category” is utilized to retrieve the element’s “length” attribute, which is formatted as “float”. Finally, “Elment. GetParameterValueByName” and “Excel. WriteToFile” are employed to extract the acquired data and store it in an Excel file at the specified location. All evaluation data obtained through Dynamo development for the case building are presented in Fig. 6.

4.2.2 WMS-based evaluation data acquisition for the residential building

For the WMS items, this study obtains the relevant evaluation data through the development of a geographic data integration and acquisition platform. The platform has the capability to automatically search for the distance, number, and names of service facilities around the building. Moreover, the platform is integrated with the API of Baidu Map, one of China’s most widely used Internet mapping services, ensuring the validity and real-time accuracy of the data. By inputting the latitude and longitude coordinates of the building into the platform, the evaluation data for all the WMS items can be acquired, as demonstrated in Fig. 7. The evaluation data can be retrieved by entering the clearly marked longitude (106.696757) and latitude (29.519323) from the construction design drawing of the case building and clicking “Start Search”.

In the search result presentation interface, “Result” and “Reference data” display the values obtained after applying restrictions. “Target” represents the quantity required by each WMS clause. When the “Result” value is 0, it indicates that no suitable results were retrieved within certain restrictions. In such cases, the platform expands the search radius to 2000 m and displays the retrieved results in the “Reference data” section for user reference.

As shown in Fig. 8, for Clause 6.1.2, “Target” is 1, and “Result” is 4, indicating that Clause 6.1.2 requires at least one public transport station within certain conditions, and there are 4 public transport stations around the case building that meet these conditions. By clicking on the box for Clause 6.1.2, detailed information about all the retrieved results can be accessed. The data with the shortest distance can be selected as the evaluation data for Clause

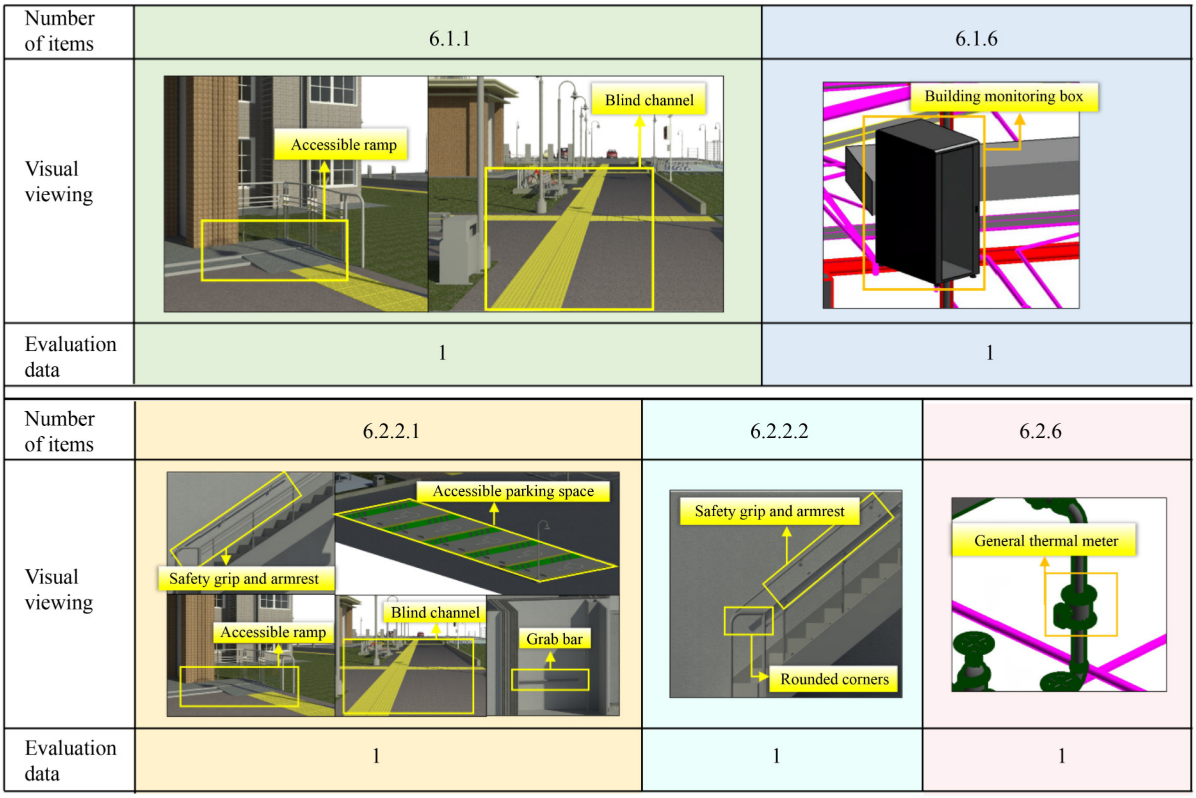

Fig. 5 Visualization of the evaluation index data based on BIM.

