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GENERATION OF ACOUSTIC ONTOLOGY FOR A HOLISTIC BUILDING PERFORMANCE DOMAIN

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Abstract

The building performance domain suffers from inaccurate, incomplete, or repeating information due to application-specific data structures, which leads to poor data integrity and interoperability. In particular, no building acoustic ontology with a generalized and integrated data structure has been published. This study aims to create a unified and generalized building acoustic ontology based on reverse engineering over acoustic software applications. The study is a starting point for design of a domain-specific ontology as a knowledge repository by serving the building acoustic performance principles in generalized conceptual modeling and linking semantics and object relations in a building information graph.

Introduction

Building information modeling (BIM), supporting rich building objects' data and information with physical and functional properties (Howard & Björk, 2008; Sacks et al., 2018), is being used for deriving building performance models and analyzing performance models. However, the challenge is obtaining generalized performance domain concepts and information while extracting information from BIM software to building performance simulation software due to a shortage of non-geometric data and geometric inconsistencies in native (vendor-specific) models (Jones et al., 2013). As a result, data extracted from the BIM model usually results in inaccurate, incomplete, or false information (Bloch & Sacks, 2018), especially in the performance domain.

To enable interoperability between diverse software applications by exchanging building information, openBIM formats (e.g., IFC) and open data schemas (e.g., gbXML) were suggested. However, these formats have (i) deficient definitions in their objects' libraries and belonging standards, which leads to left-out objects (Howard & Björk, 2008), and (ii) restricted information, semantics, and knowledge coming from modelling concepts and requirements (Zhong et al., 2018).

Consequently, in the building performance domain, the main challenges are poor interoperability between software and stakeholders (architects, engineers, and software vendors) as well as the absence of semantic contents and object relationships, and implicitly identified semantics in data schemas. Hence, a generalized and integrated performance domain ontology, as a knowledge guideline binding building performance and building information systems, is needed. This study focuses on building acoustic ontology under this perspective. The next section displays a literature review on the building acoustic performance in association with BIM including ontology and linked data studies. Following, the proposed research method and tools are explained. The generated building acoustic ontology and the findings are represented in the results and discussion section.

Building Acoustic Performance in Association with BIM

The commercially available acoustic simulation software allows data exchange from BIM tools by importing solely geometry and material information, such as in (Peters, 2011). Although BIM-based frameworks were suggested to increase data exchange and interoperability among software, studies in BIM-based building acoustic performance are quite limited (Tan et al., 2017).

Wu and Clayton displayed a BIM-based acoustic simulation framework by developing a software prototype for room acoustic simulation, via Revit API, in the early design stage. The prototype extracted data from the BIM model (geometry (e.g., room area and volume), finishing material properties with absorption coefficient, sound source, and component data (e.g., audience position)) and performed simulation (Wu & Clayton, 2013). Tan et al. embedded three main factors (e.g., building geometry, speaker position, and decoration materials) in the IFC data model and conducted an acoustic performance for indoor performance (Tan et al., 2017). Sušnik et al. evaluated acoustic performance in the aspects of reverberation time and frequency of a BIM model through Dynamo, a programing language, in Revit (Sušnik et al., 2021).

Progress in openBIM reduces dependency on proprietary discipline-specific file formats and tools by providing standardized processes and interfaces across disciplines. However, the acoustic architectural collaboration currently does not have any Model View Definitions (MVDs) available (McGinley et al., 2021). Additionally, Mastino et al. investigated IFC data schema in terms of building thermal and acoustic simulation where need precise knowledge of building components. They found that IFC has deficient data for the acoustic domain, by covering only sound insulation as a piece of indirect information. Thus, they emphasized that IFC must contain more acoustic parameters of elements or constraint conditions (e.g., vibration transmission and sound power released in the structures) (Mastino et al., 2017).

Consequently, in the literature, there is an absence of research on building acoustic performance evaluation within the BIM environment. The current BIM software is not able to perform acoustic simulation on a BIM model enriched with acoustical data, resulting in poor interoperability and data exchange between BIM and building acoustic simulation software. (Sušnik et al., 2021). The acoustic domain information is still application-specific.

Regarding data integrity concerns, an ontology is proposed since it can define structured knowledge of heterogeneous and decentralized systems. Moreover, application-specific knowledge is presented in an abstract form (Guizzardi & Halpin, 2008; Reinisch et al., 2008), capable of capturing simulation intent (Boussuge et al., 2019).

