Automatic BIM Model Auditing for Quantity Take-off Using Knowledge Graph Techniques

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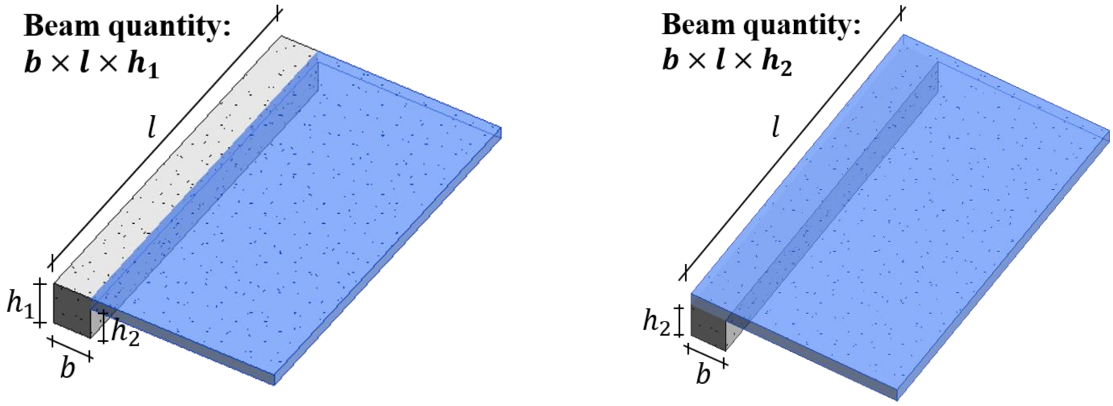
Abstract. Building Information Modeling (BIM) models require sufficient semantic information and consistent modeling style to conduct Quantity Take-off (QTO) smoothly. However, BIM models created by different BIM modelers may have various mistakes about these requirements and auditing such BIM model behavior involves tremendous human effort for manual inspection or the development of rule sets. This study proposes an automatic and efficient BIM model auditing framework for QTO utilizing knowledge graph (KG) techniques. It begins at establishing a BIM-KG definition via identifying required information for auditing purposes. Subsequently, BIM data is automatically transformed into the BIM-KG representations, the embeddings of which are trained using a knowledge graph embedding model. Automatic mechanisms are then developed to utilize the computable embeddings to effectively identify mistake BIM elements. The framework is validated using illustrative examples and the results show that 100% mistake elements can be identified successfully without human intervention.

1. Introduction

Quantity take-off (QTO) is a critical process that measures required quantities to build construction projects from design documents [1]. Traditionally, it is time-consuming and error-prone as it requires quantity surveyors to manually interpret 2D drawings and calculate results based on predefined rules in measurement standards [1]. With the development of Building Information Modelling (BIM), this process has been revolutionized as quantities can be automatically extracted from 3D models [2]. Therefore, the BIM-based QTO can provide more automatic and accurate estimation of quantities than the 2D drawing-based method [2].

In order to obtain accurate quantities that are compliant with measurement standards under the BIM-based method, BIM models need to be created in a consistent way according to specifications on modelling styles and semantic information [3]. Figure 1 (a) and (b) shows how the inconsistent modelling styles lead to inconsistent quantities from BIM models. According to the Hong Kong Standard Method of Measurement (HKSMM) [4] where the major measurement logic is similar to that in commonwealth countries (the UK, Singapore, etc.), either may be correct, depending on the concrete grade information. As shown in Figure 2, if the beam has a different concrete grade than the slab, it is measured through the slab (i.e., $b \times l \times h_1$); otherwise, it is measured to the soffit of the slab (i.e., $b \times l \times h_2$). In this example, all the beam-suspended slab joints in the BIM model should be created in either of the ways but consistently to enable easy adjustments for the output quantities to achieve accurate QTO. In addition, as Figure 2 shows, BIM models should contain sufficient semantic information such as concrete grade so that the QTO process can be conducted successfully.