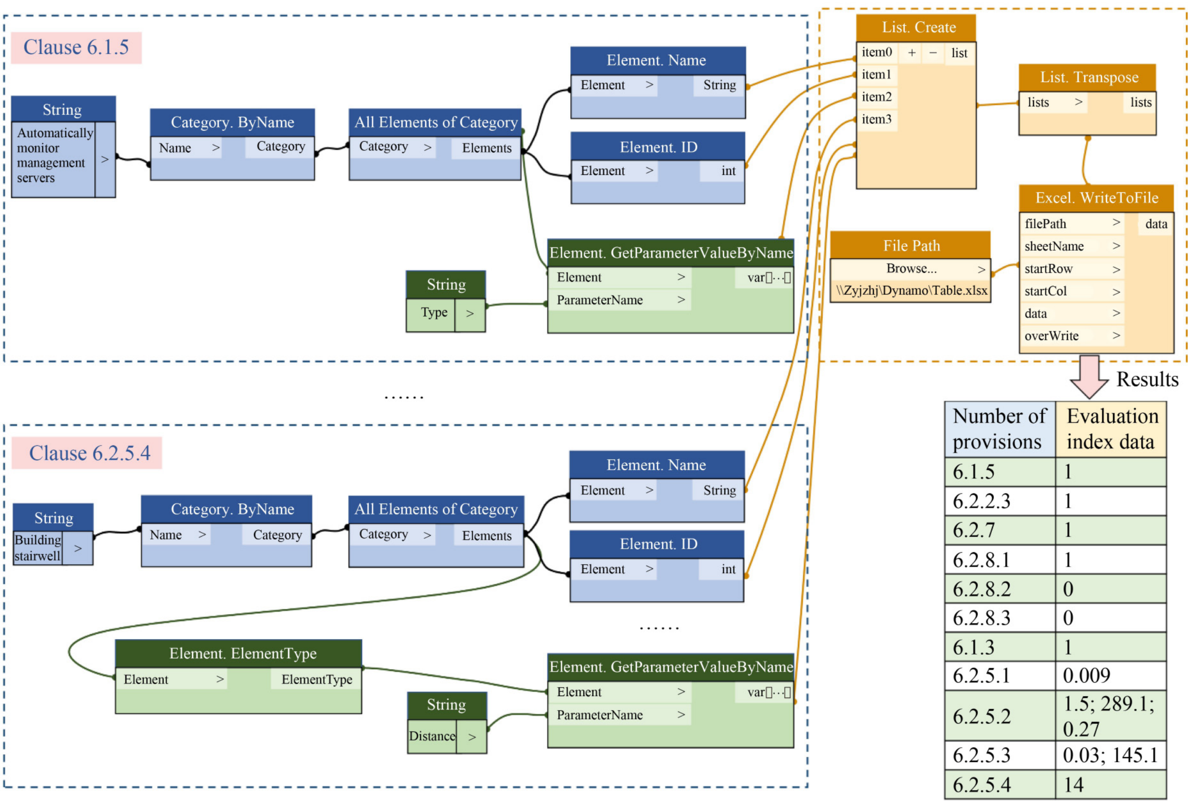

Fig. 6 Visual programming on the Dynamo platform to collect evaluation data.

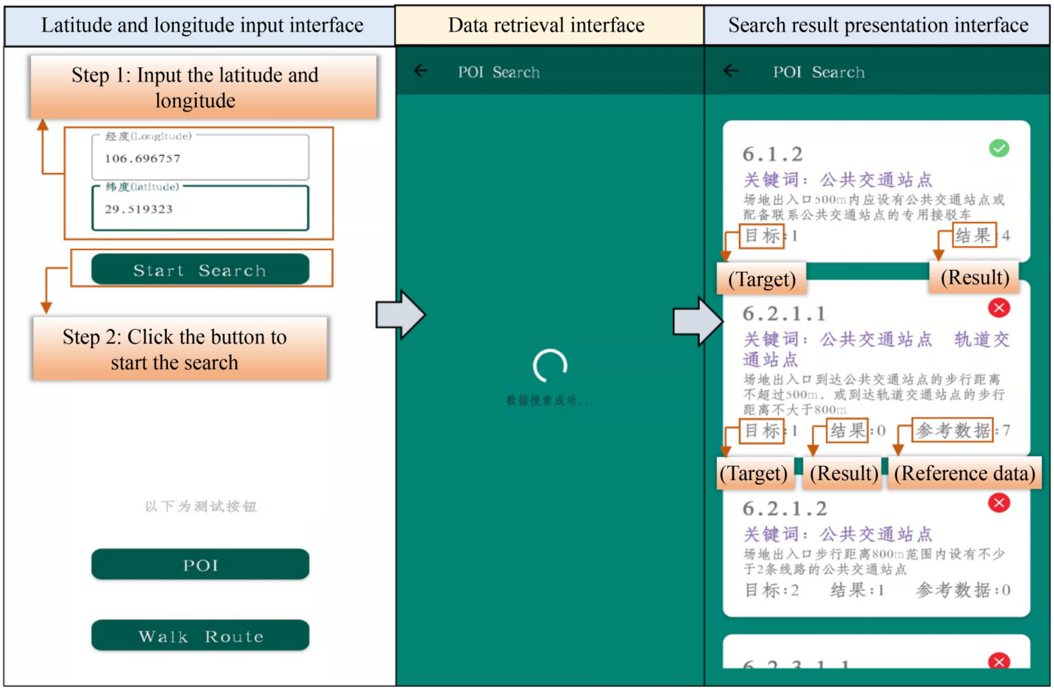

Fig. 7 The platform used to retrieve the evaluation data for WMS items.

