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Ontology-based Knowledge Modeling of Post-occupancy Evaluation for Green Building

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Abstract. Despite the development of advanced information and knowledge management technologies in the architecture, engineering, and construction (AEC) industry, there is still a missing link between the green building performance evaluation (BPE) domain and the knowledge management system. In the BPE domain, post-occupancy evaluation (POE) has been developed as an effective method to evaluate actual building performance after the building has been occupied for some time. However, the vast POE knowledge is mostly documented in various standardized references with different focuses, and it is time-consuming to manage and acquire scattered and fragmented knowledge data. Ontology, as a semantic web technology, has been widely used in the knowledge representation and management engineering field. Hence, this research integrates ontology into the green building post-occupancy assessment domain to develop a unified semantic model to systematize the fragmented knowledge. The extracted POE knowledge from evaluation standards is formalized into OWL (Ontology Web Language) ontology, which achieves knowledge systematization in the POE domain and enables the knowledge-based application systems to retrieve, share and reuse POE knowledge more effectively.

1. Introduction

In recent years, the increasingly severe environmental issues, energy over-consumption, natural resources shortages, and rapid urbanization have become the main restrictions for the sustainable development of environment, social and global economy. According to a global report [1], the architecture, engineering, and construction (AEC) industry accounted for around 36% of global final energy consumption and nearly 40% of energy-related greenhouse gas emissions in 2017. The actual building energy consumption is sometimes up to 3 times greater than the estimated calculation [2]. Cater to the sustainable development, the green building (GB) and various GB rating systems (GBRSs) with different focuses are arising to evaluate the building's performance, such as BREEAM, LEED, ASGB, LBC, WELL. However, the majority of GBRSs are design-oriented evaluation tools, mainly focus on the design and construction phase rather than the building operation and maintenance phase, and the assessment at the operation phase does not get enough attention and support among these systems. There is a missing of an actual-performance-based comprehensive evaluation system, which addresses on building's post-occupancy assessment [3]. There is a huge potential profit for developing performance assessment at the occupancy stage of green buildings, which provides guidelines for more sustainable performance improvement. There are a number of factors that have prevented the development and widespread implementation of POE practices, like the lack of unified assessment criteria and an effective knowledge retrieving and sharing system, and the scattered and fragmented evaluation knowledge, etc.

As a semantic technology to manage unstructured knowledge, ontology has been widely applied in the AEC industry in the domain of construction safety checking [4], the construction noise control [5], the sustainable building technology [6], construction cost estimation [7], etc. However, there is not a generalized knowledge model for GB post-occupancy assessment yet, therefore, this research integrates ontology into the GB post-occupancy assessment system to capture, describe, and model the knowledge in the GB-POE domain in a structured and sharable way. The ultimate goal is to promote the POE practice into the real-world construction projects to enable the knowledge-based evaluation application systems are more effectively to retrieve, exchange, and maintain the GB-POE knowledge.

The assessment criteria and constraints of the proposed framework are mainly extracted from building performance assessment regulations. In this research, the Post-occupancy Evaluation Standard for Green Building [8] (a Chinese national standard) has been demonstrated in Protégé 5.5.0 to show the ontology application capability in GB-POE work.

2. The overview of green building post-evaluation and ontology

This section briefly reviews green building post-evaluation and ontology development, includes the prominent assessment systems in the BPE domain, the essential elements to develop an ontology in the aspects of ontology description languages, methods, editors, query language, etc.

The various GBRSs have been developed from the 1990s to evaluate the performance of building at different stages with different weights of each category, the main assessment criteria are shown in Table 1. BREEAM, as the first established BRS in the world, has laid a solid foundation for other rating systems development [9]. However, the most of GBRSs focus on the green evaluation in the design and construction stage, rather than the operation and post-evaluation of green buildings. Based on the understanding of the life cycle of green buildings, the concept of post-evaluation has been proposed with the later development. POE promotes the participation of building occupants, the end-users, focuses on their requirements of buildings in the aspects of health, safety, convenience, amenity, psychological comfort, living quality and satisfaction, it emphasizes on building occupants' needs.

