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Multi-dimensional Semantic Enrichment method for Automated Code Compliance Checking of Building Fire Protection based on BIM and Knowledge Graph

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ABSTRACT: Code compliance checking of building fire protection is crucial for building design quality and safety. The BIM-based automated approach, with its low error rate and high efficiency, has drawn much research attention compared to manual checking. The integrity of the building model is essential to ensure accurate automated checking results. Semantic enrichment is an important technique to enhance building model integrity, but current methods emphasize spatial information and component attributes, lacking simulation results and path analysis which are important for building fire protection performance assessment. Besides, the descriptive ability of IFC, known as the unified data standard of BIM, could not meet the requirements for integrating multi-source and multi-format information. To address these challenges, this paper suggests an approach to improve the efficiency of semantic enrichment of the building model by introducing knowledge graph technologies. The proposed approach includes: (1) converting the building model into three interconnected sub-models based on IFC considering semantic dimensional representation (i.e., a knowledge graph), geometric dimensional representation (i.e., a set of geometric objects), and simulated dimensional representation (i.e., a FDS file); (2) analyzing semantic enrichment requirements and executing methods for the three dimensions respectively; (3) integrating the semantic enrichment information centered on the knowledge graph using knowledge fusion techniques. In this way, multi-dimensional semantic enrichment can be conducted and heterogeneous information can be integrated, laying a solid foundation for the integrity of the building model for further automated code compliance checking processes. Finally, a case study is undertaken to validate this method.

1. INTRODUCTION

Code compliance checking of building fire protection is of utmost significance for ensuring high - quality building design, safeguarding the health of occupants, and maintaining operational safety. Traditional manual checking approach is tedious, error-prone and time consuming (Eastman et al. 2009). The emergence of building information modelling (BIM) technologies has ushered in new prospects for automating and computerizing the code compliance checking process. This development has garnered substantial attention from numerous researchers (Bigdeli et al. 2024). The BIM-based automated code compliance checking (ACCC) process consists of four stages, i.e., rule interpretation, building model preparation, rule - based checking execution, and checking results reporting (Eastman et al. 2009). Among these four stages, the first two stages are considered as the fundamental pillars upon which the subsequent stages are predicated. Currently, a significant body of work has been deeply involved in the rule interpretation stage and the interpretation efficiency shows a remarkable increase with the advent of large language model (Fuchs et al. 2024, He et al. 2025). Nevertheless, most of the existing research tends to simply regards the building model preparation stage as an engineering task of building model construction, lacking discussion on the integrity of building model information which could furnish comprehensive design data and ensure the completeness of the checking results.

Semantic enrichment (SE) was proposed as a potential method to enhance the integrity of building model information (Belsky et al. 2016). Current SE approaches could be divided into rule-based SE approach (Belsky et al. 2016, Sacks ET AL. 2017), geometric computation-based SE approach (Gao et al. 2022), and machine learning-based SE approach (Bigdeli et al. 2024, Bloch and Sacks 2018, Collins et al. 2021, Emunds et al. 2022, Jin et al. 2018, Koo et al. 2021, Wang et al. 2022, Xu et al. 2022). However, these approaches focus on annotation of building elements (Bigdeli et al. 2024), creation of spatial relations (Jin et al. 2018), and classification of building element types (Collins et al. 2021, Koo et al. 2021), which cannot meet all the data requirements of ACCC of building fire protection. Furthermore, the SE process necessitates supplementary information sourced from other files, including calculation files, simulation files, and recording files. Although the Industry Foundation Classes (IFC) represents the most prevalently utilized format for BIM data exchange, the rigidity and complexity inherent in the IFC schema pose challenges when it comes to integrating the information retrieved from multi-source files that are stored in heterogeneous formats (Gómez-Romero et al. 2015).

In this paper, a SE method considering semantic dimensional representation, geometric dimensional representation, and simulated dimensional representation is proposed. To address the multi-source information integration, the proposed approach utilizes knowledge graph, which can represent the information based on a uniform data schema (i.e., triple), as the semantic dimensional representation. Meanwhile, relationships are established among various dimensional representations. Besides, different SE requirements could be adopted for various dimensional representations, respectively. The SE results are also integrated based on knowledge graph and the fused information is considered as the data foundation of the following checking process.

