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AUTOMATIC HVAC TOPOLOGY GENERATION USING BIM GEOMETRY CHECKING AND KNOWLEDGE GRAPH TECHNOLOGIES

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Abstract

Developing digital twins of buildings can enhance the design process and streamline operational management. This study presents an automated framework designed to establish HVAC topologies of buildings using IFC-BIM data inputs. It achieves this by detecting geometric relationships among HVAC elements and generating a knowledge graph that captures their interconnections. A case study involving a recently constructed building in the UK was conducted to validate this framework. The resulting HVAC topology was compared against design drawings to identify any disparities, demonstrating the workflow's efficacy. This framework shows promising potential and generalization ability for application in various types of buildings.

Keywords

Building digital twins, Geometric relation check, Knowledge graph, HVAC topology

Introduction

A building digital twin is an advanced concept that can be used to improve building design, facilitate a building's operational management, and bridge the gap between building information and building simulation models. A seamless framework to establish Heating, Ventilation, and Air Conditioning (HVAC) topology automatically from BIM data exploits the latter potential and supports the automation of the generation of Building Energy Models, especially for the active components in building performance simulation. This HVAC topology generation involves multiple tasks such as the crafting of appropriate building-centric ontologies, the extraction of semantic relationships among HVAC elements, and finally the generation of semantic graphs conforming to the ontological schemes, capturing the HVAC topology.

Towards this direction, researchers established several building-oriented ontologies to enhance the building management system, e.g., BrickSchema developed by Brick Consortium (2019), to describe fluid flows through MEP distribution elements, e.g., Flow Systems Ontology (FSO) developed by Kukkonen et al. (2022), and to model connections between spaces and elements, e.g., Building Topology Ontology (BOT) Rasmussen et al. (2021). Seidenschnur et al. (2022) proposed a common data environment to represent a BIM-based model with the virtual commissioning, to establish a common data environment for HVAC design. They conducted two case studies to achieve the co-simulations between Modelica and EnergyPlus. Mavrokapnidis et al. (2023) used the Geometric Relation Checker (GRC) tool to identify pairs of IFC geometric instances and to generate an HVAC topology in knowledge graph form. They also briefly compared the applicability of BrickSchema, BOT, and FSO on data from the building domain. Many researchers tried to introduce ontologies as the bridge between building information and building energy modelling to achieve building simulation automatically. Wu et al. (2022) proposed an ontology-based framework for building performance simulation by integrating various data sources including building information modelling, building management systems, and weather stations. Their results showed a considerable reduction in modelling time but appropriate assumptions could not be avoided.

Different data sources of building information can be introduced into the HVAC-related Building Information Modelling to Building Energy Models (BIM2BEM) transformation. Not limited to IFC-based BIM models, CityGML can also serve as a data source and be integrated into the BIM2BEM workflow. Deng et al. (2023) developed a tool for district-scale urban building energy modelling in which the geometric information of buildings was extracted from CityGML data. To facilitate the BIM2BEM generation process, González et al. (2021) integrated BIM and BEM methodologies to conduct an energy performance analysis of a residential building. Their work mainly depended on the Revit platform considering many variables including lighting efficiency, plug-load efficiency, and HVAC systems. In their study, an architectural BIM model provided the majority of necessary data, enabling non-geometric information to be derived from experimental design. Ramaji et al. (2020) devised an extension for OpenStudio that converts IFC-based BIM models into building simulation models. Validation of their algorithm was conducted through a case study involving a three-story office building in the US, revealing several advantages and limitations. Their findings highlighted certain drawbacks of the current semi-automated BIM2BEM process, particularly when dealing with large and intricate structures.

As the number of BIM2BEM-related studies grew, researchers started to summarize the related developments investigating potential topics that require to be addressed in the future, e.g., Kamel and Memari (2019) and Farzaneh et al. (2019). They concluded that there was still work to be done, to reach a seamless workflow from BIM to BEM. In this context, two specific tasks were proposed to facilitate the development of an automatic BIM2BEM framework. The first task focuses on integrating models, while the second task revolves around creating a process map to seamlessly connect work and data flows. Researchers primarily concentrated on bridging the gap between BIM and BEM architectural data focused on the generation of the second-level space boundary topology Ying and Lee (2021), Rose and Bazjanac (2015), Lilis et al. (2017), rather than addressing data translation issues specific to MEP data, like those appearing in the HVAC data domain. A potential explanation for this decision might stem from the difficulties encountered when attempting to automatically generate an HVAC topology directly from BIM data—a crucial step in translating HVAC information within a BIM2BEM process. Achieving this automated HVAC topology generation requires employing multiple ontologies describing mechanical equipment (e.g., BrickSchema Brick Consortium (2019)) and material flows (e.g., FSO ontology Kukkonen et al. (2022)), within MEP networks. Additionally, various issues and errors in BIM models lead to challenges in achieving an accurate HVAC topology, often requiring labour-intensive manual corrections.

