Abstract

Even with modern BIM software, design collaboration across disciplines remains sequential and siloed. The prevailing file-based approach to information exchange cannot support advanced functions such as proactively maintaining design consistency. This PhD study aims to explore an object-based approach of representing building information as graphs and implementing intelligent applications on BIM graphs for enhancing collaboration and easing interoperability issues. Specifically, domain-specific models are compiled as BIM graphs with the supplementary of implicit information by semantic enrichment. BIM graphs are then properly linked with topology and design intent relationships by artificial intelligence (AI) techniques. Intelligent applications, such as across-domain consistency maintenance, are applied to the linked BIM graphs for tracking and processing design changes automatically. This research validates that graph representation is a suitable approach for storing and linking BIM models, and that intelligent functions can be achieved on the linked graphs to improve the data exchange and collaboration efficiency.

Introduction

A construction project involves architects, engineers, managers, fabricators, and builders with a wide range of professional knowledge and experience who all need to share information smoothly and collaborate closely for successful project delivery. In recent decades, the Architecture, Engineering, and Construction (AEC) industry has increasingly adopted Building Information Modeling (BIM) technologies to represent building information comprehensively, reliably, and accurately. Due to the fragmentation of the industry, the traditional design and construction process is conducted in a sequential manner and lacks feedback loops, causing construction inefficiencies that can only be eased by extensive coordination in the design phase.

Although BIM provides a platform for generating and sharing information, collaboration across disciplines is still sequential and siloed. Current BIM software tools use files for storing information and require users to control the delivery of model files manually. BIM vendors each develop their own confidential data schemas which are inaccessible to other software, causing the interoperability problem. Most BIM software provides options to save models according to open data schemas, such as the Industry Foundation Classes (IFC), but the mapping and saving process commonly causes loss of information and errors. Furthermore, file-based communication requires designers to transfer files repeatedly in each design iteration to ensure all the design changes are considered. Design conflicts are detected by specialized software and labeled by users, after which designers must revert to their original separate models to apply necessary modifications. The process is commonly repeated many times through the detailed design. The file-based approach cannot support synchronous management of data inconsistencies and does not allow redundancy for alternative versions.

Additionally, building information could be lost when exchanging and delivering models. Semantic enrichment (SE) is proposed to interpret implicit building semantics and supplement them back to models, so they can be reused for multiple purposes with minimal rework. Previous studies focused primarily on methods that can be deployed in semantic enrichment tasks, such as expert systems, machine learning, and deep learning algorithms, to classify BIM objects. These studies validated the feasibility of various techniques for SE, but they usually focus on a specific type of task instead of providing comprehensive required building information.

In this research, we aim to propose an object-level approach for enhancing interoperability and improving interdisciplinary collaboration. First, we construct the theory of graph representation for BIM models to enable intelligent applications. During this process, we realize that the missing semantics from BIM design tools can limit functionality. Therefore, we proposed a framework for the generic semantic enrichment of BIM models to predict different types of building semantics (like objects, relationships, attributes, and so on) using AI techniques. Moreover, a key aspect of SE involves predicting the type of rooms. We develop a Graph Neural Networks (GNN) algorithm which can leverage the relationships of BIM objects to the accuracy of room type classification.

Research work

Graph representation for enhancing across-domain collaboration

The inter-domain consistency maintenance approach is constructed by following the CBIM concept by representing domain-specific models as separate graphs stored in a central cloud data repository and implementing semantic enrichment to link domain-specific graphs into a connected one. Next, intelligent applications are developed on top of the linked graphs.
By adopting the CBIM concept, this study devises a graph-based approach of maintaining design consistency across disciplines, as shown in Figure 1. As current BIM software does not support graph formats directly, a tool is needed to retrieve building information from local BIM editors and send it to the cloud server. The server compiles the model information as uniform graph-based repositories. After that, semantic enrichment algorithms are executed to instantiate inter-domain relationships to link the separate graphs, including spatial, functional, and constraint relationships.

We propose that the design intent constraints encapsulated in expert knowledge are the basis for enabling the consistency maintenance function. Once the nodes of the domain-specific sub-graphs have been linked with CBIM relationships, the CBIM server can receive model changes from local BIM editors and analyze them to determine whether they violate any inter-domain design intent constraints. If so, the server function can prompt actions to coordinate designs across disciplines by either suggesting propagation or providing geometry references for participants.

**Generic semantic enrichment of BIM graphs**

Generic semantic enrichment aims to construct BIM graphs from pure object geometries for enabling advanced BIM applications. The framework of generic semantic enrichment comprises the fundamental enrichment tasks and the process control mechanism, as illustrated in Figure 2. There are four types of fundamental semantic enrichment tasks under the context of graphs. Tools are constructed to accomplish enrichment tasks, and executed in a sequence. The enriched results are structured into a graph-based CDE with a core graph layer containing building objects and relationships, and a separate extension layer storing geometries. The graph-based CDE can be used for various applications, such as enriching geometry design, easing interoperability issues and linking multi-disciplinary graphs for maintaining model consistency.