2. PROPOSED METHODOLOGY

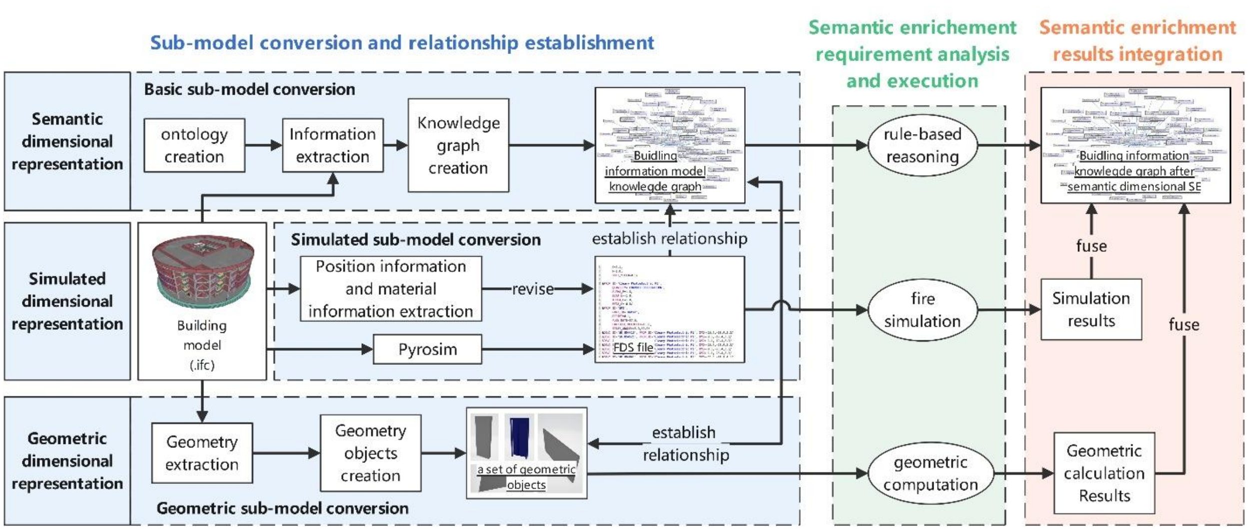

Figure 1: Proposed multi-dimensional semantic enrichment method based on BIM and knowledge graph

The proposed methodology includes three stages, i.e., sub-model conversion relationship establishment, semantic enrichment requirement analysis and execution, and semantic enrichment results integration, as shown in Figure 1. In the first stage, the building model, which is exported as IFC-STEP file, is converted into a basic sub-model represented as a knowledge graph, a geometric sub-model represented by a set of geometric objects, and simulated sub-model represented as a FDS file. Relationships among the above three sub-models are established as well. Next, SE requirements for ACCC of building fire protection are analyzed according to building codes. Accordingly, the rule-based reasoning, fire simulation, and geometric computation are executed based on the sub-models respectively. Finally, the SE results are integrated based on the basic sub-model using knowledge fusion techniques.

2.1 Sub-model conversion and relationship establishment

2.1.1 Basic sub-model conversion

The basic model conversion aims to extract the non-geometric information from the building model and then create a building information model knowledge graph (BIMKG). In this regard, a building information model ontology (BIMOnto) is proposed as the schema layer of the BIMKG first. Since the BIMKG is used to achieve ACCC, the BIMOnto in this paper is designed in line with the top-level structure of the knowledge representation of building codes (Jiang et al. 2022a) in order to alleviate semantic ambiguity between building design information and regulatory information. As shown in Figure 2, the top-level structure of BIMOnto includes two Classes (i.e., BuildingEntity and ValueNode), two Object properties (i.e., EntityRelation and EntityAttribute), and one Data property (i.e., hasValue). BuildingEntity represents a variety of building entities, such as "bedroom", "floor", "staircase", "fire exit", etc. The attributes of building entities are treated as instances of ValueNode connected with BuildingEntity through EntityAttribute and then the concrete attribute values are defined through hasValue. EntityRelation describes the relationship between building entities, such as the connection relation between spaces.