Ontologies and Linked Data

In the building information context, ontologies have been developed for the representation of building geometry (OMG) (Wagner et al., 2019), topology (BOT) (Rasmussen et al., 2021), and IFC standard (IFCOWL) (Pauwels & Terkaj, 2016). Linked Building Data was proposed to combine these building information ontologies in a semantic graph (Linked Building Data Community Group, 2022), by preserving and integrating simple, extensible, and modular ontologies: BOT for topology, as a core; OMG for managing geometry; PRODUCT ontology; BEO for building elements; MEP for distribution elements; PROPS for properties; OPM for managing properties (Pauwels et al., 2022; Petrova et al., 2019). Recently, the Cloud-based Building Information Modelling (CBIM) ontology was designed to link building element objects, considering design intents and constraints as well as interdomain object topology relationships (Sacks et al., 2022).

In the domain of sound/acoustic simulation and analysis, researchers have developed ontologies for sound stream segregation (Nakatani & Okuno, 1998); conceptual descriptions of sound objects (i.e., concepts, topics, and themes) (Hatala et al., 2004, 2005); fulfilling semantic gaps among diverse musical entities and data (Nguyen et al., 2015); and sound event classification (Jiménez et al., 2018). An ontology-driven structure for acoustic management was developed covering acoustic ontology (composed of sensor, time, location, and measurement classes) and sound ontology (formed of sound source group and types with musical instruments, machinery, natural, and speech) (Santiago & Aguilar, 2019).

Chen et al. suggested a methodology for indoor human comfort assessment regarding the thermal and acoustic index, using BIM models for geometric and semantic information and ontology for knowledge repositories of comfort management, occupant behavior, and sensor data (Chen et al., 2019). Pauwels et al. conceived an acoustic rule-checking environment via semantic web technologies to display the potential benefits of the semantic web in solving interoperability issues in the BIM system (Pauwels et al., 2011).

Consequently, to date, there is no combined and comprehensive ontology in the building acoustic performance. Although semantic web technologies, particularly the Link Data principle, were suggested to facilitate data exchange and interoperability among BIM technologies and building performance assessment (such as in (Pauwels et al., 2010; Tchouanguem Djuedja et al., 2021)).

This study sought to design an acoustic ontology, as a knowledge repository, by serving the building acoustic performance principles in generalized conceptual modeling and linking semantics and object relations with the building information graph.

Research Method and Tools

The research method is founded on qualitative research, containing four steps, to build a knowledge system in the building acoustic domain.

Step 1: Literature Survey. A literature survey was conducted on the building acoustic analysis principles that indicate relevance between parameters and terms. The findings are represented (Table 1) in the next section.

Step 2: Reverse Engineering. The building performance simulation tools have internal data schemas in binary data formats. To examine the internal data schemas and understand entity relationships in the internal data schemas, reverse engineering was applied. Reverse engineering is a method of understanding how software achieves a given task where no documentation is available (Chikofsky & Cross, 1990). The purpose is not to replicate software, but rather to understand the internal data schema. Behm et al. (1997) suggested a two-step reverse engineering approach for the mitigation of relational data schemas to object-oriented database systems. These steps are (i) schema transformation which constructs a concept model by creating classes and attributes with inheritance hierarchy and (ii) data migration which consists of instance creation and attribute assignment. The reverse engineering approach used in this study was adapted from this approach. While creating the concept model, the considerations were: (i) class inheritance hierarchy, (ii) association, aggregation, and composition relations, (iii) attributes with data equality, and (iv) cardinality constraints. Here, reverse engineering was implemented on three acoustic analysis software. These software were selected regarding their simulation scale to represent sufficiently diverse amounts of acoustic simulation. The selected commercial acoustic software was: Odeon as a room-scale acoustic simulation (Odeon A/S, 2022); SONarchitect as a building-scale acoustic simulation (Sound of Numbers, 2022); SoundPlan as an urban and building-scale acoustic simulation (SoundPLAN GmbH, 2022). The concept models, which attempt to represent the internal data schemas of the software, were compiled in Unified Modelling Language (UML) diagrams, which provide a standard technique to visualize a system design (Booch et al., 2005), using the Visual Paradigm tool (Visual Paradigm, 2022).