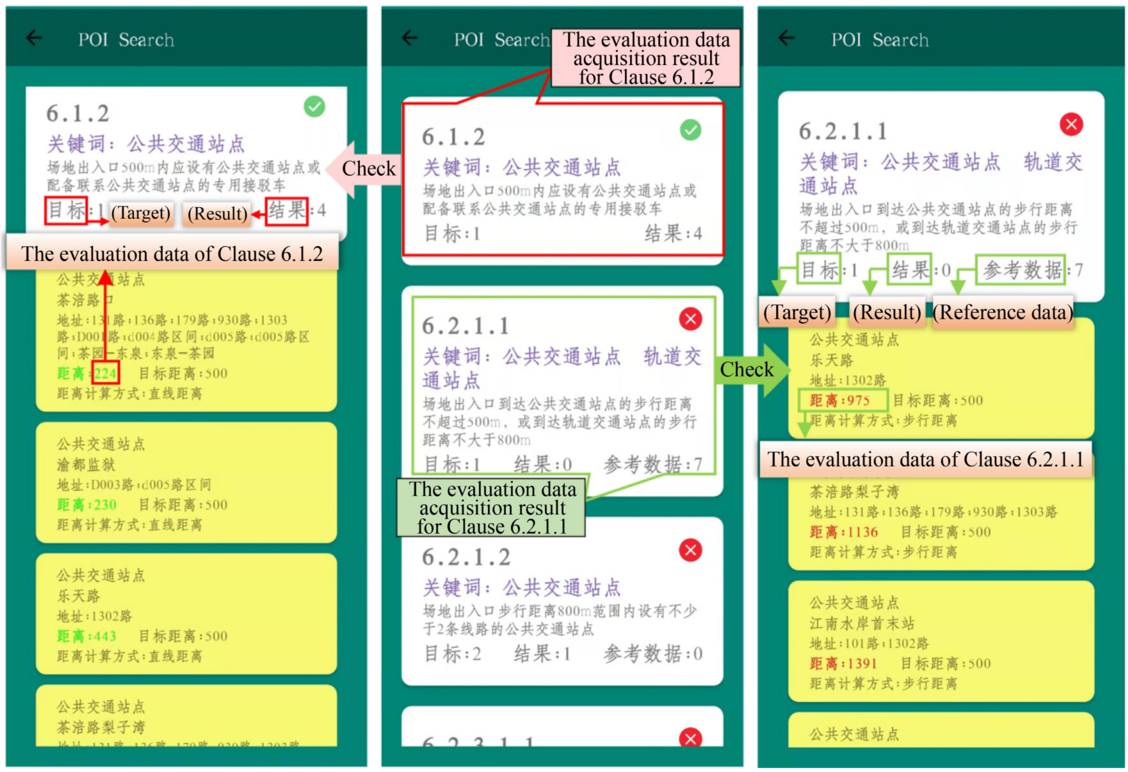

Fig. 8 Evaluation data acquisition results in APP for Clause 6.1.2 and Clause 6.2.1.1.

6.1.2, resulting in a distance value of 224.

For Clause 6.2.1.1, “Target” is 1, “Result” is 0, and “Reference data” is 7, indicating that Clause 6.2.1.1 requires at least one public transport station or rail transport station to be retrieved within certain conditions, but none meet these conditions initially. In this scenario, the platform extends the retrieval radius to 2000 m, resulting in the retrieval of 7 public transport stations that can serve as reference data. Similarly, any distance value from the reference data can be selected as the evaluation data for

Clause 6.2.1.1.

Similarly, the evaluation data for other WMS items are obtained using the same method, and the specific results are presented in Table 4.

Table 4 Evaluation data for WMS items

Number of items	Number of results required in the clause	Evaluation data
6.1.2	1	224
6.2.1.1	1	975
6.2.1.2	2	708, 2000
6.2.3.1	1	572
6.2.3.2	1	1357
6.2.3.3	1	2000
6.2.3.4	1	1264
6.2.3.5	1	1915
6.2.3.6	1	1003
6.2.3.7	3	210, 315, 273
6.2.4.1	1	1407
6.2.4.2	1	2000

4.3 Credit score inference for the residential building

4.3.1 Ontology-based knowledge storage

By analyzing all the items included in the occupant convenience credit category, the ontology model is manually established, as shown in Fig. 9. The "Classes" section presents the structure of the ontology model. The first class includes the evaluation building object (EvaluatedBuildingType), evaluation provisions (EvaluationProvision), and evaluation types (EvaluationType). The second class encompasses public buildings (PublicBuilding), residential buildings (ResidentialBuilding), prerequisite items (EvaluationControl), scoring items (EvaluationScore), and preevaluation (PreAssessment). The second-level class, in turn, includes more subclasses. "Object attributes" represent relationships between classes, such as "hasBuildingType" linking "EvaluatedBuildingType" with "PublicBuilding" and "ResidentialBuilding". "Instance" belongs to the instance under each subclass, constructed from the concrete content of the credit item and usable for the subsequent ontology application reasoning. "Instance" has data attributes, which are used to assign evaluation data.