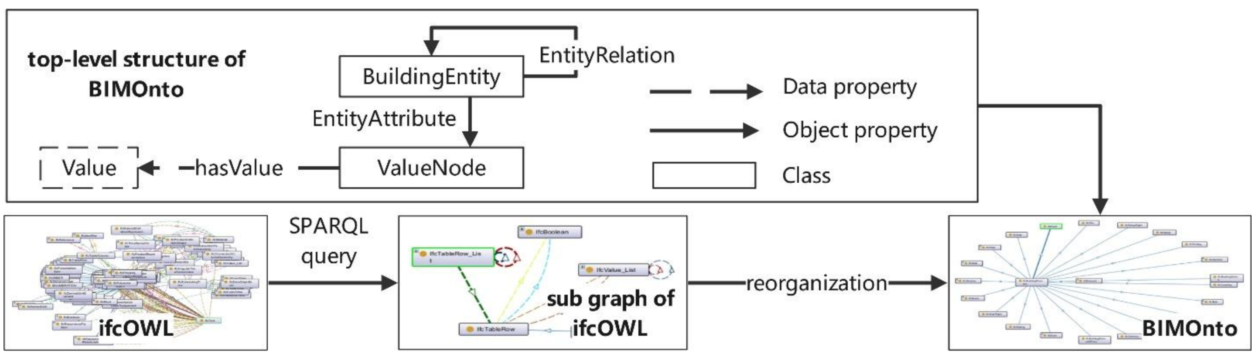

Figure 2: Automated creation method of BIMOnto based on ifcOWL

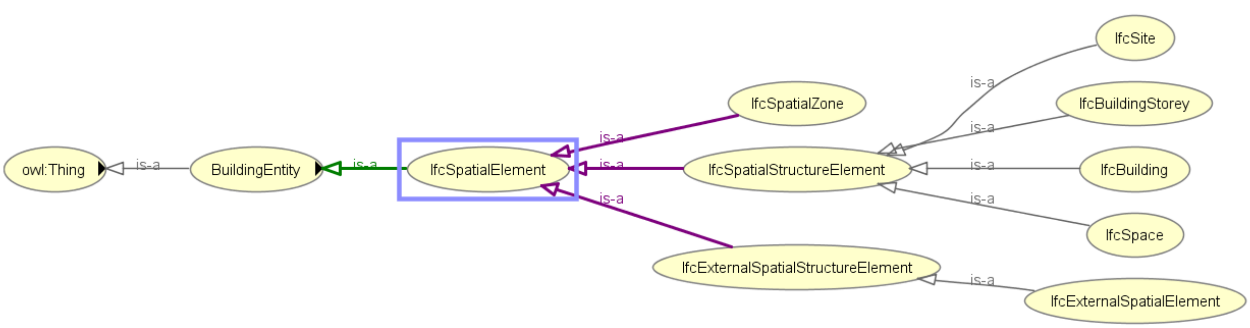

Figure 3: Hierarchical structure organization of IfcSpatialElement in BIMOnto

On the basis of the top-level structure, an automated creation method of BIMOnto is proposed in this paper. Since the creation of BIMOnto emphasizes the reorganization of IFC entity based on IFC schema whose latest version contains over 2000 IFC entities, the ifcOWL, which can offer a Web Ontology Language (OWL) representation of the IFC schema and could facilitate IFC entities acquirements using graph query language compared with EXPRESS model, is regarded as the knowledge source of BIMOnto. As shown in Figure 2, a series of SPARQL queries is utilized to obtain the sub graph and then associates or reorganizes it according to the top-level structure. For example, the SPARQL query "SELECT DISTINCT ?a ?b WHERE {{ ?a rdfs:subClassOf ?b . VALUES ?b {:IfcSpatialElement } FILTER (?a != ?b) } UNION { ?a rdfs:subClassOf ?b . ?b rdfs:subClassOf+ :IfcSpatialElement . FILTER (?a != ?b) }}" could be used to retrieve the sub-graph with IfcSpatialElement as the root node in the ifcOWL. Then the root node IfcSpatialElement is declared as a subclass of BuildingEntity. The hierarchical structure organization of IfcSpatialElement in BIMOnto is presented in Figure 3.

Next, the BIMKG is created based on information extraction from IFC-SPF (STEP Physical File). Considering the BIMOnto as the schema layer, the extracted information comprises the instance layer of the BIMKG. Each row of data record in IFC-SPF could be regarded as an instance whose type is determined by the IFC entity type. As such, the instance created in the BIMKG is named as the combination of IFC entity type and the record line number to ensure its uniqueness. As shown in Figure 4, the instance created based on record #552508 is IfcCurtainWall_552508, and the instance created based on record #552568 is IfcPlate_552568. Relationships between instances are created by parsing the relational entities in the IFC-SPF. For example, relationship between IfcCurtainWall_552508 and IfcPlate_552568 is defined as IfcRelAggregates according to record #552646 and the relation direction is defined from RelatingObject (i.e., IfcCurtainWall_552508) to RelatedObjects (i.e., IfcPlate_552568).

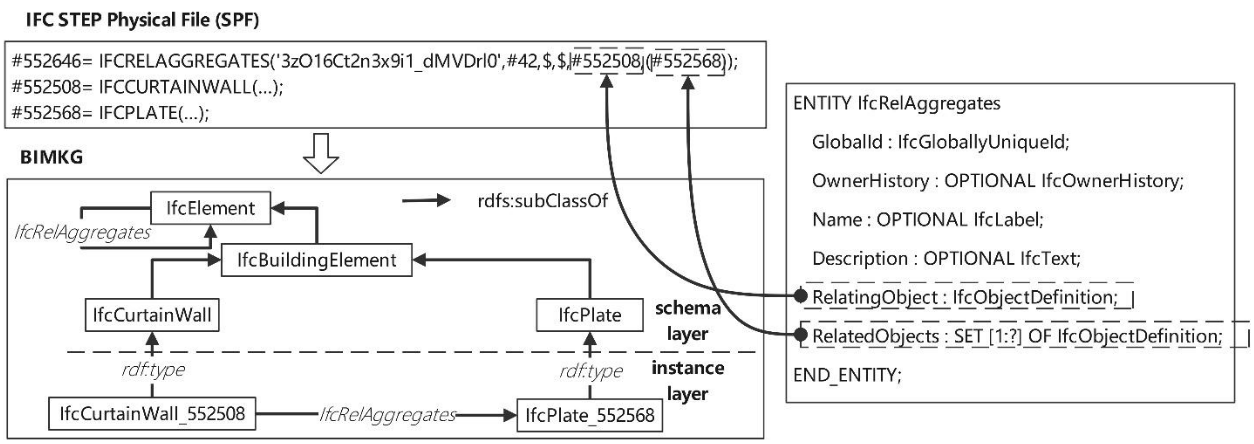

Figure 4: Example of creating instances and corresponding relationships for BIMKG