Table 1. The assessment categories of GBRSs

NO.	1	2	3	4	5	6	7	8	9	10	11
GBRSs / Top Criteria	BREEAM	LEED	Green Star	ASGB	CASBEE	DGNB	Green Globes	GBI	Green Mark	LBC	WELL
Site /Land	√	√	√	√	√	√	√	√	√	√	
Energy	√	√	√	√	√	√	√	√	√	√	
Water	√	√	√	√	√	√	√	√	√	√	√
Materials	√	√	√	√	√	√	√	√	√	√	
Indoor Environment		√	√	√	√	√	√	√	√		
Innovation	√	√	√	√				√			√
Management	√		√				√	√	√		
Transport	√	√	√						√		
Health &Wellbeing	√			√						√	
Waste	√								√		
Occupant Convenience				√							
Emissions			√				√				
Regional Priority		√									√
Pollution	√										
Economic Quality						√					
Equity										√	
Beauty										√	
Nourishment											√

Smart building Operations	√

2.1. Post-occupancy Evaluation

Building performance evaluation (BPE) origins from England and the United States, by the early work from Manning and Markus et al. [10], it has been applied in different forms since from the1960s. Along with the later development, POE has become one of the most widely applicable and sustained methods as a sub-process of BPE. Post-occupancy evaluation is a systematic method to evaluate buildings after they have been used for some time in the aspects of energy, environment, occupant comfort, to provide evaluation feedback to optimize and improve building performance throughout the whole building lifecycle, from the stage of strategic planning, design, construction, occupation to operation, and typically includes analysis of the end-users perceptions.

The value of the implementation of POE is being increasingly recognized and hundreds of POEs have been applied in different fields. The Probe (Post-occupancy Review of Buildings and their Engineering) project, which started in 1995, led by the UK government and a research team to assess the performance of commercial and public buildings, the evaluation result shows the occupants have the low satisfaction of their buildings. Another UK government led BPE project among 56 buildings in 2016 has shown that even the BREEAM certificated office buildings are not performing as they should do, the buildings consuming up to 3 to 10 times the energy they should, and some of the end-users have lower satisfaction compared with the non-certificated buildings [11]. More recently, BSRIA [12] has launched the six-phase approach named Soft landing framework to raise awareness of building performance in use in the early stage of the building life cycle, the phase 6 emphasizes and provides an effective route for the aftercare and POE of buildings. Khair et al. conducted a study by using POE tools to determine the physical environment elements of public low-costing housings based on occupants' preference in Malaysian [13]. Alborz developed a POE framework for higher education sustainable dormitories evaluation and established the evaluation criteria hierarchy [14], but this framework is not suitable for other building types, like office buildings. Teasdale-St-Hilaire has summarized the developed POE protocols, as shown in Figure 1, these protocols focus on different building types with various evaluation methods [15]. Even though the POE has a late start in China, especially in the green building domain, the government has proposed the first national standard of the Technical manual of Post-occupancy Evaluation for Green Building in 2017 [8], to promote the POE practice among the GB. In this research, the assessment constraints are mainly extracted from the technical manual to demonstrate the Ontology applicaion in POE domain.

After a brief introducing of the development of POE, the next section presents the ontology development and its application in the building performance evaluation field.

POE Protocol	Target Building Type
EcoSmart (EcoSmart Foundation 2007)	MURBs
Keen Engineering POE protocol (Keen Engineering 2005)	Office buildings
Watson (Watson 1996, 2003); Watson and Fitzgerald (1998)	Various
Higher Education Funding Council for England (HEFCE 2006)	Higher education buildings
Baird (Baird 2010)	Sustainable commercial and institutional buildings
Post-Occupancy Review of Buildings and their Engineering, or PROBE (Cohen et al. 1999; Leaman, Stevenson, and Boyce)	Offices, institutional industrial and government buildings
Soft Landings Framework (BSRIA 2009)	Non-specific
Building Research Establishment (BRE)'s Design Quality Method (Cook 2007)	Various, including schools, hospitals, and housing
Sanders (2010)	Housing
Birt and Newsham (2009)	Commercial and office buildings

Figure 1. The POE protocols of Teasdale-St-Hilaire's research [15]

2.2. The development of ontology

As a semantic technology, ontology plays a key role in the Semantic Web (SW) which was coined by Tim Berbers-Lee. Semantic Web is an extension of the current web, in which information is given a well-defined meaning to achieve its interoperability between different systems. There is no universally accepted definition of ontology, the widely cited one is defined by Gruber: "An ontology is an explicit specification of a conceptualization". Uschold and Gruninger have pointed out that the ontology is a term refers to as the shared understanding of a given domain, and it can be used as a unifying problem-solving framework [16]. Noy and McGuinness described ontology as a common domain vocabulary, which defines the machine-interpretable domain concepts and clarifies the relations among them [17]. The University of Stanford's Knowledge Systems Laboratory (KSL) has explained the ontology as a formal and declarative knowledge representation system, the terms related to the relative subject domain and the logical relationship statements between the terms are declared in this system. So, based on the above ontology understanding, Darlington and Culley consider the ontology as a useful vocabulary to represent and share knowledge about a specific subject area and a series of relations among them and make it explicit [18].