4.3.2 Ontology-based knowledge inference for residential buildings

Based on the established ontology model, SWRL rules are further established by analyzing the meaning and implied scoring rules of items. The evaluation result of a prerequisite item differs from that of a scoring item. The former is of character type, while the latter is of integer type. Therefore, this study takes a prerequisite clause, namely, Clause 6.1.2, and a scoring clause, namely, Clause 6.2.5.3, as examples to elaborate on the detailed establishment process of SWRL rules.

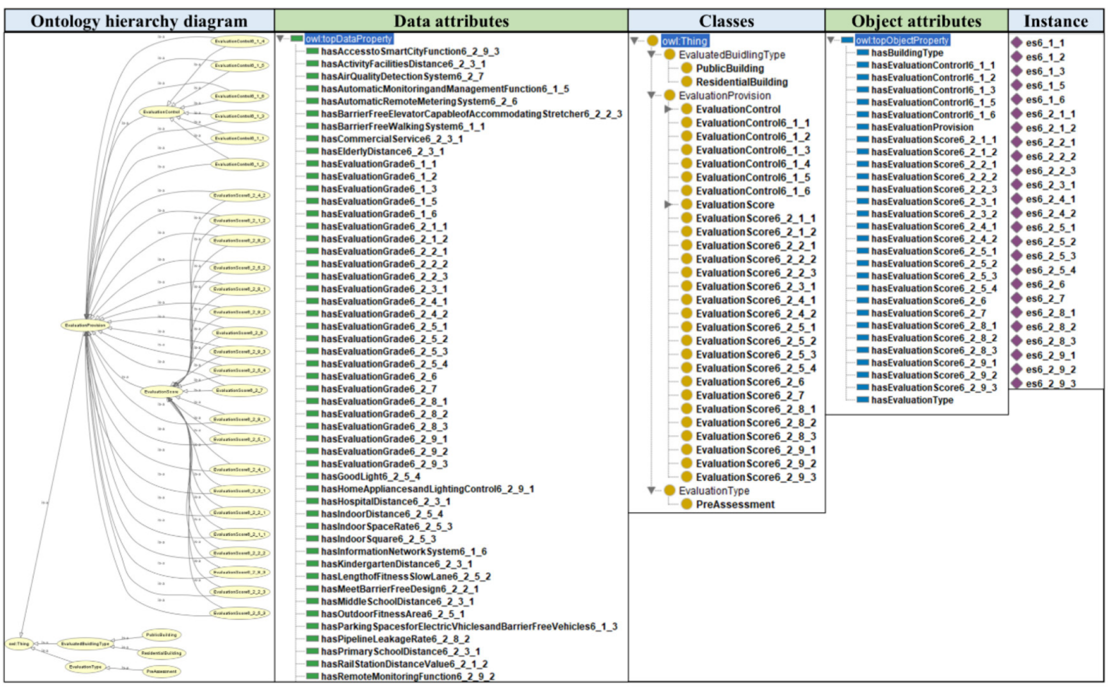

Fig. 9 Ontology model.

For Clause 6.1.2: There shall be a public transportation station or a dedicated shuttle bus to public transportation stations within 500 m of the pedestrian entrance. The data attribute of Clause 6.1.2 in the ontology model is “hasSpecialShuttleCar6_1_2”, and the restriction condition is satisfied when the distance is less than or equal to 500 m; otherwise, it is not. Therefore, in the SWRL rules, the data attribute of Clause 6.1.2 should be compared with 500. “lessThan” means less than or equal to. If the operation is successful, “Yes” is returned, indicating that prerequisite Clause 6.1.2 is met. The SWRL rule for Clause 6.1.2 is as follows:

swrlb:lessThan(?b, “500”^^xsd:int) ^ EvaluationControl 6_1_2(?a) ^ hasSpecialShuttleCar6_1_2(?a,?b) → hasEvaluationGrade6_1_2(?a, “Yes”)

For Clause 6.2.5.3: The area of indoor fitness space is not less than 0.3% of the above-ground building floor area and not less than 60 m^2, which is scored 3 points. In the ontology, Clause 6.2.5.3 has two data attributes: “hasIndoorSpaceRate6_2_5_3” and “hasIndoorSquare 6_2_5_3”. According to the content of Clause 6.2.5.3, in the SWRL rules, the ratio of indoor fitness space area (hasIndoorSpaceRate6_2_5_3) is compared to 0.003, and the indoor fitness space area (hasIndoorSquare6_2_5_3) is compared to 60. “greaterThan” means greater than or equal to. If the operation is successful, it receives 3 points; otherwise, it receives no points. The SWRL rule for Clause 6.2.5.3 is as follows:

swrlb:greaterThan(?c, “60”^^xsd:int) ^ hasIndoorSpaceRate6_2_5_3(?a,?b) ^ swrlb:greaterThan(?b, “0.003” ^^xsd:float) ^ EvaluationScore6_2_5_3(?a) ^ hasIndoorSquare6_2_5_3(?a,?c) → hasEvaluationGrade6_2_5_3 (?a, “3”^^xsd:int)

SWRL rules for the remaining items are established in Protégé 5.2.0 software using a similar analytical approach, and the results are presented in Fig. 10.

