A Novel BIM Platform Paradigm for The Building Performance Domain

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ABSTRACT: Although Building Information Modelling (BIM) promised a new collaborative work paradigm for the AEC disciplines, current workflows in the AEC sector are still sequential, fragmented, and served by diverse software, especially in the building performance disciplines. The building performance domain has multiple native performance models and data schemas from a wide variety of simulation tools, which leads to incompatible, incomplete, or redundant information and the need for rework in the current performance analysis workflows. A new paradigm is needed, in which performance domain analytical models can be prepared automatically from a database system that can also check for and maintain consistency, accuracy, and completeness within and across federated building models. This paper describes a BIM platform consisting of a holistic ontological framework for building performance modeling with cloud and semantic web technologies and founded on a knowledge-graph-driven database management system. It describes a future state-of-the-art configuration designed to address these challenges. It also outlines the suggested method and the potential workflow benefits in the AEC sector. The paradigm design is intended for software vendors, who can apply its principles to develop new generation software programs in the future.

KEYWORDS: *Building Performance Disciplines, Holistic Building Performance Models, Cloud-based Service, and Semantic Web Technologies*

1 INTRODUCTION

Building Information Modelling (BIM) has provided a technological solution to facilitate collaboration among architecture, engineering, and design professions. It applies object-oriented modeling to enable users to enrich objects' data and information, visualize 3D, and analyze building performance models. Open BIM standards have been developed for interoperability between diverse software applications by exchanging building information through the building life cycle. Thus, BIM has brought benefits to the design process in generating complicated building shells while expediting generation and evaluation of the concept design. In particular, BIM has provided new information workflows that share information among existing simulation and analysis tools by addressing engineering integration of a sole system or multiple systems based on shared data (Sacks et al. 2018). Nevertheless, generation of building performance models within the BIM platforms is still neither fully integrated nor automated.

One of the main issues is that different BIM applications and analysis tools have native models with different aggregating, identifying, and parametrizing objects (Bloch & Sacks 2018). Therefore, when extracting data from a building information model to a building performance model, the outcome is generally delivered with inaccurate, incomplete, or false information. To address this kind of data integrity concern, ontologies have been proposed for storing, structuring, and visualizing knowledge, independent of heterogeneous and decentralized systems. Diverse research communities, such as computer science, engineering, decision science have adopted ontological frameworks. Furthermore, these research groups have collaborated with international communities (e.g., (Linked Building Data Community Group 2022, World Wide Web Consortium (W3C) 2022)) in accordance with the web of data, linked data, and semantic web technologies.

Researchers in the building performance domain, which is a specialization within the AEC sector, have also adopted the ontological framework approach. Among the developed ontologies are building geometry (Wagner et al. 2019), topology (Rasmussen et al. 2021), smart applications and automation devices (Bonino & Corno 2008, Daniele et al. 2020, Reinisch et al. 2010), building systems

(Balaji et al. 2016), standard IFC data in the ontology web language format, ifcOWL, (Pauwels & Terkaj 2016), and building energy modeling (Y. Li et al. 2019, Pauwels et al. 2014). The current building performance ontologies apply primarily to the energy domain and the integration of application-specific intelligent devices in buildings. To date, there is no combined multidisciplinary building performance ontology.

Another main issue is that the current performance simulation software tools have weaknesses and gaps in tool functionality, as well as a loosely tied-integrated simulation in all phases of the building process (Augenbroe 2002). To address this issue, previous work researchers have sought to implement an ontological framework for more intelligent application services relying upon semantic web technologies and linked data (Corry et al. 2015, Curry et al. 2013, Hu et al. 2016, 2018, Y. Li et al. 2019, 2021, O'Donnell et al. 2013). However, the implementation techniques still rely on conventional databases or the manual conversion of conventional databases to graph formats. A web-based distributed simulation can be seen as a natural environment for building performance analysis. However, development of a common engineering representation that will provide the high-level architecture to share model components is a major challenge (Augenbroe 2002).