To tackle these challenges, this work develops a framework that automatically generates the HVAC topology of a building that can be used to mirror real-world conditions. To demonstrate its efficacy and feasibility, we apply this framework to a recently built structure with complex HVAC systems. Concurrently, the proposed framework seeks to enhance any automated BIM2BEM conversion process by providing a fast and efficient translation method for possible MEP data that could be part of this process.

To introduce this approach the structure of the paper is as follows: The methodology section outlines the framework and its pertinent stages. The case study section provides an in-depth overview of the chosen building and its HVAC setup. Following this, the results and discussions section delves into the generated HVAC topology, highlighting the strengths and limitations. Finally, the conclusion section summarizes the findings and proposes avenues for future research.

Methodology

The proposed HVAC topology generation process involves three major steps as illustrated in the block diagram of Figure 1. These steps are: (1) Extraction of information from BIM (IFC) files related to architectural (ARC) and mechanical, electrical, and plumbing (MEP) data, (2) Checking of the extracted BIM content to detect geometric (2a) and semantic (2b) relations among HVAC elements and space volumes, and (3) Establishment of the HVAC topology via knowledge graph generation and path-finding.

- In step 1 (Extraction), the IFC geometry exporter is used to extract the geometric representations (parametric and non-parametric) of the building space and MEP elements from the ARC-IFC and MEP-IFC files. These representations are then used to form XML files that are used as input to a geometric relation-checking (GRC) tool. These XML files contain the detailed geometric representations of each entity to be checked, together with their IFC global unique ID. Additionally, in this step, the IfcOpenShell is used for parsing the MEP IFC file to extract the semantic connectivity data.
- In step 2 (Checking), connectivity and containment entity pairs are extracted via geometric (step 2a) and semantic (step 2b) relation checks. In case semantic relations are absent from the BIM data, the GRC tool is applied to identify geometric relations among the solid representations of the MEP elements (containment, clash, and adjacency) and infer the missing semantics. Finally, the Oriented Bounding Box (OBB) method is introduced to address the HVAC elements that can not be handled by the GRC tool. Hence, a hierarchy of checks (BIM context - GRC - OBB) is formed to extract all connectivity and containment relations among the involved elements.
- In Step 3 (Establishment), an ontology-based knowledge graph is created to represent the HVAC elements and their connectivity, leveraging the outcomes of Step 2. Subsequently, a path-finding method is implemented to establish logical links from terminals to systems and from pumps to units, thereby simplifying the knowledge graph of the HVAC topology.