2.2.1. Ontology methodologies, languages, and editors. There is no single correct methodology to design an ontology for any given domain, here are few commend ontology-design methods, for example, Grüninger and Fox's methodology, Uschold and King's method, METHONTOLOGY, and Simple-Knowledge Engineering Methodology (SKEM), also known as '7-Steps', which is the most prevailing one. Catering to improve ontology's expressivity capability, the W3C developed several ontology description languages, including XML, RDF, RDFS, OWL. Because of the ability to represent rich and complex knowledge and reasoning ability, OWL is recommended by W3C as a proper ontology description language to be used in ontology developing. There are several available ontology editors, for example, OntoEdit, WebODE Swoop, OntoStudio and Protégé which is a free, open-source, user-friendly ontology editor and framework for building intelligent systems, and also the most widely used one.

2.2.2. Ontology application in POE knowledge representation. As the core part of the semantic web, ontology has been widely applied in the domain of knowledge management, information representation and extraction, and logical inference. After having a broad literature review, there are some existing ontologies have been developed to support knowledge representation and management within the building evaluation domain. However, due to the limited space, the following introduced ontologies are taken as examples to explain their usage in the building evaluation domain.

- CQIEOntology:

Construction Quality Inspection and Evaluation Ontology is developed against manual construction quality compliance checking, which is time-costing, cumbrous and error-prone. It enables the construction quality checking to be carried out as a concurrent activity along with the construction process, rather than afterward [19]. However, this ontology mainly focuses on the quality checking on the construction stage, not suitable for the post-occupancy evaluation.

- SBT ontology:

Sustainable Building Technology Ontology explains the three main concepts in the SBT domain to represent the emerging sustainable building technologies knowledge in UK construction, they are building construction technology, organization and the standards required for the design of construction technologies respectively. Each of these three concepts consists of different subclass [20].

- eeBIM-ontology (Energy Enhanced BIM) framework:

This ontology framework used for the building energy performance analysis, and facilitates to identify the energy performance problems at the early design stage [21]. However, this ontology framework more focuses on building energy performance simulations at the early design stage, not fit the total building performance evaluation from the whole lifecycle of the building.

- Building safe evacuation design support ontology:

Boje [22] proposed a method to integrate ontology as a knowledge representation technique into BIM supported building fire evacuation design process to facilitate automatic evacuation design decision-making processing and improve the interoperability of the BIM systems.

There are some other representable ontologies in the AEC knowledge management field, such as the ifcOntology, the CSCOntology for construction safety checking knowledge, the CNCOntology for construction noise control knowledge structure, and so on. These above-reviewed ontologies are specialized in different AEC industry domain, there is still a lack of knowledge systematization in the GB post-occupancy assessment domain, however. The next section illustrates the proposed ontology building methodology and processes.

3. The development of proposed POE ontology

Based on the previous review on POE and ontology, this section states the methodologies for the proposed POE ontology. The above-mentioned existing ontologies are taken as references to build the POE ontology in this research. The key to develop the POE ontology is establishing the POE key performance indicators (KPIs) framework first and then following the '7-steps' (SKEM) development guide proposed by Noy and McGuinness [16] to develop the POE ontology.

3.1. Development of the proposed ontology

In this case, based on the systematic review of the existing green building post-evaluation standards, the extracted GB-POE criteria class hierarchy is shown in Figure 2. The POE related standard knowledge and evaluation restrictions have been modeled in Protégé 5.5.0 to show the ontology practical application in the knowledge engineering domain.

3.2. Development of the proposed ontology

Based on the above review, the assessment criteria framework has been this research follows the instruction of Noy and McGuinness's '7-steps' methodology to build the ontology model through the Protégé platform with the OWL description language. The ontology building processes are shown below:

- Step 1. Determine the domain and scope of the ontology:

The proposed ontology knowledge model is for post-occupancy evaluation of the green building, which includes the concepts extracted from different evaluation systems and relevant researches, like the various evaluation criteria, evaluation methods, assessment standards, etc.