In summary, the current workflow of building performance modeling is recursive, semi-automated, and has poor interoperability among software and stakeholders due to the paucity of semantic contents and object relationships. The industry needs a future workflow that covers all building performance disciplines, automates the generation of the building performance models, and enables two-way information exchange among the BIM models and different building performance simulation tools. This implies the need for an entirely new BIM platform paradigm for the performance domain. The following questions arise: (1) What kind of platform paradigm can represent the whole building performance analysis domain, in a generic intelligent model, as an alternative to the multiple divergent existing workflows? (2) How can this new paradigm automate the generation of the building performance models and the performance domain analytical models? (3) Could it automate two-way information exchanges among the generic building model and different building performance simulation tools?

Consequently, this study proposes an ontological framework for a holistic building performance model with cloud and semantic web technologies. The novel paradigm encompasses an ontological framework that will replace local file-based databases with extensible knowledge graph-driven systems (as data, information, logic, and design intent), with dynamic response and cloud storage.

2 RESEARCH METHODOLOGY

This study follows a design science methodology (Rossi et al. 2013), and this paper discusses the problem identification and objectives definition steps. It is an exploratory work on the future state-of-the-art configuration, suggesting a solution to handle the limitations and issues of the current workflows in the AEC industry. As such, it proposes an innovative combination of processes and digital technology and a vision for the future. The remaining steps (design, development, demonstration and experiment, validation, and evaluation) are part of ongoing work. The further study will serve as a proof-of-concept, seeking to demonstrate the novel paradigm's feasibility by examining the technical processes and the use of digital technology.

3 BUILDING PERFORMANCE MODELING WORKFLOW IN THE NOVEL PARADIGM

The novel paradigm proposed here imagines a radically changed building modeling workflow for all design stakeholders. Each design team will use a new generation of software tools, knowledge graph-based, to model their discipline-specific models. When the design team begins creating their models in the graphical user interfaces of the new generation software, knowledge graphs will be generated automatically in the background of these tools via their management systems using graph algorithms. Thus, discipline-specific designers will be able to compile their models as domain-specific knowledge graphs. The model view function in the graphical user interfaces (Fig. 1) will enable the design team to visualize domain-specific knowledge graphs as 3D models.

Each knowledge graph will contain an ontology covering domain class and attribution with semantic nets in the terminology box (Tbox) and instances of each class in the assertion box (Abox). Logical statements and rules will be appended to this ontology. Thus, each knowledge graph will represent an expert system of a performance discipline, which supplies high-level internal representation. It will be possible to implement semantic web and linked data techniques on each knowledge graph for collaboration and distribution of knowledge across different performance disciplines. The knowledge graphs cover the data, information, logic, design intent, and an appropriate level of detail (LOD) for building objects. The graphs will be stored in a cloud service, forming a holistic building performance knowledge graph database, which refers to an open architecture for modification, replacement, deletion, and extension.

The new paradigm must incorporate and exploit information about design intent if it is to automate building performance modeling. Thus, reflecting the design intent in a new workflow is one of the main considerations. The design intent reflects experts' experience in problem-solving and their domain knowledge. This phenomenon has long been considered in research to develop expert and knowledge systems as well as intuitive and cognitive design. Eastman explained that a cognitive information-processing model can be used to analyze intuitive design relating to the physical environment (Eastman 1968). In the architectural domain, Rosenman and Gero highlighted the potential of expert systems, which attempt to simulate human expertise, and of knowledge-based systems, which organize, categorize, store, and recall facts, logic, and semantics from a knowledge base by knowledge engineering (Rosenman & Gero 1985). When knowledge systems capture what an expert knows, they become expert systems (Gero & Coyne 1984).

Researchers have proposed expert and knowledge-based systems to encapsulate large volumes of logical statements describing the design process. These systems have three main mechanisms: (1) encoding knowledge in the form of facts, variables, and assigned values; (2) setting rules as logical statements among facts relationships; and (3) using inference mechanisms for examining and drawing facts (Papamichael & Selkowitz 1990). Additionally, an automatic design production system was suggested as conveying information by implementing an intelligent information management system in obtaining, displaying, storing, retrieving, editing, interpreting, and reasoning with information. Seamless integration of the information in the databases would be achieved through knowledge-based representations of information (Myers et al. 1992). There are two types of design intent knowledge: (1) explicit information, which can be modeled in knowledge-based systems by applying knowledge engineering, and (2) implicit knowledge, which derives from experts' experience and can be inferred using cognitive information-processing models.