Based on the established ontology model and SWRL rules, the points for the case building in terms of the occupant convenience credit category are further determined. For example, as depicted in Fig. 11, Clause 6.2.4.1 specifies that the walking distance from the entrance to the urban park green space should not exceed 300 m. It can be deduced that Clause 6.2.4.1 has a data attribute, represented as “hasWalkingDistancetoCityPark 6_2_4_1” in the ontology model. The data attribute “hasWalkingDistancetoCityPark6_2_4_1” for the instance “es6_2_4_1” is assigned the value 1407, as obtained from the geographic information collection platform. Similarly, the data attributes of the remaining instances are assigned new values in the same manner.

Using the established ontology model, SWRL rules, and data attributes assigned with specific values, ontology inference is further conducted through the SWRLTab plug-in in Protégé. As illustrated in Fig. 12, the process begins with the execution of “OWL+SWRL->Drools”, which converts the OWL axioms into a rule engine and

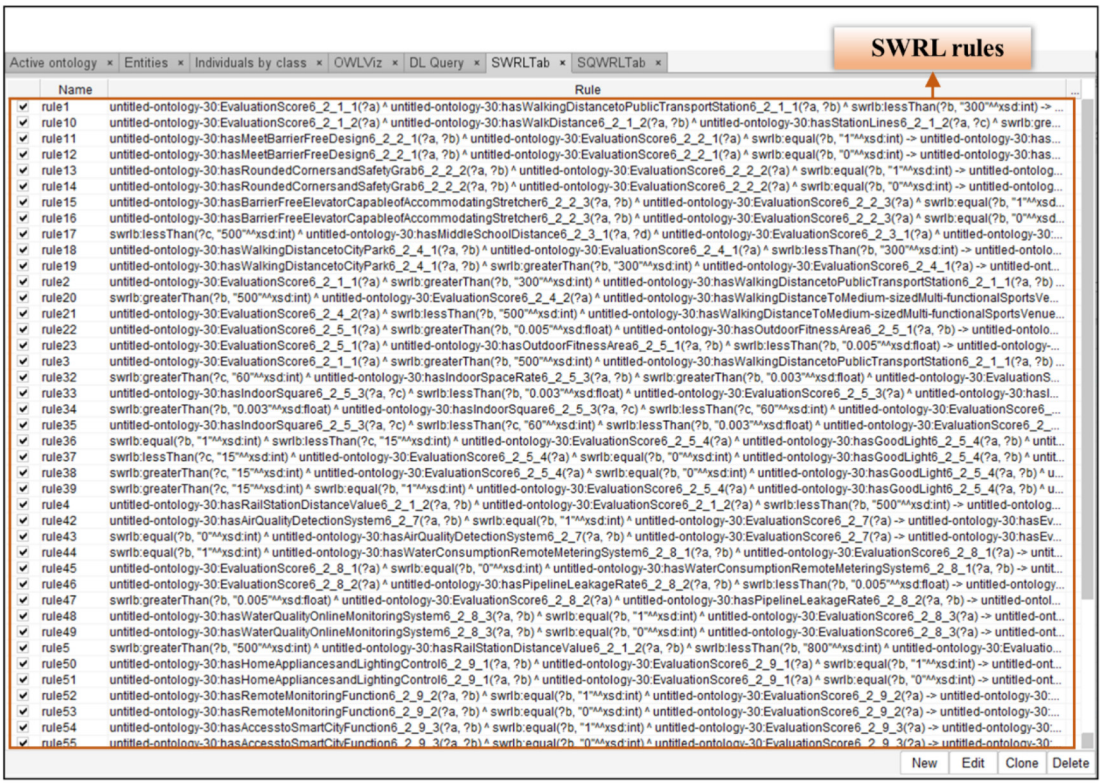

Fig. 10 SWRL rules.