(a). Beams take precedence over slabs (b). Slabs take precedence over beams

Figure 1. Inconsistent modelling styles for a beam-suspended slab joint [5]

CLASSIFICATION TABLE					MEASUREMENT RULES
18. **Suspended slabs** 19. **Coffered and troughed slabs**			m^3	1. Horizontal 2. Sloping ≤ 15° 3. Sloping > 15°	M.12 The measurement of suspended slabs is taken across columns and beams, except where the columns or beams are of a different mix.

Figure 2. Measuring slab quantities in HKSMM [4]

Nevertheless, it is not uncommon to see different BIM modelers using different methods of modelling in practice [3], resulting in different modelling styles for the same thing. In addition, they are not as aware of the importance of the required information in BIM models for QTO as quantity surveyors are. Therefore, it is necessary to audit BIM model behaviour (i.e., modelling style and semantic information) against agreed specifications. For this purpose, previous studies mainly explored ways that formulate systematic frameworks utilizing different software tools such as Autodesk Revit and Solibri Model Checker to ensure BIM models contain required semantic attributes [6] and satisfy layout and geometry constraints [7]. However, this is essentially a checklist-based way that relies on predefined rule patterns and external software tools. Developing such rule patterns involves considerable effort from domain experts, which is a labour-consuming process.

In this study, we explored a knowledge graph (KG)-based approach to this BIM model auditing problem. In simple terms, a KG is comprised of nodes that represent entities or concepts and edges that represent various relationships between them. Such a representation technique provides new insights to represent and analyse BIM information that inherently contains heterogeneous entities and relationships explicitly and automatically. For example, it can be utilized to express the semantic information and relationships (e.g., connectivity, containment) in BIM models for efficient topological queries [8]. The graph representation form can also support generative building design in BIM through representing spaces as entities and adjacencies as relationships [9]. Thus, there may be values in developing automatic and efficient KG representation, manipulation and inference mechanisms for the BIM model auditing, where the potential of KG has yet to be appreciated.

2. Methodology

Figure 3 presents an overview of the proposed methodology. Knowledge from QTO-related BIM modelling specifications is leveraged to identify the requirements on semantics and topology etc. to establish a BIM-KG definition. Following this, the gold BIM model is defined as a BIM model that has sufficient semantic information and consistent modelling style according to the requirements. Based on the BIM-KG definition, BIM model information of interest is automatically transformed from a gold BIM model to BIM-KG instances. A knowledge graph embedding model is then used to get the embeddings for them. For the new BIM model to be audited, the corresponding new BIM-KG instances are generated and scored. The scores are compared with a threshold to decide on the auditing results (i.e., accept/reject). In this study, BIM Model Information Requirements for Quantity Take-off (BIM MIR for QTO) [10] is selected as an example BIM modelling specification for illustration.