Step 3: Generalization. When generalizing a hierarchy, each class is usually mapped to a table with attributes corresponding to columns, with a common key (Premerlani & Blaha, 1993). In this way, each class that represents semantic content and its properties, generated in UML diagrams, was mapped to a table (see Table 2). The semantic contents and object relations among the internal data schemas were searched and mapped to generalize them in practical terms (e.g., geometry, space, placement, building elements, and aggregation relationships). The identified generic semantics and relations were interpreted to communicate with other domain ontologies, especially relevant to the building information.

Step 4: Create Acoustic Ontology. Vo and Hoang suggested the rules for transforming a UML diagram into an OWL ontology (Ontology Web Language as a semantic web language) (Vo & Hoang, 2020). Relying on the defined rules, the generated UML diagrams with the generalized semantic concepts were transformed into OWL ontology. The basic implementation strategies (Trinkunas & Vasilecas, 2007) were: transform each UML class to the OWL class identified by a URI; transform the UML relationships to OWL object properties; transform each attribute to an OWL data type property; transform each cardinality constraint to an OWL object property restriction (i.e., only, exact, min, max). Consequently, the building acoustic ontology was established on the generalized concepts and relations with constraints and cardinalities, using OWL language and HermiT reasoning in Protégé as an ontology editor (Stanford University, 2020).

Results and Discussion

The building acoustic analysis is mainly interested in the reduction of noise levels inside an enclosed space. Noise in a building occurs from (i) air-borne noise due to propagated sound waves indoors; (ii) structural-borne noise because of impact noise or vibrations incorporated into a structure, and (iii) mechanical-borne noise originating from mechanical system equipment (Kuttruff, 2016; Templeton & Saunders, 1987). Table 1 represents sound phenomena in the building with their dependent criteria. To sum up, the building acoustic phenomena are strictly dependent on the building geometry and structure, building physical objects (e.g., building enclosing, structural, and service elements), and sound source properties.

In the following, we detail findings for three internal data schemas examined. While examining the internal data schemas via reverse engineering, UML diagrams of each selected software were generated. Figure 1 displays a generated internal schema in the UML diagram. The generated three UML diagrams are not shown here due to space limitations. Some of the classes, with their sub-classes and properties, were application-specific and therefore were not suitable for generalization. For instance, although the modeling technique was a generalized concept, the acoustic analysis calculation packages associated with environmental settings (e.g., atmospheric conditions) were application-specific. Another application-specific class was project/site aggregating with standards, geolocation, and diverse outside sound emissions sources such as road, railway, parking load, and industry. Besides, the application-specific properties and sub-classes were found such as, respectively: (i) reflection loss and construction year in the building entity and (ii) array source and multi-surface source in the sound source entity. As a result, these application-specific classes, sub-classes, and properties were not involved in the building acoustic ontology, which implies semantic reduction. Table 2 represents the generalized semantics with their properties in the internal data schemas after reverse engineering of three software. These generalized semantics are the foundation of the building acoustic ontology.

Another concern in this study was to make the designed acoustic ontology compatible with the existing building model ontologies. The main criteria for combining existing ontologies was to align the building physical objects and topological relationships among them. Thus, the distribution element class representing the physical objects in MEP ontology was retrieved with its IRI (Internationalized Resource Identifier) into the acoustic ontology. Likewise, the building element class in BEO ontology was incorporated in the acoustic ontology. The BOT ontology regarding building topology and the *CBIM:BuildingElement* class from the CBIM ontology (for supporting interdomain topological relationships among building elements) were incorporated with their IRIs into the acoustic ontology. The classes (*BEO:BuildingElement, MEP:DistributionElement,* and *CBIM:BuildingElement*), which represent physical objects, were linked with the functional object class with *hasFunction* and *isFunctionalized* relationships. Figure 2 displays the generated building acoustic ontology.

The functional object class, referring to the domain functionality of the physical objects, is composed of three sub-classes with their properties. The insulation material class has the properties of color, density, mass, frequency, absorption, reduction of impact noise, sound reduction index, improvement of sound reduction, and normalized sound level difference. These properties were referenced from material properties shown in Table 2. The properties of the receiver class are decibel scale, decibel day and night limit, and decibel day and night level, which is represented in Table 2. The sound source class has the properties of frequency, emission spectrum, and correction factor, which can also be seen in Table 2.