Figure 1 depicts the workflows and the information flows that characterise the new platform paradigm. It includes three knowledge graph database management system functions that perform three types of semantic enrichment processes with intelligent functionalities to collectively deal with expression of design intent. These semantic enrichment processes are explained in the following subsections.

3.1 *Process 1: Classification of Building Elements*

The new generation of software libraries will collect building design and code compliance constraints (derived from laws, regulatory codes, standards, as well as user requirements) based on analysis of code provisions. Initially, building objects will be classified according to the concepts defined by the design codes or user design libraries. Then, a set of rules will be implemented to conduct semantic enrichment tasks based on concepts and properties. Design intent and constraints based on object properties can be considered as introductory, and further semantic enrichment such as new concept creation and association tasks will rely on the introductory step.

As an example of this introductory step, fire safety regulations would have been identified with their concepts (i.e., occupant load, required capacity of egress path spatial component) and stored in the new generation software library (Bloch 2020). The door objects will be classified as an egress door or interior door based on criteria such as the door size, the attached wall dimension, and connected space (interior or exterior); these are property classification semantic enrichment tasks. This classification would be obtained via rule-based inferencing running in the background of the software.

By applying knowledge engineering techniques to a knowledge-graph database based on the introductory design intent and constraints, geometries and spatial relationships based on the model objects will be initialized. Those spatial relationships will be added to the knowledge graph databases. As part of knowledge graph management system functionality, this process will diagnose any missing building objects, attributes, and design intents. The management system will notify users of missing objects and attributes and ask them to edit the model. Should there be no missing design intent detected, the enriched knowledge graph generated by running the first process will be stored and updated in the knowledge database.

3.2 *Process 2: Identifying and Modeling Implicit Constraints*

The second process will make implicit constraints explicit using external knowledge, which might stem from previous projects or knowledge graph learning. Constraints added by applying rule-based or graph-based machine learning will be checked for compliance with building standards and regulations - where data from archived projects will be used for machine learning. The enriched knowledge-graph database will be used to query and apply artificial intelligence graph algorithms to perform domain-specific consistency and property checking.

As an example of consistency checking, in the building model, two walls meeting at a corner may be modeled without intersecting each other. The gap between corner walls may be insignificant in the architectural model; however, this inconsistency will influence the subsequent performance analysis steps of building design.