- Step 2. Consider reusing existing ontologies:

This research has taken the above-analysed ontologies as references to develop the POE ontology. However, the above-referred ontologies are specific to different knowledge domains in the AEC industry, there is not a comprehensive GB-POE ontology yet.

- Step 3. Enumerate import terms in the ontology:

As analysed above, the selected main categories of KPIs are energy, water, materials, land, IEQ, pollution & waste, wellbeing & health, management, emissions, etc. As shown in Figure 2, under each of the top criteria, there are some sub-criteria, for example, the sub-criteria of the energy category are energy monitoring, renewable energy utilization, electricity/gas consumption, HAVC energy-saving rate, etc., the sub-criteria of the wellbeing & health are safety, occupant satisfaction, occupant convenience, thermal comfort, visual comfort, indoor air quality, acoustic comfort, acoustic comfort, user control, etc.,

- Step 4. Define the classes and the class hierarchy:

The class hierarchy represents an "is-a" relation. For example, in this proposed ontology, land utilization criteria is a subclass of evaluation criteria, energy-saving and utilization criteria is a subclass of evaluation Criteria, plot ratio is a subclass of the land utilization criteria and so on. After determining the key criteria from step 3, the main criteria class hierarchies of this preliminary ontology have been built as in Figure 2.

- Step 5. Define the properties of classes – slots:

There are two main types of properties, the object property which describes the internal relations of concepts, and data property which defines the relations between the listed concepts and the data type's value. As shown in Figure 3, the relation between the evaluation task and the evaluation criteria can be defined as "hasEvaluationCriteria", that is, the evaluation task has the evaluation criteria of 'EvaluationCriteria4-2-1', 'EvaluationCriteria4-2-2', etc.