Table 1: Sound phenomena that occur in buildings

Sound Phenomenon	Dependent Criteria
Direct sound	Closed-environment geometry; Sound characteristics
Diffusion	Material properties (absorption coefficient, area, and density); Surface thickness; Sound power; Distance between the source and observation
Reverberant sound level	Sound power; Absorption
Reverberation time	Enclosed volume; Surface area; Absorption
Sound reduction index (R)	Frequency; Material properties
Standardized-weighted sound level difference (DnTw)	Reverberant sound level (Li); Incident sound level (Lj); Sound reduction index (R); Absorption

*Note: This table is prepared as a result of the literature survey on the building acoustic principles (International Organization for Standardization (ISO), 2017; Kuttruff, 2016; Templeton & Saunders, 1987).

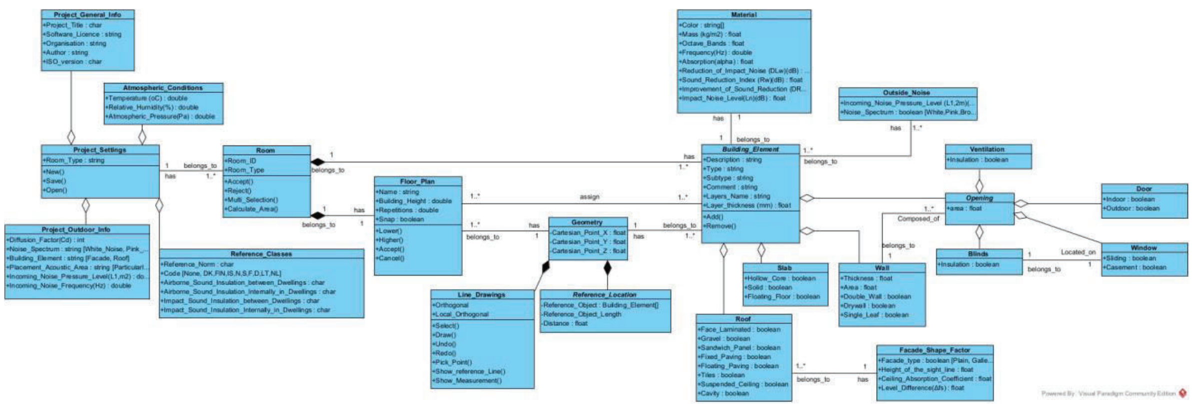


Figure 1: Representation of a generated internal schema (in UML diagram) via reverse engineering on an acoustic simulation software

Furthermore, the geometry of the objects is represented in the abstract geometry class with the bounding box, space boundary, surface, and 3D points. The positions of the functional objects and/or physical objects are defined via the relative geometry class. For example, a sound source can be located within a distance of a wall. In this case, the distance class will represent the value between the source and physical building element with the relationships of hasObject and hasSubject.