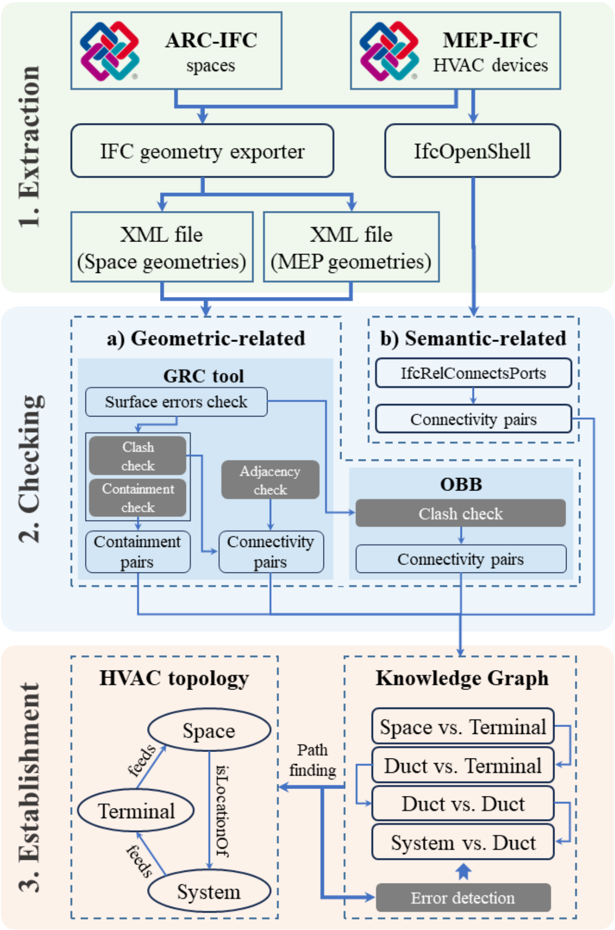


Figure 1: Introduced three-step framework

Information extraction from BIM - Step 1

The proposed workflow used two types of BIM models, i.e., ARC-IFC and MEP-IFC files. From the ARC-IFC file, only the class of IfcSpace was extracted and transferred to a set of entities in the knowledge graph that are detailed in the following sections. To extract the MEP information related to the duct network, data from multiple IFC classes were gathered, including (1) the classes of IfcAirTerminal, IfcDuctSegment, IfcDuctFitting, IfcAirToAirHeatRecovery, IfcBuildingElementProxy that are used to construct the air loop network of the HVAC system, and (2) the classes of IfcPump, IfcValve, IfcPipeFitting, IfcPipeSegment, and IfcFlowMeter that are used to construct the water loop network of the HVAC system. Instances of the previous classes that are contained in the IFC files were mapped, in a one-to-one manner, to entities in the knowledge graph.

Furthermore, the IFC Geometry Exporter Katsigarakis et al. (2021), was used to extract geometric descriptions of the elements from input IFC files, which is the prerequisite to implement the geometric relationship check that is conducted using low-level C++ geometric routines. The exporter extracted serialized geometric descriptions from the two types of IFC files, transformed them into a hierarchical tree-structured format, and created two XML files containing these transformed descriptions. The generated XML files were then used as input to the Geometric Relation Checker (GRC) tool, to identify the geometric relationship among the building's MEP and space elements.

Geometric relation checking - Step 2a

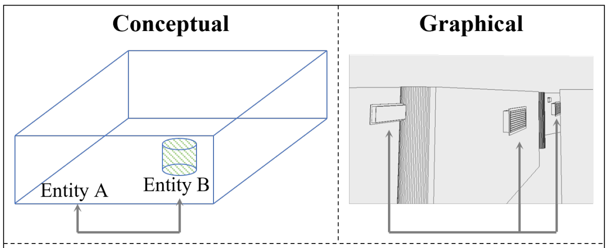
Three types of geometric relationships are defined: containment, clash, and adjacency to deduce semantic connections among the elements within the ARC and MEP IFC files. Detailed explanations of these relationships are provided in subsequent subsections.

Containment

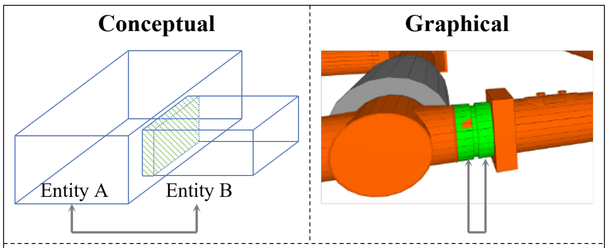
A containment relationship between two solids exists when the surfaces enclosing one solid are entirely within the 3D boundaries of the other. Consequently, this relationship serves as a means to identify semantic links between spaces and terminals. It enables the detection of the specific space to which an HVAC terminal belongs. This association is particularly relevant, as numerous air terminal units, such as diffusers and grilles, are typically entirely enclosed within the volume of the building space, as depicted in Figure 2 a).

Clash

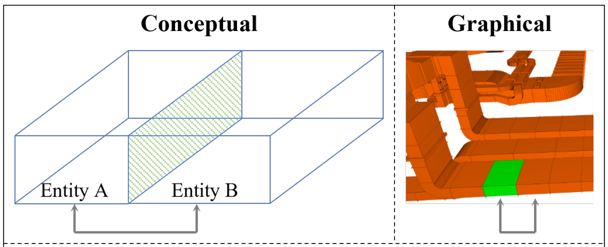
A clash relationship between two solids exists when surfaces or parts of the surfaces of the boundary representation of one solid are entirely within the 3D boundaries of the other. Figure 2 b) illustrates the clash relationship between two elements. This is the most common geometric relationship among many pairs of elements within the air loops, including spaces vs. terminals, terminals vs. ducts, ducts vs. ducts, and ducts vs. systems. Similarly, within the water loops, it also extends to relationships between terminals vs. pipes, pipes vs. pipes, pipes vs. pipe fittings, and pipes vs. pumps. Clashes can be used to infer connectivity between elements as well as containment when a portion of one element is inside another.



a) Geometric relation: **Containment** → Semantic relation: **Containment**



b) Geometric relation: **Clash** → Semantic relation: **Connectivity**



c) Geometric relation: **Adjacency** → Semantic relation: **Connectivity**

Figure 2: Conceptual and graphical illustration of a containment relationship.