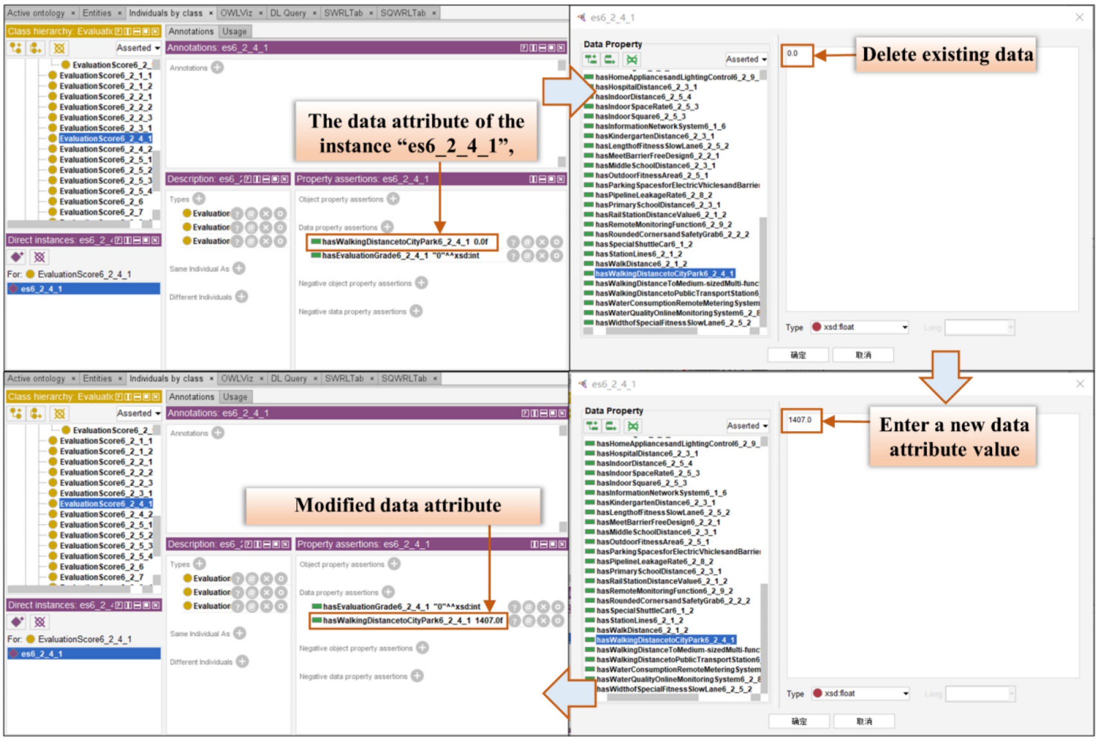

Fig. 11 Modify the data attribute of instance es6_2_4_1.

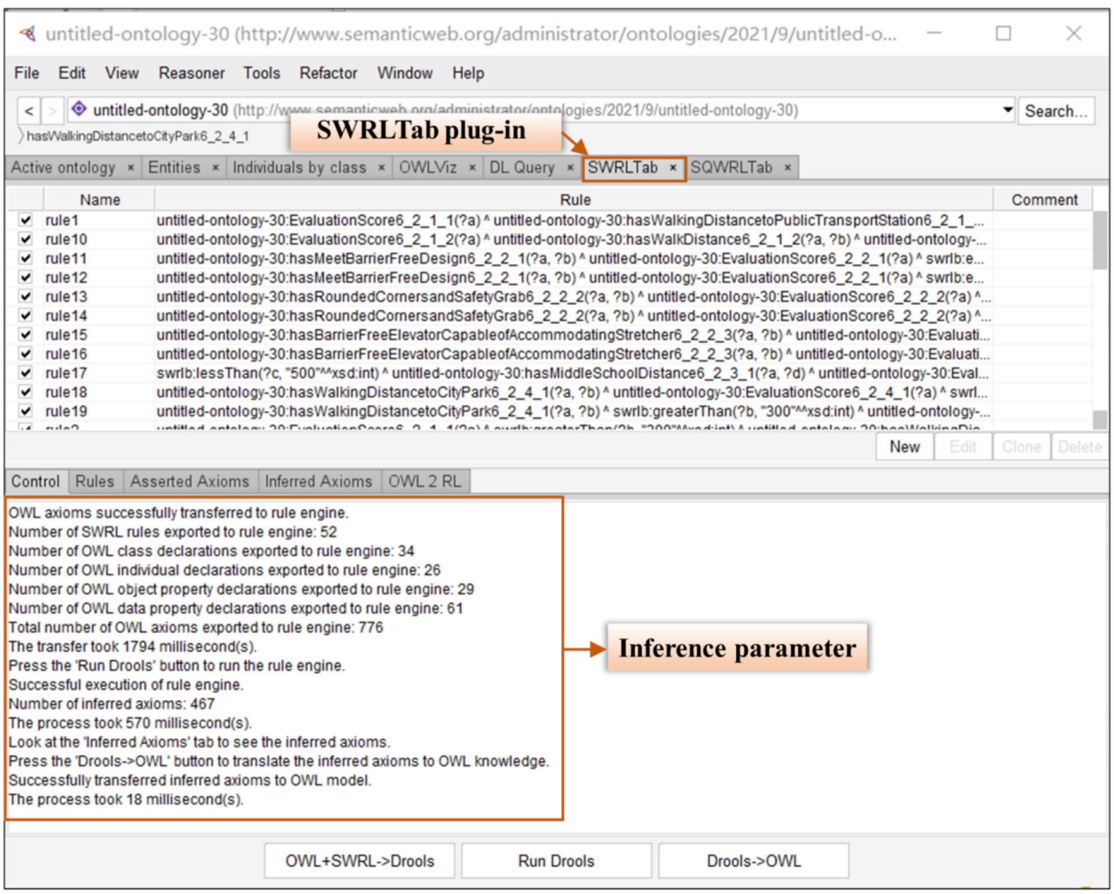

Fig. 12 Ontology inference.

takes 1794 ms. Next, “Run Drools” is executed to run the rule engine, resulting in 467 axioms. This step consumes 570 ms. Finally, “Drools->OWL” is executed to convert the reasoned axioms into OWL knowledge, requiring 18 ms. It can be calculated that the time required to evaluate the case building’s score in these items using the established ontology model and SWRL rules is 2382 ms.