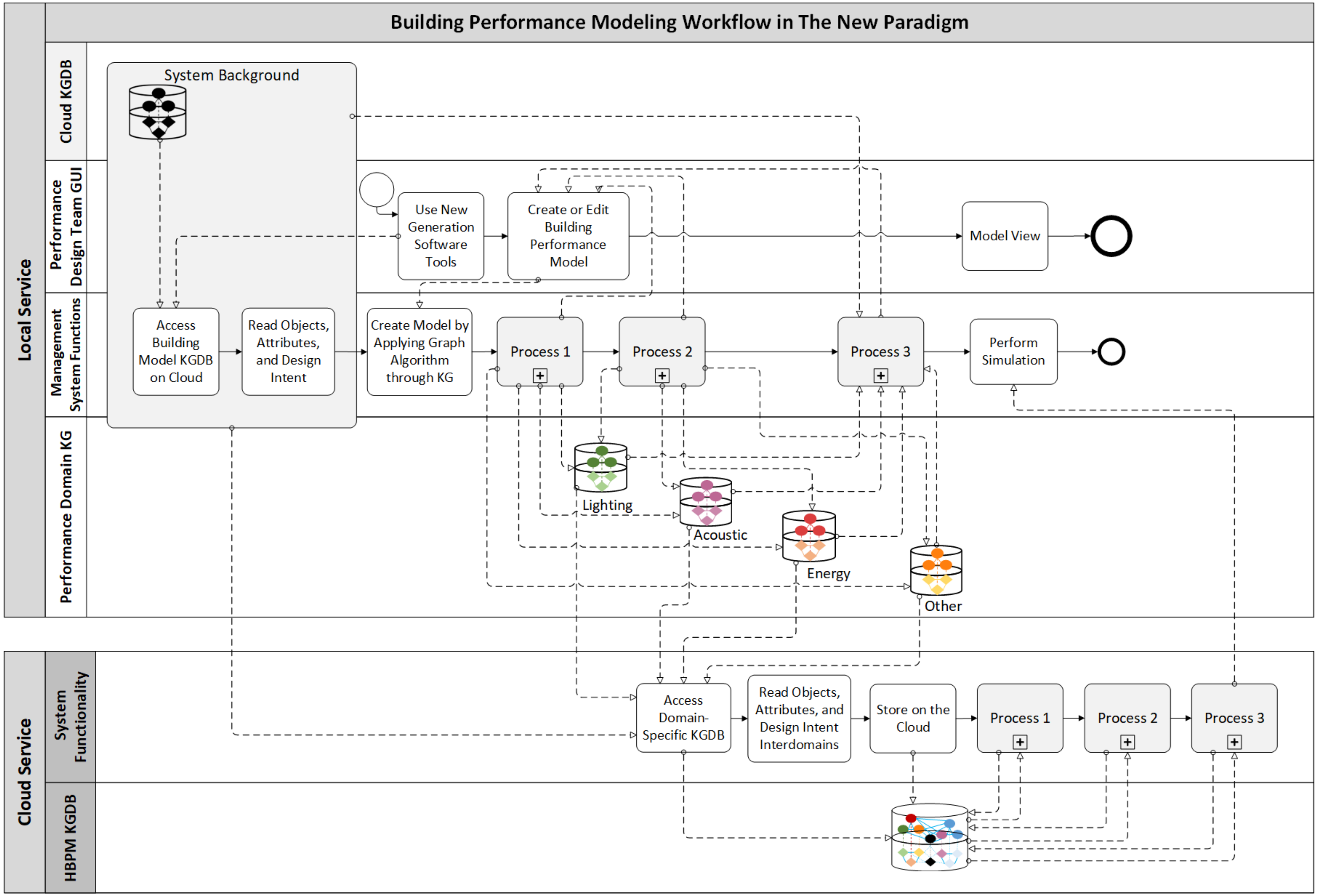

Figure 1. Blueprint Building Performance Modeling in The Novel Paradigm

The most common checking property example is for material assignment. If there is an unassigned material property in the building model, the checking property algorithm will diagnose it. Once these algorithms find a piece of missing information and/or inconsistency, the management system will inform users to edit the building model.

3.3 *Process 3: Model Consistency, Accuracy, and Integrity*

This process will simultaneously address inter-domain consistency, accuracy, timeliness, and completeness. A consistency check will identify conflicts in the performance systems model. An accuracy check will examine the performance model requirements. A timeliness check will identify the versions of objects in the building model. If an object in the performance model is out-of-date, the management system informs users to update it. A completeness check will determine whether the created building performance model fulfills all design intents and requirements. Once all processes represented in Figure 1 are complete, a performance simulation will be run in the management system.

3.4 *Local and Cloud Service*

The building modeling workflow in a novel paradigm will bring a new direction; however, generating the building performance models needs a new notation. The key points are: (1) the building model will need to represent the different building performance disciplines from specialized systems; and (2) the building performance model must provide and integrate an appropriate degree of knowledge for objects that preserve domain-specific or application-specific information from multiple knowledge datasets. Thus, two more steps are required in the new generation building performance tools: a local service system background and a cloud service, as represented in Figure 1.

In the local service system background, the first step will be to access the building model knowledge graph in the cloud service. After accessing the building model knowledge graph, the objects, attributes, and design intent in it will be read. These accessing and reading tasks will run in the local service system background.

To automate holistic building performance models (HBPM), semantic enrichment and performance-specific functional modules will be shifted to the cloud service and implement the knowledge-graph-driven technique that considers design intent and the gap between building physical models. In this context, a management system based on the knowledge-graph database of a holistic building performance model will be able to access individual knowledge graph databases of the new generation of software design tools.