Similarly, the attributes of the building entities in BIMKG could be created by parsing information through IfcRelDefinesByType and IfcRelDefinesByProperties in IFC-SPF. The retrieved attributes are considered as instances of ValueNode and these instances are connected with the building entities through the attribute name which is defined as the sub property of EntityAttribute. An example is illustrated in Figure 5.

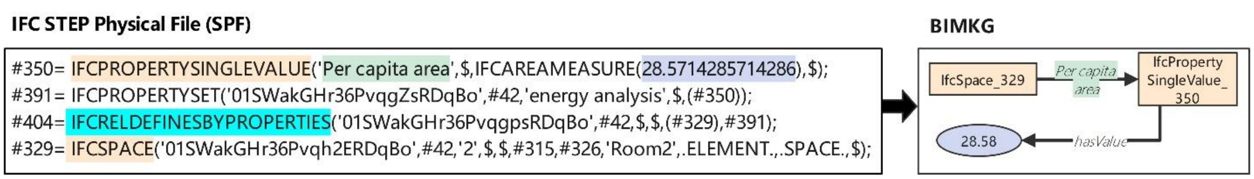

Figure 5: Example of creating attributes of building entities in BIMKG

2.1.2 Geometric sub-model conversion and relationship establishment

The geometric representation is strictly defined in the IFC data model and such a definition will become more complex and redundant when transformed into a semantic web-based representation (McGlinn et al. 2019). Meanwhile, it is inconvenient to display the shape of building entities with the semantic web-based representation. Therefore, this paper adopts a distributed storage strategy. First, the geometric shapes of building entities are extracted from IFC-SPF. Next, the extracted geometric shapes are converted into a set of geometric objects whose formats are determined based on actual circumstances. Finally, the storage positions of the geometric objects are recorded in the BIMKG to achieve the relationship establishment.

2.1.3 Simulated sub-model conversion and relationship establishment

This paper presents a semi-automated method leveraging Pyrosim and IFC for the creation of the simulated sub-model which stands as the cornerstone of performance-based design of building fire protection. As depicted in Figure 6, the fire simulation software, Pyrosim, is employed to transform the IFC-SPF into an initial FDS file. This transformation involves the creation of geometric representations and the definition of global parameters, including simulated time, mesh, combustion source, and other parameters relevant to the performance-based design of building fire protection. Nevertheless, in the initial FDS file, all building elements are uniformly defined as obstructions, resulting in the loss of certain semantic information associated with specific building elements. For instance, to facilitate the spread of smoke between rooms, doors and windows are typically designated as holes rather than obstructions. To address this issue, the relationship between the initial FDS file and the basic sub-model (i.e., BIMKG) is established first. Subsequently, the semantic information extracted from the BIMKG is utilized to refine the initial FDS file, thereby creating the simulated sub-model.

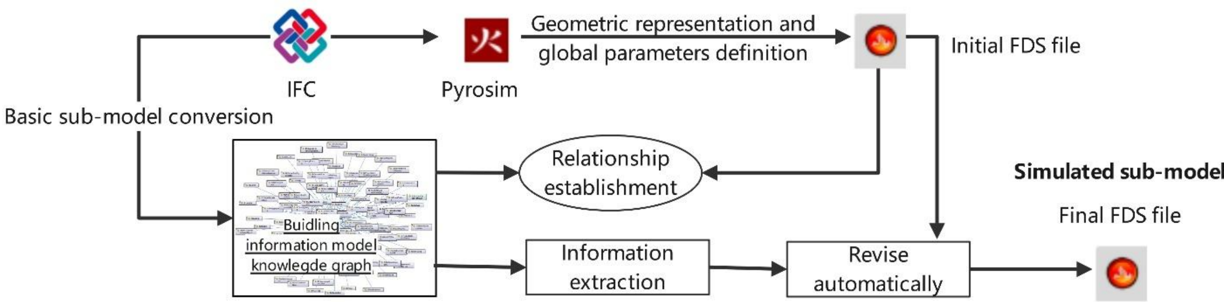

Figure 6: Semi-automated method of simulated sub-model creation based on Pyrosim and IFC

2.2 Semantic enrichment requirement analysis and execution

To determine the requirements for SE, a comprehensive analysis of relevant Chinese building design codes pertaining to building fire protection has been carried out. The primary SE indicators are listed in Table 1.