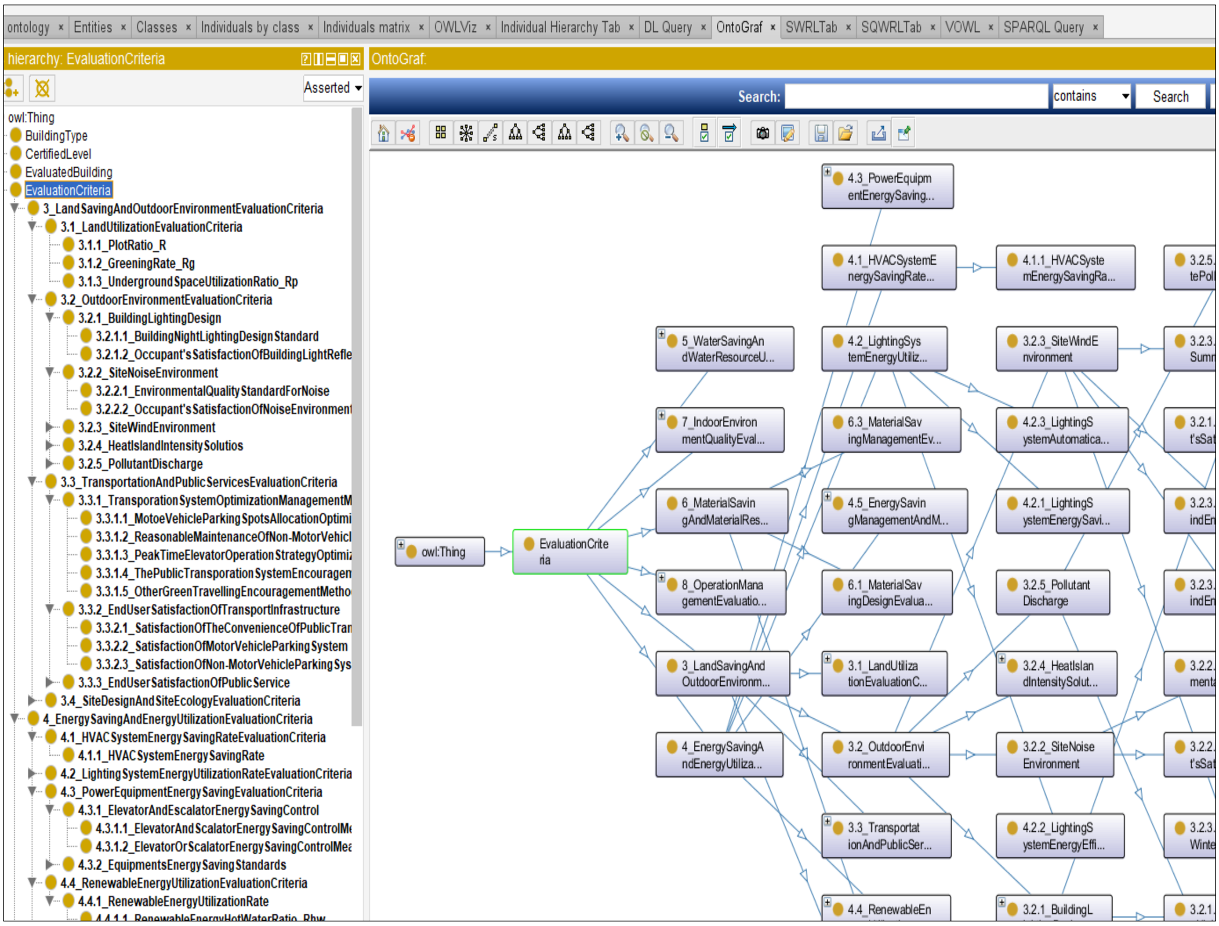
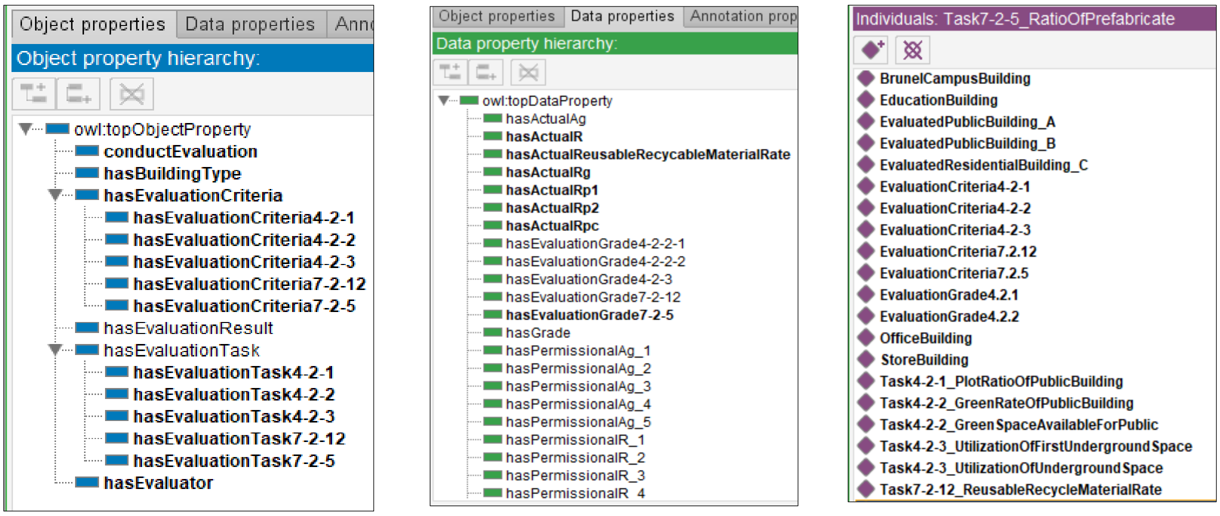


Figure 2. The criteria class hierarchy of POE ontology



(a). Object property **(b).** Data property **(c).** Individual instances

Figure 3. The properties of POE ontology

- Step 6. Define the facets of the slots:

Facets mean the slot restrictions which describe what types of values can fill in the slot, allowed values, the number of the values (slot cardinality) and any other characteristics of the values that slots can take. For example, as shown in Figure 4, the green plot ratio of building is defined as EvaluaitonCriteria4-2-1 in this model, which has four allowed thresholds values of 0.5, 0.8, 1.5, 3.5. The EvaluationCriteria4-2-1 has exactly 1 permission value for each of the data property, and the type of the value is float type.

- Step 7: Create instances:

The last step is creating instances of the classes. First, select the classes, then create the individual instances of the chosen classes, and fill in the values of the instances. The specific individual instances are shown in Figure 4.