Adjacency

Two solids share an adjacency relationship when the surfaces of one solid's boundary representation lie in the same plane and intersect with the surfaces of the other solid's boundary representation. Figure 2 c) illustrates the adjacency between two elements that frequently appear in pairs of ducts and ducts and systems, especially in rectangle-shaped ducts. Unlike the previous geometric relationships, a threshold value (0.01 m in this case) is used to check adjacency. This value sets the allowable distance between the planes of the intersecting surfaces that define the adjacency. If the distance between these planes exceeds this value, intersection and adjacency are not detected.

GRC tool

To detect the presence of the previous geometric relations among the solid representations of the BIM elements, a geometric relationship-checking tool, named Geometric Relation Checker (GRC), is introduced. The performance of this tool is validated on BIM elements from the architecture and construction domains. GRC is a domain-agnostic application that can be used to identify predefined geometric relationships in any IFC element pair. To achieve the necessary execution speed, the GRC tool is implemented in C++ and uses binary space partitioning to carry out fast Constructive Solid Geometry (CSG) set operations on polyhedra, required for clash detection, using multithreaded executions. GRC can not only identify relationships including containment, clash, and adjacency, but also the surfaces at which the related elements intersect or touch each other. Moreover, a threshold of the gap between each element can be set to define the adjacency and to address potential element mismatching issues.

Oriented bounding box

If surface errors are present in the solid representations of the compared BIM elements, certain Geometric Relation-checking processes like clash and containment detection cannot be performed. Surface errors refer to surface inversions and missing surfaces that form wholes in the boundary representations. To address such scenarios, the study introduced the oriented bounding box (OBB) method to carry out the relevant geometric relationship checks. The GRC tool identifies these cases and automatically routes the problematic elements to the OBB-based clash-checking process. Furthermore, inflation is used during the OBB-based clash-checking process to expand the bounding box in the direction of each face, with the inflation threshold aligned with the gap threshold used by the GRC tool. This method ensures that the OBB-based clash-checking process complements the GRC method, facilitating comprehensive geometric relationship checks for all elements within the IFC file.

Entity linking via semantic checking - Step 2b

Although numerous IfcRelationship entities exist within the BIM context to depict relationships among MEP entities, they often fail to encompass all entities within air loops and water loops. The previously described geometric relationship check processes were introduced to address this gap, enabling the deduction of missing semantics between pairs of MEP elements. Thus, the proposed GRC-OBB-BIM workflow streamlines the extraction of existing and potential containment/connectivity pairs, enhancing the linkage between HVAC elements and helping to finalize the generated HVAC topology.

HVAC topology establishment - Step 3

The HVAC topology establishment process was divided into knowledge graph generation, pathfinding, and error detection, as analyzed in the following subsections. Firstly, knowledge was transferred directly on the basis of the detected geometric relationships to the knowledge graph. At the same time, the path-finding algorithm was used to enrich the semantic linking between the critical HVAC components (e.g., terminal2VAVbox, VAVbox2system, system2pump). The knowledge graph generation was based on the integration of two open-source ontologies, named BrickSchema Brick Consortium (2019) and FSO Kukkonen et al. (2022), as described next.

Knowledge graph generation

BrickSchema, developed by Brick Consortium, standardizes semantic descriptions of the buildings' assets/devices and their inner relationships, which was introduced into this work to represent the HVAC components with a series of Brick entities (`brick:Room`, `brick:Terminal_Unit`, `brick:AHU`, `Brick:DOAS`, `brick:Chiller`, `brick:HX`, `brick:Pump`, and so on). As a supplement, the Flow Systems Ontology (FSO), which focuses on interconnected systems and their energy flows, was incorporated to model both pipework and ductwork segments by using FSO entities (`fso:Segment` and `fso:Fitting`). Furthermore, within the scope of geometric relationships among HVAC elements, `brick:isAssociatedWith` is used to denote connectivity relationships, that is, connectivity pairs resulting from clashes and adjacencies because these detected geometric relationships were downstream/upstream direction agnostic. Regarding the containment pairs, `brick:isLocationOf` was introduced to indicate the containment relationships with specific directions (e.g. space - isLocationOf - system).

Path-finding

In this study, a path-finding algorithm was utilized to discover routes between distinct entities within the knowledge graph by analyzing multi-hop connections. These routes were established among terminal units (such as air terminals), source systems (such as AHUs), and potential nodes (like VAV boxes) that might exist between the source and terminal units within air loops. Similarly, connections were formed between AHUs/FCUs, pumps, and heat exchangers or chillers within the water loops. These routes collectively formed the final HVAC topology. In this topology, the `brick:isFedBy` relation was used to replace the `brick:isAssociatedWith` relation between the critical HVAC components connected via path-finding. The flow direction along these connection links was determined by the ID of the connected elements, wherein each element's ID contains a specific string indicating whether it pertains to an air supply or an air return unit. Figure 3 illustrates how path-finding contributes to the generation of an HVAC topology instance.