Table 1: Primary semantic enrichment requirements from different dimensions

Dimension	Primary indicators	Example	Possible methods
Semantic dimension	Mapping between IFC entity types and regulatory terminologies	Mapping between IfcDoor and fire door	Rule-based reasoning
	Attribute statements of building entities	Fire resistant rating of fire door	
	Relations creation between building entities	Connectivity between rooms	
	Calculation of building entities	Numbers of escape exits	
Geometric dimension	Area of building entities	Area of fire compartment	Geometric calculation
	Escape route	Distance of evacuation path	
Simulated dimension	Fire development	Temperature, visibility, smoke	Fire dynamic simulation
	Fire evacuation	Evacuation time	Evacuation simulation

In the semantic dimension, the SE requirements aim to enhance the semantic meanings of building models through several key aspects, including terminology mapping, attribute specification, relationship establishment, and numerical computation. Given that the semantic dimensional representation is structured as a knowledge graph, rule-based reasoning can be effectively employed to accomplish the SE process (Jiang et al. 2022b).

From the geometric dimension perspective, geometric calculations based on geometric objects can be performed. These calculations serve to enrich the building model by determining the areas of building entities and the properties of escape routes, which are crucial for safety assessment.

Regarding the simulated dimension, both fire dynamic simulations and evacuation simulations are indispensable. These simulations are essential for obtaining indicators that reflect fire development and evacuation scenarios, which play a vital role in the performance-based design of building fire protection.

2.3 Semantic enrichment results integration

The integration of SE results is achieved through knowledge fusion based on BIMKG. In this process, the SE results from the semantic dimension are incorporated as novel facts into the BIMKG subsequent to rule-based reasoning. For the geometric dimension, the SE results are integrated into the BIMKG by introducing a sub-structural representation. As shown in Figure 7, because the geometric dimensional SE results not only establish connections with building entities but also hold specific numerical values, new nodes, which are linked to the BuildingEntity via the "relatedTo" relationship and to the ValueNode through the "hasValueNode" relationship, are created in BIMKG.

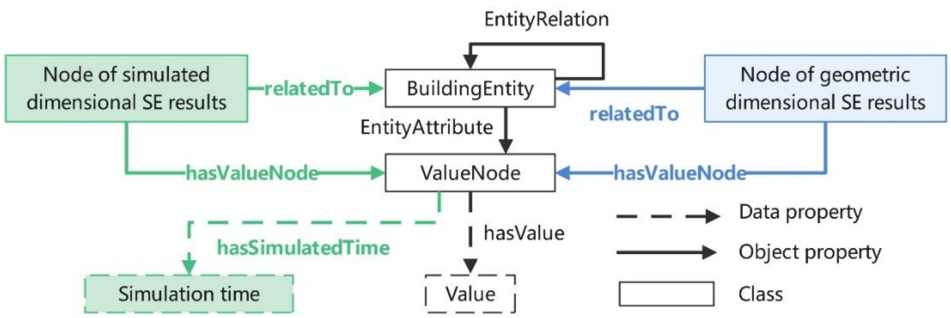

Figure 7 Integration of geometric and simulated dimensional semantic enrichment results base on BIMKG

The approach mentioned in Mulatibieke et al. (2022) is used for reference to achieve the integration of the simulated dimensional SE results. Information extraction techniques are applied to the simulation files to parse the essential SE information which is then treated as new triples in the BIMKG. The simulation results are also represented as new nodes that are associated with both the BuildingEntity and the ValueNode. Additionally, considering the temporal characteristics of the simulation results, the simulation time is defined as a data property of the instances of ValueNode related to nodes of simulated dimensional SE results.

3. CASE STUDY AND IMPLEMENTATION

To validate the proposed methodology, a small case study is carried out on a small building model created by Revit 2022. The test model is transformed into an IFC-SPF in accordance with the IFC4 schema. The clauses as presented in Table 2 are selected to verify the proposed approach.

Table 2: Selected clauses used to verify proposed approach

No.	Code	Clause content
#1	General code for fire protection of buildings and constructions (GB 55037—2022)	7.4.2 In public buildings, for rooms equipped with only one exit door, the straight-line distance from any point within the room to the exit door shall not exceed 15m, and the net width of the exit door shall not be less than 1.40m.
#2	Technical standard for smoke management systems in buildings (GB51251-2017)	4.6 It is to calculate the area of the natural smoke exhaust window (or outlet), which is equal to the calculated exhaust smoke volume divided by the wind speed at the natural smoke exhaust window (or outlet).