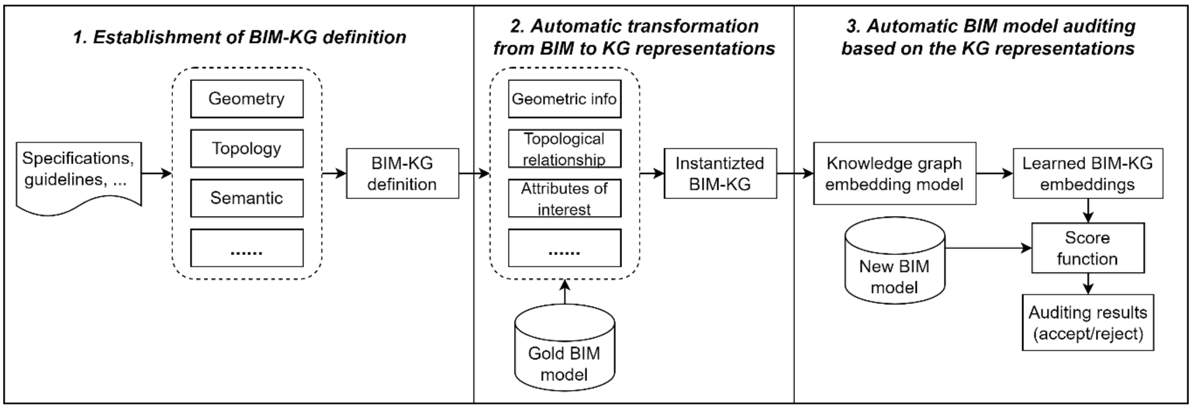


Figure 3. Overview of the proposed methodology

2.1. Establishment of BIM-KG definition

Regarding the scope, typical building elements (i.e., slab, beam, column, wall) are selected for illustrative purposes. Figure 4 shows the details of the BIM-KG definition. Each element should specify the *type* and contain certain properties (e.g., *concrete grade*) to perform QTO logic. As shown in Figure 1, different modelling styles come from different topological arrangement relationships between elements. Such information in represented through introducing the *contact_with* relationship that associates element faces (i.e., *top*, *side*, *bottom*) with other elements. Of note is that the element entity can be a real element or empty since elements and their faces may not join/contact with anything. To construct this BIM-KG, triples in the form of <*head, relation, tail*> (e.g., <*beam_top, contact_with*, *slab_123*>) with auxiliary information (e.g., levels of the elements) are generated from the BIM models, which is introduced in the next section.

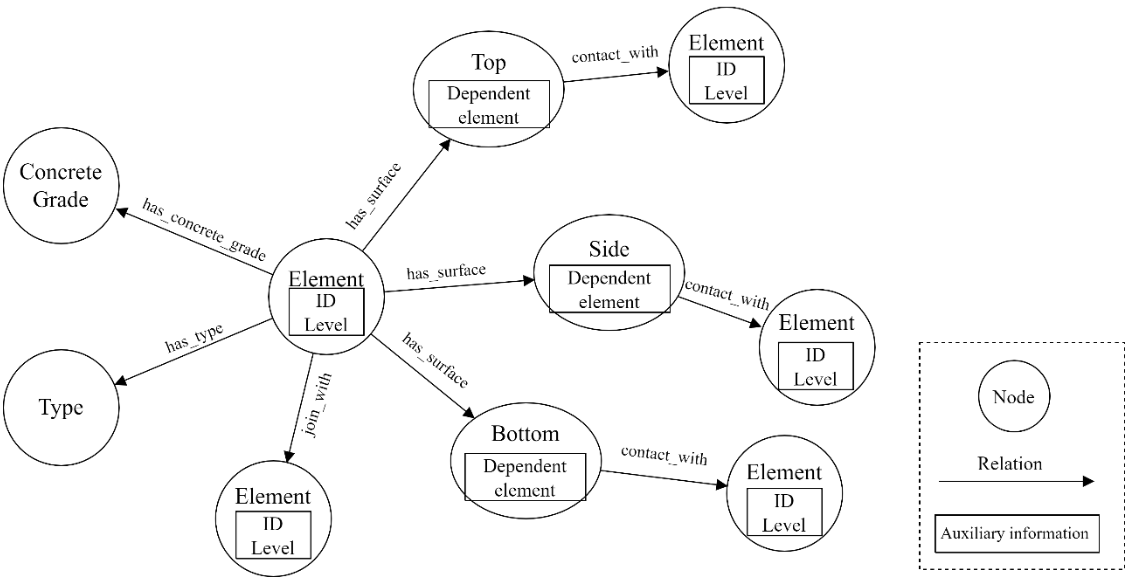


Figure 4. BIM-KG definition for QTO-oriented BIM model auditing

2.2. Automatic transformation from BIM to KG representations

With respect to the BIM-KG definition in Section 2.1, BIM data is transformed into BIM-KG triples to construct the BIM-KG. The semantic attributes and joining elements are extracted directly from BIM models to generate triples about semantic information and element connectivity such as *<beam_123, has_concrete_grade, empty>* and *<beam_123, join_with, slab_234>*. The generation of triples related to the topological contact information between elements is based on [5]. The details are illustrated in Figure 5 with *beam_123* as an example. The faces of the element are extracted and thickened on both sides. Intersection checking is performed between the corresponding generated solids and other elements to detect the elements in contact with the faces. As a result, triples such as *<beam_side, contact_with, slab_234>* and *<beam_side, contact_with, empty>* are obtained. Finally, these triples form the base of the BIM-KG for model auditing.