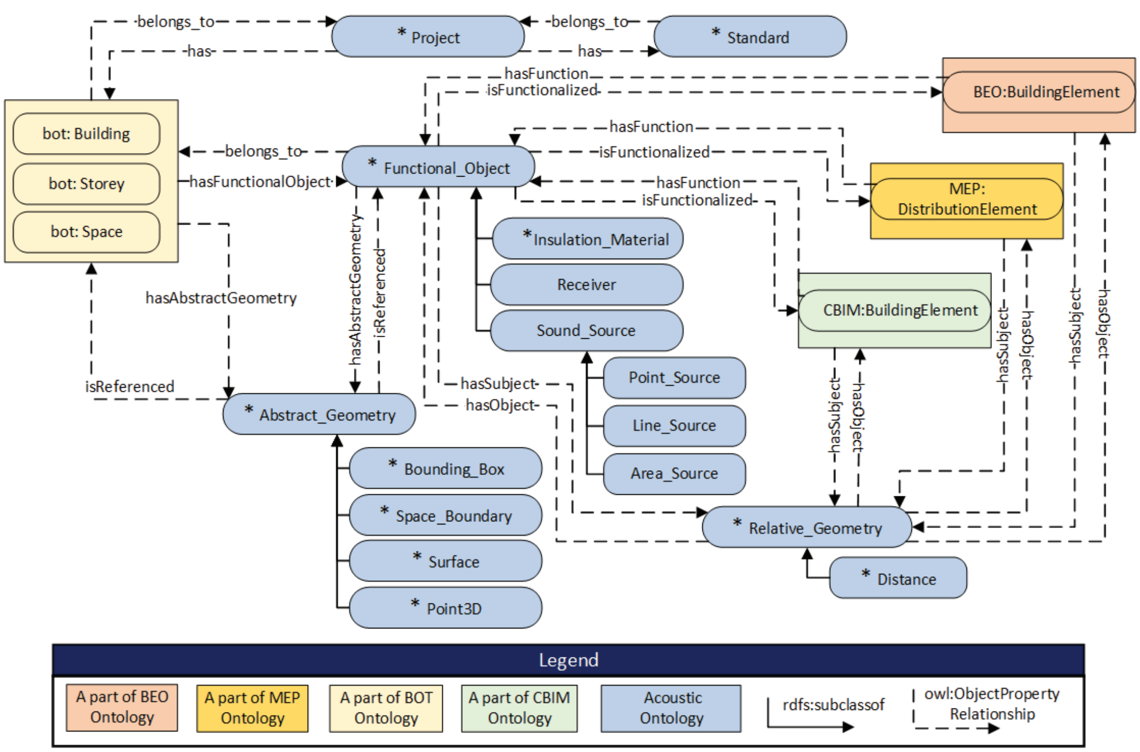
Regarding geometry modeling and management in ontologies, researchers have suggested different converters and semantic methods by implementing semantic queries and rules. However, the main problem is the complexity and ambiguity of the management of semantic links (Pauwels et al. 2017), especially in geometric information handling. Therefore, Ouyang et al. (2022) suggested a Linked Data-based Common Data Environment (CDE) considering geometry models. In the suggested approach, there are two levels in the dataset: (i) the core graph layer that stores data/information, in RDF format, about semantics and objects' relationships in the BIM model; and, (ii) the extension layer that stores BIM-related resources such as object geometry (in STL or PLY files containing 3D object data in a collection of polygons). According to this approach, the objects' geometry models will be stored in an external database, as the second layer of the Linked Data-based Common Data Environment. In addition, semantic relations will link relative geometry classes in the building acoustic ontology to the database via abstracted geometry.

To embody the building acoustic domain knowledge explicitly, the constraints and cardinalities among the semantic concepts and relationships were established and HermiT reasoner was performed to examine the consistency of the constructed ontology. As a result, the building acoustic ontology consists of: 24 classes; eight object properties (four inverse object properties and four inverse functional properties); 58 data properties (compiled on the outcome from literature survey and generalized properties from the reverse engineering on internal data schemas); 313 axioms (222 logical axioms and 91 declaration axioms).

Table 2: Generalized classes and properties from internal data schemas after reverse engineering the software

Class	Property	Software A	Software B	Software C
Modeling Technique	2D- Geometry	✓	✓	✓
	3D- Geometry	✓	×	✓
Building	Dimension (H,W,L)	✓	✓	✓
	Functional Unit; Color	×	✓	✓
Space/ Room	Dimension (H,W,L); Reverberation	✓	✓	✓
	Airborne Noise Insulation; Impact Noise Insulation	×	✓	✓
	Indoor Sound Pressure Level	✓	×	✓
Component	Name; Dimension (H,W,L); Area	✓	✓	✓
Material	Color; Frequency; Frequency Band; Sound Reduction Index (R)	✓	✓	✓
	Mass; Impact Noise Level (Ln); Improvement of Sound Reduction	×	✓	×
	Density; Normalized Sound Level Difference	×	×	✓
	Absorption (alpha)	✓	✓	×
Sound Source	Frequency; Spectrum; Sound Power	✓	✓	✓
	Position; Point Source; Line Source; Area Source	✓	×	✓
Receiver	Number; Position	✓	×	✓
	Decibel Scale; Decibel Day&Night Limit; Decibel Day&Night Level	×	×	✓

✓: Represented concepts in the internal data schema ×: Missing concepts in the internal data schema



Note: The acoustic ontology classes marked with asterisks will be incorporated as part of a more general holistic building performance ontology(HBPO) in the next steps of this research.