In terms of algorithmic methodology, the Depth-First Search (DFS) path-finding algorithm was introduced to convert the generated knowledge graph into the final HVAC topology. DFS prioritizes depth, exploring as deeply as possible along each branch of the graph before backtracking. Additionally, DFS offers the flexibility to omit particular nodes from the search process. For example, when seeking a route from Terminal 1 to AHU 1, other AHUs can and should be excluded. It is essential to prevent path-finding processes from entangling within water loops and air loops. Two simple approaches to accomplish this are splitting the knowledge graph into distinct subgraphs or assigning a specific attribute to knowledge graph links to distinguish connection relationships.

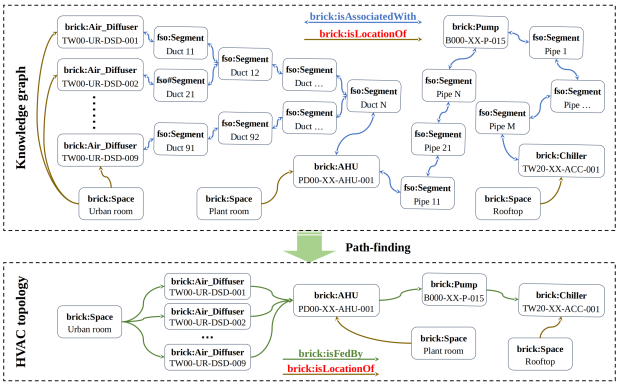


Figure 3: Illustration of the path-finding process to transform the knowledge graph into the HVAC topology.

BIM error handling

Although the preceding workflow's processes are executed automatically, errors within the BIM data can result in either zero or multiple paths detected, from the supply to terminal units. Alternatively, it might be found that one air terminal unit is linked to multiple AHUs or FCUs. These errors manifest in four distinct types, as illustrated in Figure 4, which include:

(a) An abnormal clash is an incorrect intersection among MEP elements that is due to design errors.

(b) A missing element is the absence of an MEP element in a sequence of connected elements.

(c) A geometric mismatch is a misalignment of MEP elements that leads to connection absence.

(d) A space containment issue occurs when a building space volume does not contain or does not intersect, at least, with a solid geometric representation of a terminal unit.

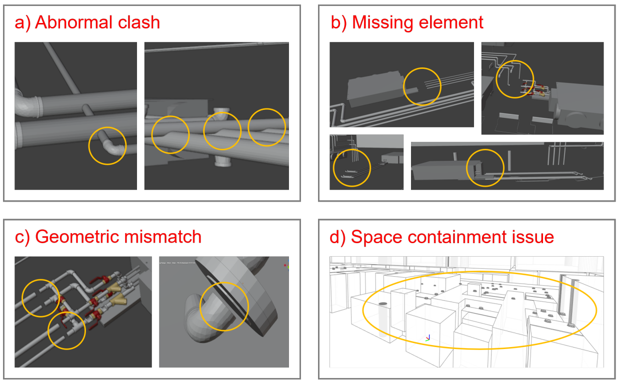


Figure 4: BIM error-type illustration examples

Error types (a), (b), and (c) impact the established routes from the supply to the terminal units within the HVAC domain, while error type (d) influences the containment connection between terminal units and their corresponding building spaces. Visual inspection is applied on the detected paths from supply to terminal units, and on the building space volume geometries, to pinpoint these errors. Subsequently, manual corrections are implemented on the produced knowledge graph to rectify the affected graph nodes and edges.

Case study

The introduced process was applied to BIM data from a new building, named One Pool Street (OPS) located at the UCL East Campus. OPS is a multi-function building that uses a state-of-the-art energy supply and management system. This work concentrated on the automatic generation of the HVAC topology of the podium part of the OPS building. The HVAC topology of this building part is ideal for demonstration purposes, as its energy supply system is complex and includes a set of diverse ventilation units. For cooling purposes, several Air Handling Units (AHUs) are installed with chilled water and hot water units that supply thermostatic air via hundreds of air terminals during the summer and winter periods. Additionally, Fan Coils (FCUs) are also used in some rooms to meet their cooling and heating requirements. Door heaters (DHs) and air curtains (ACs) are also installed for heating purposes only. Besides, Mechanical Ventilation Heat Recovery (MVHR) systems are installed to recycle the waste heat and improve energy performances in several building spaces. Consequently, the manual generation of the HVAC topology for these complex systems is a time-consuming and error-prone process. Hence, the OPS podium was selected as a case study to illustrate the effectiveness of the proposed workflow.