The process of sub-model conversion and relationship establishment is implemented using Python. A set of essential packages, such as ifcopenshell, pythonOCC, and rdflib, are employed during the process. The converted BIMKG, also known as the basic sub-model, is serialized in the Turtle format. The extracted geometric objects are saved in the STL（Standard Tessellation Language）format and linked to BIMKG by documenting the storage position of the geometry files, as depicted in Figure 8. The simulated sub-model, generated by Pyrosim, is linked to BIMKG through the names of building elements. The input parameters of the FDS file are revised based on information extraction from the BIMKG. For example, the definitions of doors and windows are modified from "OBST" to "HOLE" in the simulated sub-model. Additionally, while the code offers empirical formulas for calculating the exhaust smoke volume, a more accurate exhaust smoke volume can lead to a superior design. Consequently, a flow measuring device, positioned at the opening of the external window, is defined in the FDS file.

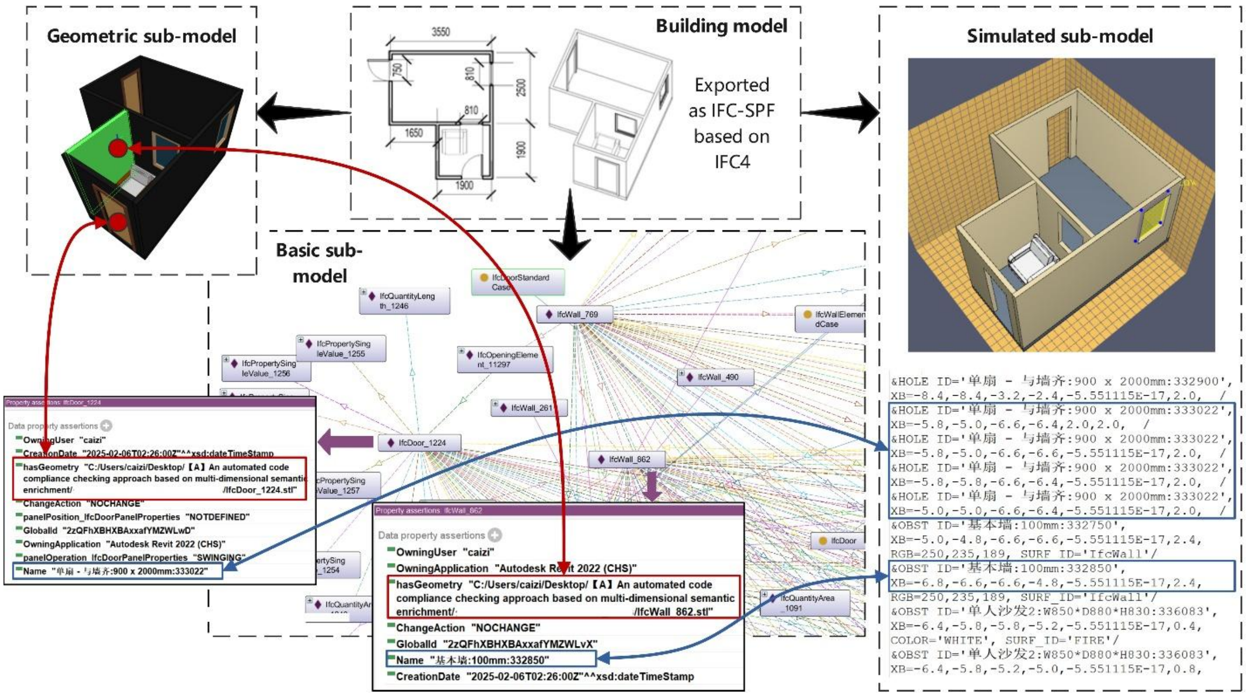

Figure 8. Linkage among three sub-models

By analyzing the clause text, the Jena rules (a kind of production rule used for semantic web-based reasoning) as outlined in Table 3 are used to achieve the semantic dimensional SE.

Table 3: Jena rules used to achieve semantic dimensional SE

Jena rules	SE requirements
[rule: (?x rdf:type ifc:IfcSpace)(?y rdf:type ifc:IfcDoor)(?x ifc:IfcRelSpaceBoundary ?y) -> (?x ifc:has ?y)]	Relation creation between IfcDoor and IfcSpace
[rule: (?x rdf:type ifc:IfcDoor) -> (?x rdf:type ifc:ExitDoor)]	Terminology mapping between IfcDoor and exit door
[rule: (?x rdf:type ifc:ExitDoor)(?x ifc:width ?vn)(?vn core:hasValue ?v) -> (?x ifc:netWidth ?v)]	Attribute statements of exit door

Regarding the geometric dimensional SE, the longest straight-line distance from any point inside the room to the exit door is computed based on the geometric sub-model. Initially, all the vertices of the room's geometric shape and the midpoints of the associated doors are extracted. Subsequently, distance calculations are performed between each combination of a vertex and a midpoint. Among these calculated distances, the maximum value is selected as the result of the geometric dimensional SE. The integration of the geometric dimensional SE is illustrated in Figure 9. The longest straight-line distances of the two rooms are calculated to be 3.90 meters and 2.15 meters, respectively.