The green score of the case building in terms of the occupant convenience credit category is presented in Fig. 13. The case building satisfies all prerequisite items in this credit category and attains a score of 33 points. Upon comparing the evaluation results with the assessment certificates acquired for the case buildings, it becomes evident that the evaluation outcomes obtained through the conceptual framework proposed in this study align with the evaluations conducted by experts. This verification affirms the feasibility of the conceptual framework introduced in this study.

Furthermore, a consultant from a third-party assessment consulting institution and a designer from China Construction Bureau No. 4 were enlisted to employ the proposed framework in a comparison of time consumption with traditional methods. The conclusion reached was that the proposed framework requires less time for data collection and evaluation of these items. This underscores that the proposed framework substantially enhances the efficiency of green building evaluation. Additionally, when assessing a larger number of items, the proposed framework would yield even greater time savings.

5 Discussion and conclusions

The ASGB serves as a metric for assessing the environmental performance of buildings. Given the increasing emphasis on green performance for new constructions in China, the development of automated tools for green building evaluation has become increasingly crucial. In this study, a novel theoretical framework is proposed, integrating BIM, ontology, and WMS for the automated evaluation of green buildings, a concept validated through engineering case studies. BIM and WMS are harnessed for automated data collection, while ontology models are established for the storage of green building evaluation knowledge and scoring logic.

Recently, ontology technology has gained traction among scholars as a means of storing normative or standard knowledge (Zhang et al., 2015; Du et al., 2016). This is due to the structured and logical nature of normative or standard knowledge. Additionally, ontology facilitates the organization and management of such knowledge. In a pioneering effort, Jiang et al. (2018) introduced ontology technology into the realm of green building evaluation.

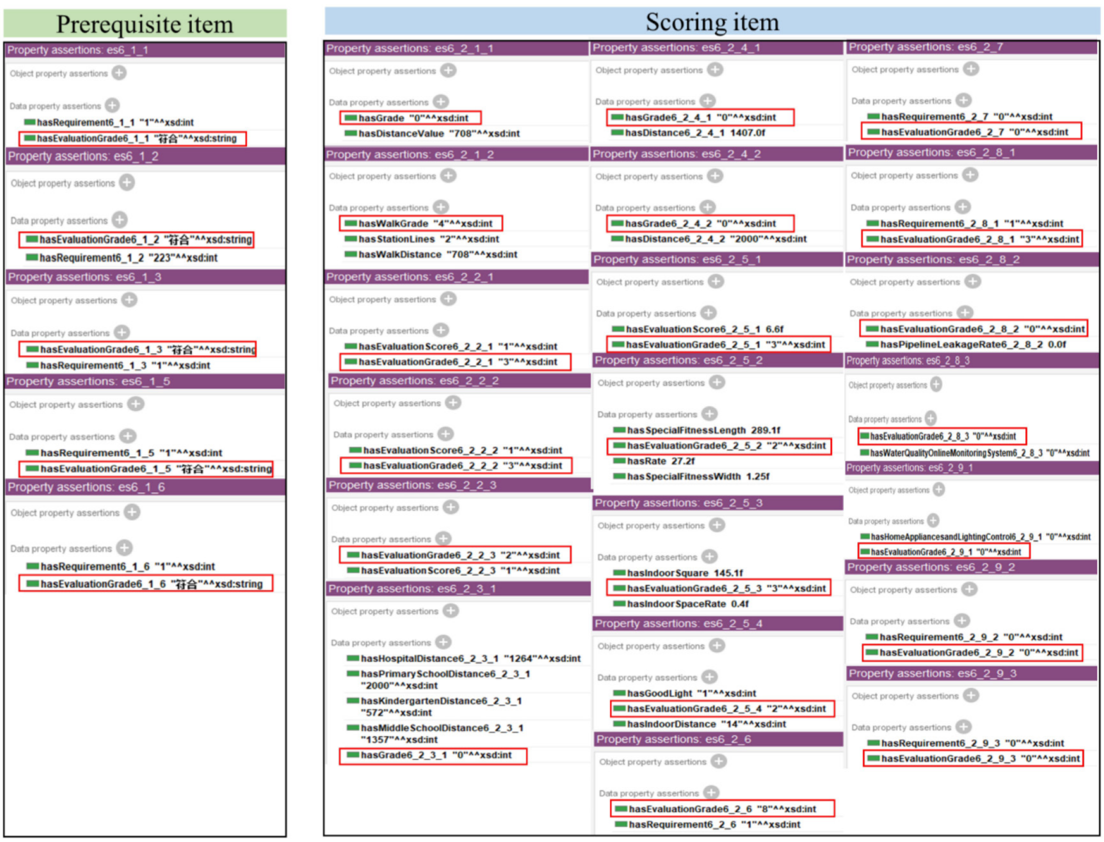

Fig. 13 Green score of case building.