Figure 5 illustrates the 3D representations of the contents found in the ARC-IFC and MEP-IFC files, which encompass both air loops and water loops of the OPS podium. In terms of data quality, the Level of Development (LOD) for the IFC4 file varies between LOD 300-400 (following US standards) and LOD 4-5 (according to UK standards). This file comprises over 22,000 MEP elements, posing a significant challenge due to memory limitations on standard computers when handling MEP-IFC files. To address this challenge, it was imperative to divide the MEP-IFC file of the OPS building into two smaller IFC files, specifically focusing on air loops and water loops.

Results and discussions

In this section, the performance of the proposed workflow and its limitations are also discussed.

Established HVAC topology

The proposed workflow was conducted on a laptop computer, and the geometric relationship checking process consumed the most computing resources of the workflow. The geometric relationship checking between air terminals and spaces took several minutes and involved approxi-

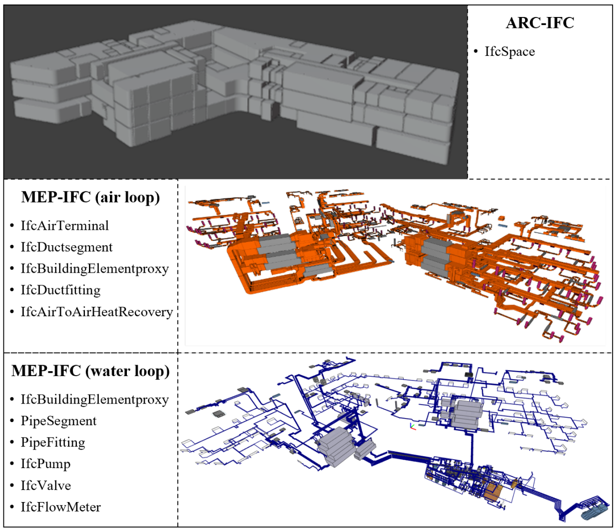
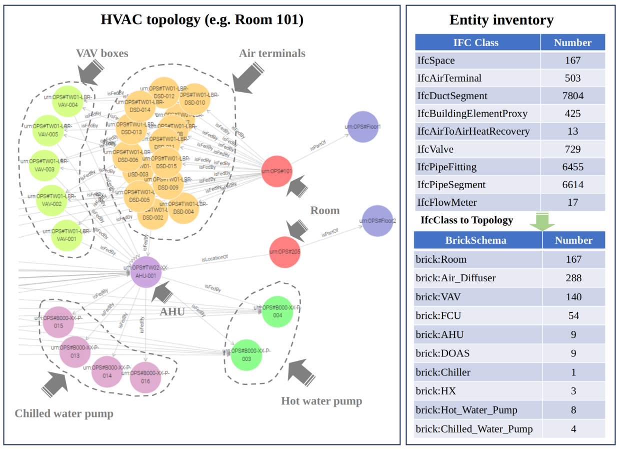


Figure 5: Visual representation of the content of ARC-IFC and MEP-IFC files.

mately 84,000 element pairs. The checking process among the HVAC elements took a few hours and involved approximately 38,000,000 pairs within air-loop elements and 101,000,000 pairs within water-loop elements. In addition, the path-finding process to link terminals, systems, and pumps, took dozens of minutes.

Figure 6 displays a part of the generated HVAC topology referring to Room 101. In this figure, the return air terminals are hidden because they are not as significant as the supply air terminals from the energy simulation perspective. Within the air loops, the air terminals (displacement diffusers) were identified successfully, and the VAV boxes within the duct network were also detected, defining the paths from the system (AHU) to air terminals (DSDs). Since the air terminals had IDs with the special string (DSD: displacement supply diffuser), the directional relations `brick:Feeds/brick:isFeedBy` were determined, linking the air terminals with the system. In the context of water loops, Figure 6 highlights the connection of four chilled water pumps and two hot water pumps with this AHU. However, the uncertain status of the valves, particularly the bypass valves, presents a challenge. This uncertainty makes it impossible to ascertain which pumps are on standby and which are operational, or to determine their positioning relative to the AHU, whether upstream or downstream. Hence, in the HVAC topology, the directional relations `brick:Feeds/brick:isFeedBy` were determined to illustrate the links between pumps and AHUs. Similarly, this approach was also applicable to establishing links from heat exchangers to pumps. The entity inventory of the original IFC files and the HVAC topology are both depicted in the right portion of Figure 6. The podium section of the OPS building comprises approximately 8,800 air-loop MEP entities and over 13,900 water-loop MEP entities, which are integrated into the proposed workflow. Approximately 7,000 of the air-loop entities are modelled using boundary representations and require additional checks by the GRC tool for potential surface errors. However, this step will become unnecessary in the future if boundary representations are substituted with parametric ones.