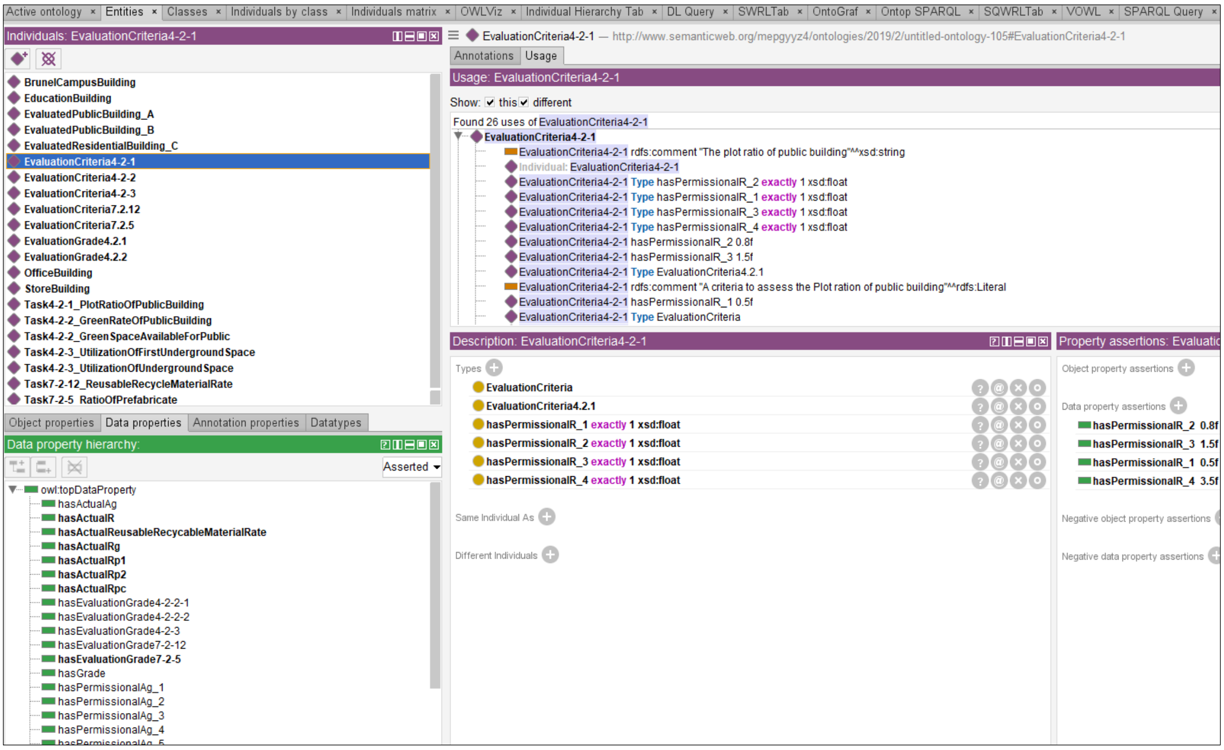


Figure 4. The overview of the Ontology

Following the instruction of Noy and McGuinness's '7-steps' method, the proposed preliminary green building post-occupancy assessment knowledge management ontology model has been partly completed in this research. This proposed ontology model realizes the structural representation, sharing and reuse of fragmented standard among the knowledge-based systems and the experts, and achieve the standardization of the POE knowledge to show the ontology practical application in the knowledge engineering domain. In practice, this research also develops a comprehensive assessment methodology or tool for the building assessment at the post-occupancy stage, which is more effective and cost-effective.

4. Conclusions

As stated above, the lack of systematic assessment indicators and a unified knowledge retrieval system for the scattered and fragmented POE knowledge have inhibited the development of POE. Because of its interoperability in different systems, ontology has been adopted in this research to build a POE domain ontology knowledge to show the ontology practical application in the knowledge engineering domain. At present, the preliminary POE criteria ontology model has been developed, which can be

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used in different knowledge representation information systems in AEC industry, especially in the GB evaluation domain, to achieve the sharing of the common understanding of the structured machine-interpretable knowledge and information between the people and software agents, and enable reuse of domain knowledge and make domain assumptions explicit, also to help raise the awareness of POE implementation and sustainability concerns in the AEC industry.

This preliminary ontology is developed based on the top-level criteria, there are more detailed sub-criteria that need to be developed and added in the future. Establishing the weighting system for the POE framework through the multiple-criteria decision analysis methods is also another important task in the future.

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