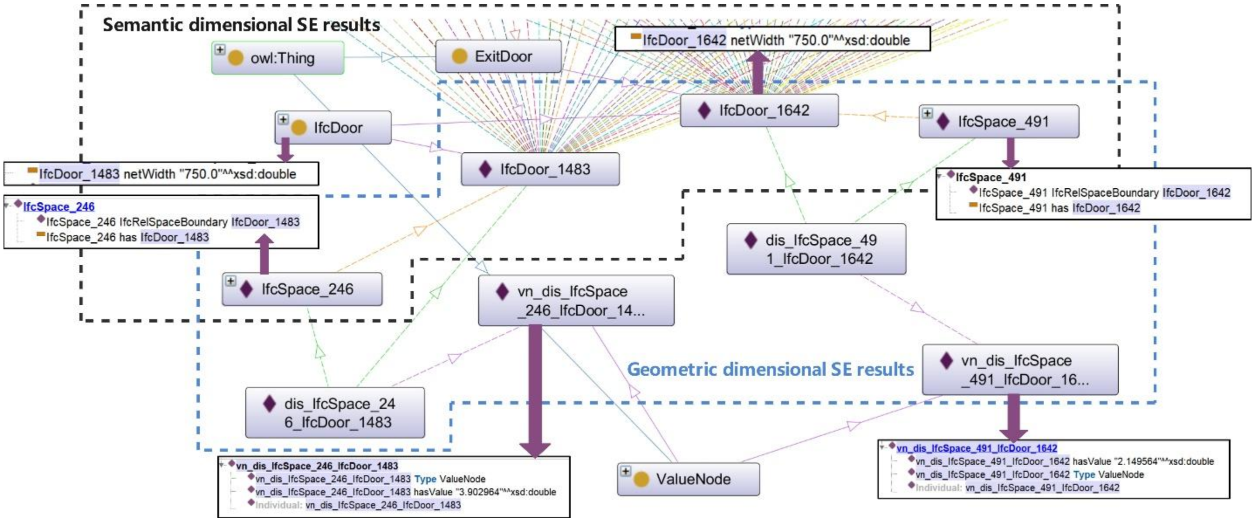

Figure 9. Integration of semantic and geometric dimensional semantic enrichment results in BIMKG

The simulation results are saved in the CSV file format. In accordance with the schema described in Section 2.3, the information extracted from each row of the CSV file is considered as a new fact within the context of the BIMKG. As depicted in Figure 10, the volume flow rate of the room represented by IfcSpace_246 passing through the external window identified as IfcWindow_1873 attains a value of 0.592m^3/s at 30.9s.

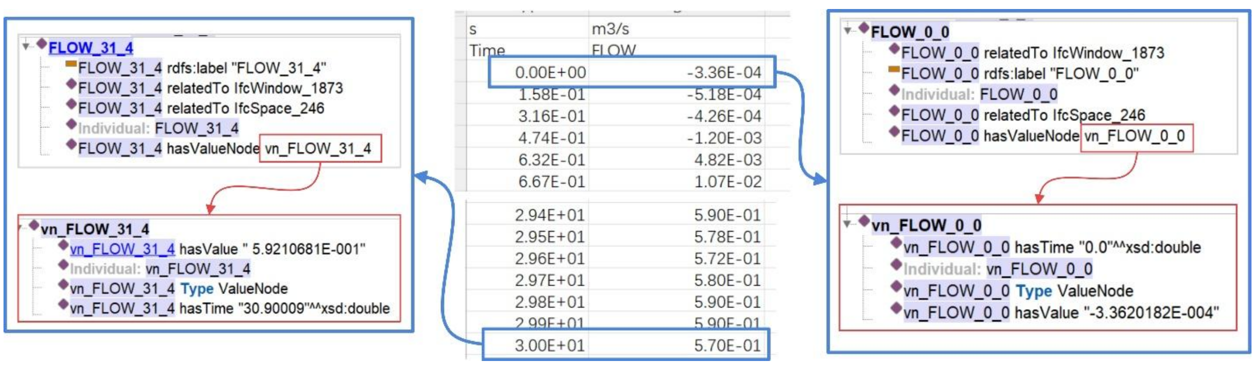

Figure 10. Integration of simulated dimensional semantic enrichment results in BIMKG

Table 4: SPARQL queries used for automated code compliance checking

No.	SPARQL query

Q1	SELECT DISTINCT ?a WHERE {
	?dis rdf:type ifc:distanceRoomToDoor . ?dis ifc:relatedTo ?a . ?dis ifc:relatedTo ?b .
	?a rdf:type ifc:IfcSpace . ?b rdf:type ifc:ExitDoor . ?a ifc:has ?b .
	FILTER NOT EXISTS { ?d1 rdf:type ifc:ExitDoor . ?a ifc:has ?d1 . FILTER (?b = ?d1)}
	?dis ifc:hasValueNode ?vn. ?vn core:hasValue ?v. FILTER (?v > 15)
	}