Entity inventory

IFC Class	Number
IfcSpace	167
IfcAirTerminal	503
IfcDuctSegment	7804
IfcBuildingElementProxy	425
IfcAirToAirHeatRecovery	13
IfcValve	729
IfcPipeFitting	6455
IfcPipeSegment	6614
IfcFlowMeter	17

IfcClass to Topology

BrickSchema	Number
brick:Room	167
brick:Air_Diffuser	288
brick:VAV	140
brick:FCU	54
brick:AHU	9
brick:DOAS	9
brick:Chiller	1
brick:HX	3
brick:Hot_Water_Pump	8
brick:Chilled_Water_Pump	4

Figure 6: The generated HVAC topology for Room 101 (the exhausted air terminals are hidden) and the inventory of IFC entities and relevant entities.

MEP element - Space containment issues

Accuracy is one of the critical indicators for validating the performance of this HVAC topology-generation workflow. In this case, the HVAC design drawings of the OPS building were also obtained and acted as a reference point for validation. Figure 7 shows the statistical results of the semantic linking between the air terminals and the podium spaces. More than 70% of the air terminals were linked to their correct spaces. However, about 18% of them were not linked to any spaces because there are design errors in the geometry of the spaces in the IFC file, e.g. some spaces are not extended high enough to reach the ceiling surfaces. Additionally, elements with surface errors caused delays when conducting the GRC executions since pairwise element clash checking requires at least one of the elements in a pair, to be surface error-free. Meanwhile, nearly 8.5% of the air terminals intersected with more than one space, requiring manual work to decide the correct space. The reasons for these misalignments are mainly surface errors (requiring the OBB check) and design errors (human errors), both of which are related to the data quality of the geometric representations of the elements. The suggested workflow can efficiently identify the geometric containment relationships between air terminals and spaces, as long as the input IFC file reaches LOD-4 level or beyond.

MEP element connectivity issues

Another critical aspect of an HVAC topology pertains to the connection between air terminals and systems. Figure 8 illustrates the efficacy of the proposed workflow in identifying paths from air terminals to systems within the air loops. Initially, only half of the air terminals were accurately linked to the correct AHU, MVHR, and FCU, as depicted in Figure 8 (a), before addressing the errors. This discrepancy arose due to the dense arrangement of ducts,

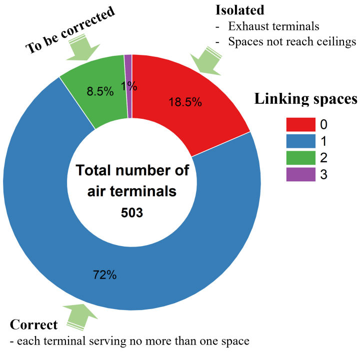


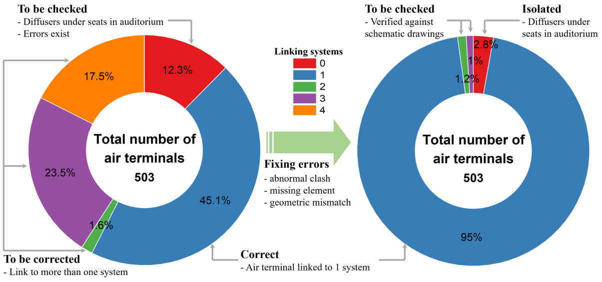
Figure 7: The distribution of air terminals and the number of their linking spaces.

often closely positioned near the systems. The GRC tool's capability to manage such placements is hindered by surface errors affecting these elements. Consequently, in situations where both elements of a pair exhibit surface errors, rendering clash detection impractical, the OBB method serves as an alternative, albeit less precise than the GRC tool. Furthermore, around 12% of air terminals faced challenges in establishing connection paths with systems. This hurdle arose from certain terminals being designed independently from other air-loop elements, such as diffusers situated beneath seats in auditoriums. Additionally, some instances involved design errors, evident in Figure 4 b) and c), where gaps exist between these elements and adjacent ducts. Adjusting the GRC threshold for adjacency checking proved effective in addressing this issue, although it carries the risk of detecting connections that do not actually exist.