They attempted to create an ontology model and SWRL rules for three clauses in the “scoring items” category, ultimately enabling scoring based on these clauses. Unlike prior studies, our research delves further into the establishment of ontology models and SWRL rules for “prerequisite items” based on data attributes in string format. This study demonstrates the applicability of ontology to a broader spectrum of green building evaluation systems.

BIM models serve as a rich data source for acquiring green building evaluation data. However, previous studies primarily focused on extracting evaluation data for LEED from BIM models through secondary development (Jalaei et al., 2020) while overlooking the acquisition of evaluation data for ASGB, which is essential for China, the world’s largest construction market. In this study, we edited programs using Dynamo to extract evaluation data from BIM models, facilitating real-time data interaction by exporting it to Excel. Additionally, Internet map service providers offer a reliable avenue for obtaining green building evaluation data. Past research was confined to data acquisition for LEED based on Google Maps. Through the use of Baidu Map’s API and its geographic data retrieval codebases, this study developed a platform for swiftly acquiring information about the accessibility of surrounding service facilities as stipulated in ASGB. This enriches the body of research on the automated evaluation of green buildings.

The theoretical contributions of this study enhance existing research on the automation of China’s green building evaluation system. Furthermore, the insights gained here could provide valuable guidance for other countries seeking to develop automated evaluation tools tailored to their respective green building evaluation systems. In practical terms, the results of this research can be applied by design and construction firms to self-assess whether their design proposals align with the desired green ratings.

There are still several limitations in this study that warrant further exploration in future research. For example, first, the automatic evaluation framework proposed in this paper is exclusively applicable to quantitative aspects of the green building evaluation system, rendering it unsuitable for qualitative items lacking explicit evaluation criteria. While qualitative items are relatively scarce within the evaluation system, it remains worthwhile to investigate a comprehensive automatic evaluation framework that can accommodate both quantitative and qualitative aspects. Additionally, the development of automated programs to facilitate the data import process into the ontology model should be explored. Second, the successful implementation of the framework proposed in this study relies on the availability of a sufficiently precise BIM model. Currently, China places significant emphasis on BIM models, and the government has begun mandating the submission of BIM models before construction commences. However, this study does not delve into the specific accuracy requirements imposed by the evaluation system on BIM models, leaving room for further examination in the future to ensure the effective functioning of automated evaluation tools.

In conclusion, this study represents an extension of existing research, not only enriching the current body of knowledge concerning the automated evaluation of green buildings but also offering valuable insights for other domains. For instance, it can serve as a reference for storing knowledge related to building safety standards within ontology models and inferring the level of building safety risk through data input into these models. Furthermore, this research holds practical value for real-world applications.

Competing Interests The authors declare that they have no competing interests.

Appendix A

Table A1 Analysis of BIM items

Number of items	Evaluation object	Evaluation index	Data acquisition method	LOD
6.1.1	Walking system	Features of accessibility	Visual viewing	300
6.1.3	Car parking space	Barrier-free car parking space proportion	Dynamo based development	300
6.1.5	Equipment management system	Automatic monitoring and management functions	Dynamo based development	300
6.1.6	Information network system	Equipped with this system	Visual viewing	200
6.2.2.1	Public road or place	Barrier-free	Visual viewing	300
6.2.2.2	Wall or column	Rounded	Visual viewing	300
6.2.2.3	Elevator	Stretcher-capable and barrier-free	Dynamo based development	300
6.2.3.2.1	Conference facilities or fitness facilities	Serving the public	Dynamo based development	400
6.2.3.2.2	Library, stadium, or parking space	Serving the public	Dynamo based development	300

(*Continued*)

Number of items	Evaluation object	Evaluation index	Data acquisition method	LOD
6.2.3.2.3	Parking spaces with charging points	Quantity	Dynamo based development	300
6.2.3.2.5	Grounds or public walkways	Serving the public	Dynamo based development	400
6.2.5.1	Outdoor fitness venue	Area	Dynamo based development	300
6.2.5.2	Fitness lane	Width and circumference	Dynamo based development	300
6.2.5.3	Indoor fitness venue	Area	Dynamo based development	300
6.2.5.4	Stairwell	Distance	Dynamo based development	400
6.2.6	Energy management system	Use energy automatic remote transmission function and energy consumption monitoring, analysis, and management functions	Visual viewing	400
6.2.7	Air quality monitoring system	Monitor PM_{10}, $PM_{2.5}$, CO_2 function and store monitoring data function and real-time display	Dynamo based development	400
6.2.8.1	Water remote metering system	Classification, grading record, and statistical analysis of various water use functions	Dynamo based development	400
6.2.8.2	Water remote metering system	Automatic monitoring, analysis and rectification functions	Dynamo based development	400
6.2.8.3	Water quality monitoring system	Monitor the water quality and save the results	Dynamo based development	500
6.2.9.1	Intelligent service system	Alarm, monitoring and control functions	Dynamo based development	400
6.2.9.2	Intelligent service system	Remote monitoring function	Dynamo based development	400
6.2.9.3	Intelligent service system	Access smart city functions	Dynamo based development	400

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