Figure 2: Representation of the acoustic ontology with the linked building model ontologies

The main question concerns how the building acoustic ontology supports building acoustic analysis from the aspects of its contained classes and relationships. Therefore, the acoustic ontology was extended with the target object, simulation run, and simulation result classes (Figure 3). The target object class refers to the analysis environment defined by physical objects. As an example, a space, as a desired analysis environment, is determined by its surrounding building elements. Thus, the building elements are instantiated into the target object class by retrieving their abstract geometries via semantic links *(hasAbstractGeometry* and *isreferenced*). The simulation run class binds: (i) the used sound source from the functional object class; (ii) simulation environment boundaries from the target object class with the abstract geometry class. The simulation run class binds (i) the used sound source from the functional object class with the linkage of its abstract geometry; and, (ii) simulation environment boundaries from the target object class with the linkage of its abstract geometry. When a new simulation run initializes, a new instance of the project class (Figure 2) is created. When the simulation ends, the results are collected in the simulation result class that is linked to the simulation run class with *CalculatedBy* and *hasResults* relationships.

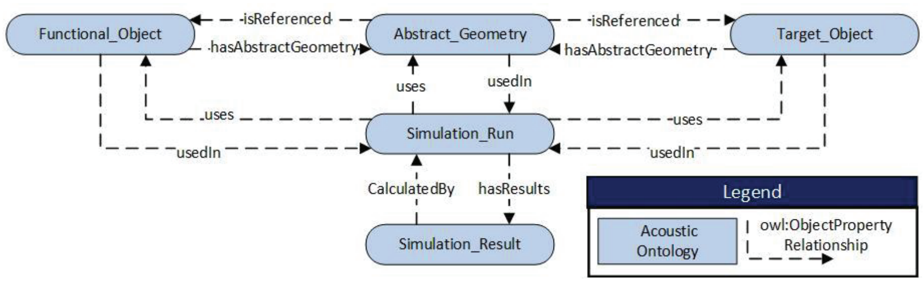


Figure 3: Representation of extension of the acoustic ontology.

In future work, the functional object class would be a higher-level semantic class in a holistic performance ontology by containing multiple domains in its sub-classes (e.g., lighting and energy domain functional objects). In Figure 2, the ontology classes that may belong to a holistic building performance ontology in the later step are marked with an asterisk. Additionally, buildingSMART has announced Information Delivery Specifications (IDS) to identify information requirements that are compliant with IFC and that link objects' classes and properties via an ontology-based-data dictionary (building Smart Data Dictionary, bSDD)(van Berlo et al., 2021). The ultimate building acoustic ontology, which is validated and verified with instance knowledge graph and published through the Web, may be integrated with a bSDD, which may lead to transfer of acoustic specifications to IFC. Consequently, future work will consider (i) which semantic concepts can be assigned to a higher-level building performance ontology, rather than to the acoustic-specific ontology; and, (ii) how the final building acoustic ontology can interoperate with ontology-based and openBIM based data structures.

Conclusions

Building acoustic performance information can currently be retrieved from BIM models, but it is limited to the aspects of building geometry and material. However, this information is incomplete in the acoustic domain, owing to (i) the lack of agreement on application-specific models in the native data schemas, (ii) the incompatible data exchange, and (iii) poor interoperability. To date, efforts to solve these problems using a linked data approach in an ontology-based framework have not yet achieved full interoperability. This study focuses on exploring a generalized building acoustic ontology by identifying building acoustic information concepts from the literature and by examining internal data schemas of the selected three acoustic simulation software using reverse engineering. It aimed to encapsulate the building acoustic domain-specific knowledge explicitly with semantic concepts, relationships, constraints, cardinalities, and logical rules of statements or assertions using OWL language and reasoning. Another goal is coordination with the existing building model ontologies (e.g., BOT, BEO, MEP, and CBIM) throughout the acoustic ontology.

The contribution of the building acoustic ontology is in providing a knowledge-domain guide by ascertaining (i) domain conceptual models; (ii) generalized semantic concepts and relationships among them; (iii) required information from different simulation software as well as unique concepts and information; finally (iv) semantic links between the domain-specific objects and building model. Future work will include the validation of the ontology and its extension with other performance domains (e.g., energy, lighting, and including commercial, social, legal, and economic aspects) to reach a holistic building performance ontology.

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