The HBPM management system, when it accesses the domain-specific knowledge-graph database, will read objects, attributes, and design intents contained in the domain-specific knowledge graphs. As a result of reading domain-specific knowledge graphs, the detected objects, attributes, and design intents will be appended to the HBPM as instances by using semantic web and linked data techniques. The semantic enrichment processes (processes 1-3 in the local service management systems functions of Fig. 1), will also be implemented in the cloud service system functionality.

To sum up, the suggested method converts the BIM models to a federated and semantically enriched knowledge graph covering the data, information, logic, design intent, and an appropriate level of detail (LOD) for building objects, subsequently storing them on the cloud in a knowledge graph database. The management and application systems function through this database. The essential functions for the building performance models will be based on a holistic building performance ontology, implementing semantic enrichment via rule-based inferencing and machine learning. The method will replace file-based database systems with extensible knowledge graph-driven cloud storage for the next generation of software programs.

4 ASPECTS OF IMPLEMENTATION

The current building performance analysis and evaluation processes require the generation of application-specific performance models in the framework of standalone or state-of-the-art BIM design and performance software tools. To try to achieve interoperability, BIM software vendors developed custom interfaces, dependent on model view definitions (MVD), between design and analysis tools. Yet the interfaces for each tool differed, so that it was not possible to solve the problem of the need to create multiple models, of manual data entry, of editing, and of translating. Therefore, developments toward a new paradigm while working with current building performance tools will require semantic associations among different domains covering both domain-specific attributes and instance-specific attributes (Sanguinetti et al. 2012).

The expected results of this research are the elaboration of a) the workflows in building performance modeling and b) a new generation building performance software architecture for tools that work within the knowledge graph environment. The software architecture consists of: (1) a graphical user interface that outlines practical benefits of automation of maintenance of consistency and integrity while modeling; (2) a logic layer that encapsulates the modeling principles and intelligence functions by semantic enrichment methods in the cloud service; and (3) a data layer that parses, serializes, stores, queries, and updates data, information, logic, and even design intent into knowledge-graph form and database via semantic web technologies.

The suggested intelligent management and application systems, within the three processes of semantic enrichment, will be conducted intradomain for: (1) embedding knowledge from previous observations and interpretation of past cases; (2) determining intradomain conflicts and the topological and design intent relationships; (3) and supplying localized design decisions. On the other hand, the three processes of semantic enrichment on the cloud service will be conducted across domains for conflicts and relationships, and to automate holistic building performance models.

The cloud service management and application systems will launch through the open database. The essential functions for the building performance models (checking consistency, accuracy, timeliness, and completeness) will operate on the holistic building performance ontology, implementing the three processes of semantic enrichment via rule-based inferencing and machine learning. Thus, the new generation software architecture will emphasize the partnership between users and the intelligent functionalities that they use.

5 DISCUSSION

The main argument in this work is that building performance modeling can be improved through a holistic, generalizable, and extensible performance ontology for the modeling disciplines and their principles that support a knowledge graph could platform for the data of any project. In order to extend this argument, this section examines opportunities and limitations of the novel paradigm, separating concept adaptation and implementation.

5.1 *Potential Benefits for Users*

The primary benefactors of the novel paradigm are the design teams in the AEC sector (architects, engineers, and design managers), especially those involved in building performance, since the current workflow in the AEC sector is expected to change thoroughly with the new paradigm, reducing the remodeling and rework necessary in the current workflows. While using these new-generation software tools, the design team will be informed of any missing building objects, attributes, and design intents while generating building models. Furthermore, the design team will receive suggestions of domain-specific consistency and property checking while generating building models.

In current BIM workflows, the information contained in BIM models from different vendors is often incomplete, suffering frequently from incorrect object labels and misclassified objects. The next generation of software programs will not rely on the data/information quality from the models. The suggested software programs will apply semantic enrichment processes (Processes 1-3) to check and if necessary rebuild the object classification and object relationships, thus providing high resilience even with low-quality data.

5.2 *AEC Sector Benefits*

New generation software working on the novel platform paradigm will bring practical benefits in the AEC sector, including:

- An extensible and dynamic knowledge graph database and management system, rather than file-based common data environment (CDE), can support encompassing data flows to connect all performance domains independent of file-based data exchange formats.
- The system may eliminate inaccurate, incomplete, or redundant information and reduce manual work, reducing the number of mistakes and errors in the building performance models. The new generation software will respond to the users’ demands and intents, meanwhile resolving the challenges and limitations of building performance modeling. It will support automated production of analysis models.
- Maintaining the building performance models' key features and functionalities (e.g., consistency, accuracy, completeness, timeliness) may enable whole system optimization.