Q2	SELECT DISTINCT ?a ?b WHERE {
	?a rdf:type ifc:IfcSpace . ?b rdf:type ifc:ExitDoor . ?a ifc:has ?b .
	FILTER NOT EXISTS { ?d1 rdf:type ifc:ExitDoor . ?a ifc:has ?d1 . FILTER (?b = ?d1)}
	?b ifc:netWidth ?v. FILTER (?v < 1400)
	}

On the basis of the enriched BIMKG, SPARQL queries formulated in accordance with specific clauses can be employed to carry out the subsequent ACCC process. For example, Clause #1 in Table 2 can be interpreted as a set of SPARQL queries as presented in Table 4. Both the queries are designed with the objective of identifying rooms that possess only a single exit door, leveraging the "FILTER NOT EXISTS" constraint. Additionally, Query Q1 is utilized to retrieve the rooms within which the straight-line distance from any point to the exit door is larger than 15m, and Query Q2 is utilized to retrieve the doors whose net width is less than 1.40m and the associated rooms.

The rule checking process is implemented using a Java framework tailored for semantic web applications, namely Apache Jena. The checking results are presented in Figure 11. As depicted, all the rooms have passed the distance check, but the net width of the doors could not meet relevant regulatory requirements.

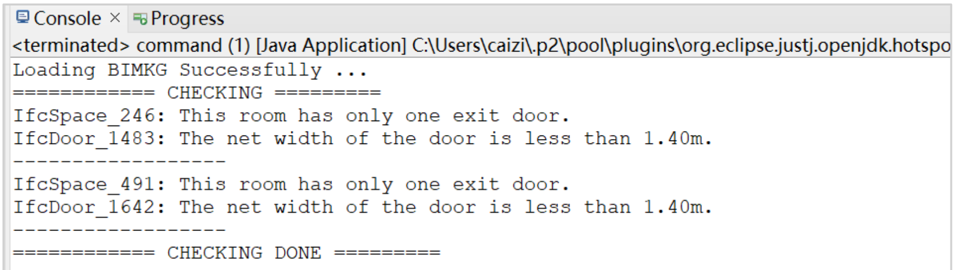

Figure 11. Results of automated code compliance checking of building fire protection

4. CONCLUSIONS AND FUTURE WORK

Code compliance checking of building fire protection plays an important role in ensuring building design quality and safety. The preparation of the building model is an indispensable step during the process of BIM-based ACCC. To enhance the integrity of the building model, a multi-dimensional SE method based on IFC and knowledge graph technology is proposed for BIM-based ACCC of building fire protection in this paper. The proposed approach takes into account three key aspects of SE, i.e., semantic dimensional SE, geometric dimensional SE, and simulated dimensional SE. Corresponding to these three dimensions, three interconnected sub-models are constructed based on IFC-SPF. With these sub-models as the foundation, various SE techniques can be applied, such as rule-based reasoning for the semantic dimension, geometric calculations for the geometric dimension, and simulation analysis for the simulated dimension. Furthermore, the SE results obtained from different dimensions can be integrated based on a knowledge graph. The knowledge graph can serve as a unified and fused data model for the subsequent rule checking stage, enabling the integration of multi-source and multi-format SE information.

The proposed method could address three pain points in current industry practice: (1) the interoperability challenge of BIM models and simulation data, (2) the semantic ambiguity between BIM models and domain knowledge, and (3) the automation potential of code compliance checking based on BIM. To further improve the proposed approach, future research efforts are essential to enhance its efficiency and broaden its applicability. On the one hand, in terms of technical implementation, the automated conversion process between IFC and FDS demands more in-depth exploration and refinement. On the other hand, regarding its application scope, the utilization of the proposed approach in the performance-based design of building fire protection, which takes into account both fire simulation and evacuation simulation, represents a significant area that warrants thorough investigation.

To demonstrate the practical feasibility and effectiveness of the proposed approach, a case study has been carried out. The findings from this case study provide evidence of the approach's potential to enhance the accuracy and efficiency of BIM-based ACCC in building fire protection applications. On-site fire experiments and systematic optimization of engineering applications in combination constitute critical future work to enable industrial adoption. Furthermore, the proposed multi-dimensional SE framework could be regarded as a modular system applicable to diverse engineering scenarios. For example, correlations between seismic simulation results and the building model can be established via the simulated dimension SE, thereby enabling automated structural design through iterative optimization algorithms. During the building operation and maintenance phase, integrating BIM with multi-source heterogeneous sensing data through the proposed multi-dimensional SE method could form the data foundation for realizing a digital twin of the building.

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