Moreover, the initial results revealed that approximately 40% of air terminals remained connected to more than one system due to BIM design errors as previously defined. Most of these instances stemmed from the alternative OBB method, which erroneously identified nonexistent intersections between bend ducts positioned in parallel and very close proximity to each other. After manual efforts to correct the detected errors in the generated knowledge graph, the path-finding process was re-executed on the updated knowledge graph. The statistical results of this process can be found in Figure 8 (b). Notably, 95% of the air terminals were accurately linked to the systems (AHU/MVHR/FCU), while only 2% still required verification against schematic drawings. It is advisable to verify the remaining 2.8% (isolated air terminals) against schematic drawings to ensure the completeness of the HVAC topology.

Furthermore, Figure 9 illustrates the results (after error correction) of the water-loop units in the established HVAC topology. In the OPS building, there are a total of 80 water-loop units, including AHU, MVHR, FCU, DH, and AC, within the water loops, supplied by Hot Water Pumps (HWPs) or Chilled Water Pumps (CWPs). Using the path-finding method, it is possible to determine connections between each unit and HWPs, CWPs, or both.

As depicted in Figure 9, among the 9 AHUs, 6 are linked



(a) Initial **(b) After fixing errors**

Figure 8: The distribution of air terminals and the number of their linking systems.

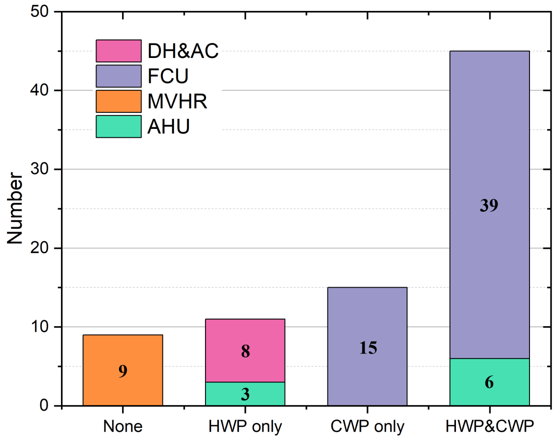


Figure 9: The distribution of units and their HWP/CWP connections.

to both HWPs and CWPs, while the remaining 3 are solely connected to HWPs. None of the 9 MVHRs are connected to either HWPs or CWPs. Of the 54 FCUs, 39 are connected to both HWPs and CWPs, with the remaining 15 solely linked to CWPs. All DHs and ACs are connected exclusively to HWPs. Additionally, this path-finding method could be extended to examine the 93 Radiators (RADs) in the OPS building for their connections to HWPs, although this is not detailed here due to length constraints. Finally, all mentioned results have been validated against the schematic drawings.

Limitations and implications

The effectiveness of the framework was assessed through a case study involving a complex HVAC system, revealing various challenges related to the accuracy and completeness of the HVAC topology when dealing with imperfect MEP-BIM data. Initial inaccuracies were attributed to human errors in BIM design and surface errors in the solid geometric representations of certain MEP-BIM elements, which hindered the effectiveness of the GRC tool. Additionally, a complication arose from adjacent duct entities in the BIM model that were not physically connected, a discrepancy not detectable through geometric relationship checking alone. While this study successfully identifies and locates these errors, manual correction remains necessary and time-consuming.

Conclusions

To automate the creation of an HVAC topology, this study introduced a framework utilizing ARC-IFC and MEP-IFC files as BIM input data sources. Initially, semantic checks were conducted using relevant IFC relationship classes to extract connectivity pairs. A hierarchical checking workflow was then employed to infer missing semantic relations. In the workflow's initial stages, the Geometric Relation Checking (GRC) tool facilitated pairwise adjacency, clash, and containment relation checks among MEP and space BIM entities. If surface errors were reported in the geometric representations of BIM elements by the GRC tool, the clash and containment detection were carried out using the OBB process. Ultimately, this process yielded a set of connectivity and containment pairs. Subsequently, a knowledge graph-based HVAC topology, encompassing air loops and water loops, was generated by applying the DFS path-finding algorithm to the obtained connectivity and containment pairs. A case study involving a newly constructed building was conducted to test the framework's performance, demonstrating its feasibility in various and intricate modern HVAC systems.

In the future, significant improvement can be achieved by incorporating a module that converts the IFC geometries to watertight solid boundary representations. This can speed up the process substantially by reducing the need for surface error checking. Meanwhile, beyond the current building case, the plan is to implement the framework in other scenarios to enhance its generalization capabilities. Besides, further investigation will be undertaken to determine how the generated HVAC topology can be leveraged to enhance BEM models that contain information related solely to the building fabric. This effort aims to support the automatic establishment of active components within the HVAC domain, thereby supporting the development of BEM2BEM research.

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