5.3 *Implementation*

Current technical enablers that are relevant for implementation of this paradigm include graph converters and graph databases. The available graph converters are IFCtoRDF (Pauwels 2021) and IFCtoLBD (Oraskari et al. 2021). Concerning graph databases, there are commercial products such as Neo4J (Neo4j Inc. 2022) and GraphDB (Ontotext 2020). Using data compiled by the graph converters and databases, graph library packages such as the RDF library for Python (RDFLib Team 2021) can be used to access, query, and update the graphs. As Li et al. demonstrated for the case of geographic data (H. Li et al. 2021), this graph can be extended and accessed subsequently to provide input for simulations implemented via web services.

5.4 *Limitations*

The limitations on the suggested novel paradigm and the new generation software tools that will operate within it are categorized into three aspects.

Privacy and legacy software limitations. A significant limitation is that for the full realization of the concept, existing software programs will need to be replaced by systems whose architecture allows them to interface directly with knowledge graph-driven databases. The current software tools depend on native and proprietary data schemas as well as conventional database and management systems. Therefore, the software vendors will need to create their application-specific knowledge graphs, which leads to a comprehensive change in the software database and management system. Some vendors may resist this path of development given the apparent lack of customer demand for change.

Management of semantic links. If each software vendor creates their own knowledge graph, the cloud service of the holistic building performance model knowledge graph will have to support all of them, which leads to complexity and ambiguity of the management of semantic links. This is an ongoing problem even now (Pauwels et al. 2017). Besides the limitations on the management of semantic links and ontologies in the holistic performance model knowledge graph, the building models must be built via collaboration of performance disciplines. As a second issue, it is unclear who would take responsibility for developing an open and standardized holistic building performance model to support the knowledge graphs. Since the performance domain is diverse, an expert community such as IBPSA (International Building Performance Simulation Association. 2022) will need to set up interdomain relations and semantics.

Research limitations. This research proposed a novel paradigm and new generation software inside it. As such, it is a theoretical search for a practical solution based on the current building performance disciplines' needs. The proposed paradigm's relevance in practical terms will be validated through development and testing of prototype tools for multiple performance disciplines, with at least three domains. Testing and implementing a holistic ontology framework for the selected subset domains will ensure that a sufficiently different range of domains is addressed and represents all (or a large majority of) possible domains. After proving the paradigm's relevance through practical examples and showing the benefits, software vendors may decide to change direction towards knowledge-based software architectures.

6 CONCLUSION

In this research, the premise is that the ontological framework of building performance modeling can be improved by using a holistic, generalizable, and extensible knowledge graph in the cloud and management systems that are applicable to all modeling disciplines and their principles.

This novel approach shifts building performance models’ key features and functions to a cloud service and implements a knowledge-graph-driven technique that considers design intent, modeling disciplines, and principles. Progress in this direction is expected to contribute a new direction for building performance modeling by suggesting a generalized holistic ontological framework for the performance disciplines and by providing insight into future cloud-based and knowledge graph-driven databases and management systems. With the new paradigm, the current workflow in the AEC sector should be thoroughly transformed, benefiting stakeholders by reducing the need for remodeling and rework in current workflows.

A major limitation of the concept is that new software systems will have to be designed that will interface directly with knowledge graph databases to realize the full benefits of the concept. Once the benefits of the proposed paradigm are realized, it is expected that it will contribute to the workflow in the AEC sector by affecting architects, engineers, and end-users. The most significant impact will likely be on software vendors, who are the primary audience for this research, as it may point the way to the nature of future BIM and building performance simulation and analysis software.

Further research will need to implement and test a proof of concept of the novel paradigm's relevance by investigating, developing, and testing for a particular set of domains. In addition to researching technical feasibility, it will be necessary to explore additional aspects that impact design workflows, including commercial, social, legal, and economic aspects.

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