We have defined four fundamental SE tasks: object classification, attribute computation, relationship determination and object generation. Object classification utilizes methods to predict the types of objects. Attribute computation aims to calculate object properties, such as dimensions. Once computed, these attributes can be inserted back into object nodes.

**Node classification of BIM graphs for enriching semantics**

![Diagram of using GNN to classify room types.](image3.png)
Semantic enrichment of BIM models supplements models with the implicit semantics for further applications. We use the room classification task to develop, test and illustrate a novel approach to semantic enrichment of BIM models – representation of models as graphs and application of graph neural networks (GNNs). A dedicated graph dataset consisting of 224 apartment layouts with nine room types and node/edge features was compiled. An improved GNN algorithm, SAGE-E, was developed for processing both node and edge features and a batch method were used to improve efficiency. The experiments showed that 1) The novel approach of adopting graphs and GNNs was feasible. 2) SAGE-E achieved higher accuracy (79%) and more balanced prediction (F1 = 0.79) when compared with other machine learning algorithms.3) SAGE-E shortened the training and validation process.

Achievements

Journal Papers


Conference proceedings and posters


Deliverables


Awards

[1] Best paper award at CIB W78 2021 Conference

Courses and training schools

[1] Advanced BIM (88/100), Technion, 2020
[5] TE2: BIM-Based Sensing and Data Collection, CARTIF, 2021
[8] PhD Student Summer School, EC3, 2021

Secondments

[1] University of Cambridge, UK, March – August 2022
[2] Technical University of Munich, Germany, October – December 2022
[3] Trimble, Finland, October – November 2023 (Planned)
[4] LocLab, Germany, November – December 2023 (Planned)

Conclusion

Summary of work

Even with state-of-the-art BIM technology, design teams from different disciplines still follow the sequential file-based approach for collaboration and encounter the problem of BIM data interoperability. This PhD research explores an object-based approach to representing BIM models, aiming to enhance collaboration efficiency across disciplines and alleviate the data interoperability problem. Specifically, it encompasses three main sub-topics. The first one proposes a graph-based theory for representing BIM models as graphs and linking domain-specific graphs to enable intelligent applications, such as
consistency maintenance. It defines constraint classes to relate objects across disciplines and devise a mechanism to resolve conflicts. A case study prototype was implemented with federated building models to demonstrate the system's response to design changes made by one discipline that impact others. It detects conflicts that violate design intent, and in simple cases, such as translations, it can resolve inconsistencies by actively propagating corrections subject to users' approvals.

One potential limitation of the first work when applying in reality is its reliance on semantics exported from BIM editors. To eliminate the dependency on proprietary schemas, the subsequent stage of the research explores the reconstruction of a BIM graph from fundamental model data, specifically, pure object geometries, and then organized the predicted results into a graph-based Common Data Environment (CDE) to support intelligent applications.

Consequently, we propose a framework of generic semantic enrichment which includes four fundamental tasks in the context of graphs and a process control mechanism to execute a set of tools in a proper sequence. To validate its feasibility, we selected a real-world apartment model and developed six tools to generate the graph-based CDE from its object geometries to support applications, such as enriching a pure geometry model from SketchUp to a BIM model in Revit.

During the semantic enrichment process, we explore the usage of GNN to enrich BIM graphs in the third work. We use the room classification task to develop, test and illustrate the approach. A dedicated graph dataset consisting of 224 apartment layouts with nine room types and node, or edge features was compiled. An improved GNN algorithm, SAGE-E, was developed for processing both node and edge features. The experiments showed that the novel approach of adopting graphs and GNN was feasible, and SAGE-E achieved higher accuracy (79\%) and more balanced prediction (F1 = 0.79) when compared with other machine learning algorithms.

**Contribution to knowledge**

The first work, consistency maintenance, demonstrates the feasibility of the approach of representing BIM models as graphs and linking BIM graphs to enable intelligent applications. To our best knowledge, this is the first work of implementing intelligent applications on BIM graphs.

The second work, generic semantic enrichment of BIM models, demonstrates the feasibility of generating BIM graphs from pure object geometries through semantic enrichment. It establishes a theoretical foundation for graph semantic enrichment which can get rid of the reliance on proprietary schemas and paves the way for the adoption of the graph-based approach in different domains and BIM editors.

GNN for room type classification, the third work, illustrates the feasibility of compiling BIM models and applying advanced computer vision techniques on BIM graphs for semantic enrichment. It also validates the advantages of BIM graphs by leveraging the relationships between BIM objects which are hard to be presented by other data formats.

By combining the three works together, the whole PhD validates that,

- BIM models can be compiled as graphs to enable machine learning techniques for semantic enrichment.
- BIM graphs can be linked together to support intelligent cross-domain applications.

Therefore, the most important contribution of this PhD is that graph representation of BIM models provides a novel direction to develop intelligent BIM applications for enhancing multidisciplinary design collaboration and easing the interoperability problem.