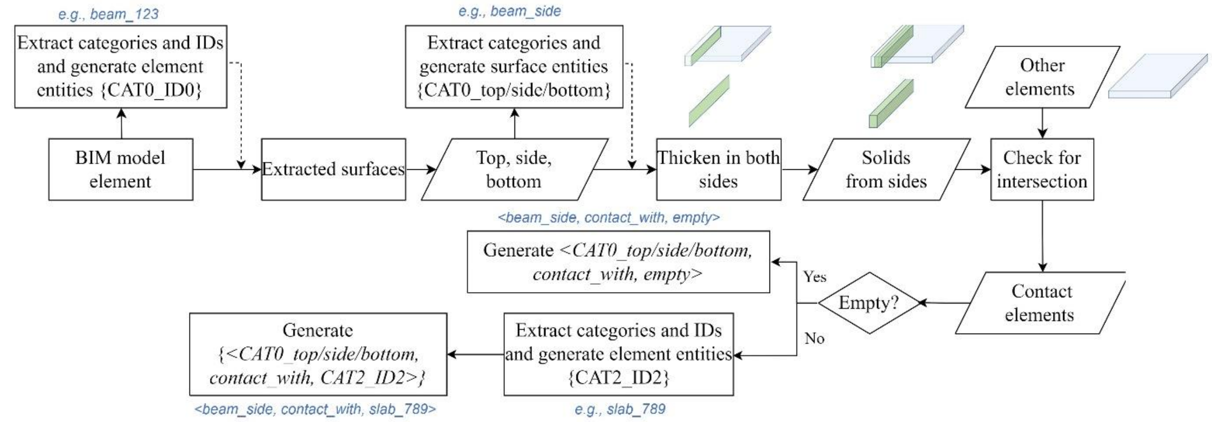


Figure 5. Mechanism to transform BIM data to KG triples

2.3. Automatic BIM model auditing based on the KG representations

2.3.1. Knowledge graph embedding model to obtain KG embeddings. After the gold BIM-KG representations are generated from the gold BIM model, a knowledge graph embedding model is used to train the embeddings for the entities and relations. Knowledge graph embedding is a technique that converts entities and relations in a KG to vector representations. For this purpose, TransR [11] is a representative model. It embeds the entities and relations in the real vector space, following the translational distance-based principle (i.e., $\vec{h}+\vec{r}\approx\vec{t}$ if (h,r,t) holds). The entities are embedded in the same space while different relations are embedded in different relation spaces. Projections matrixes for different relations are introduced to project the entity embeddings into the relation-specific spaces for scoring, as shown in equations (1) – (2), where $\vec{h}$ and $\vec{t}$ are the embeddings of the head and tail entities, respectively, M_r is the relation-specific projection matrix, $\overrightarrow{h_\perp}$ and $\overrightarrow{t_\perp}$ are the corresponding projected embeddings of head and tail entities. The embeddings and projection matrixes are initialized randomly and then iteratively optimized to favor high scores for triples that hold in the KG (i.e., make $\overrightarrow{h_\perp}+\vec{r}\approx\overrightarrow{t_\perp}$) and low scores for those that do not appear in the KG. The scoring function is defined based on the Euclidean distance, as shown in equation (3), where $\vec{r}$ is the embedding of the relation, and $f(h,r,t)$ is the score of the triple (h,r,t).

$$\overrightarrow{h_\perp} = M_r\vec{h} \quad (1)$$

$$\overrightarrow{t_\perp} = M_r\vec{t} \quad (2)$$

$$f(h,r,t) = -\left\|\overrightarrow{h_\perp} + \vec{r} - \overrightarrow{t_\perp}\right\|_{L_1/L_2} \quad (3)$$

2.3.2. Self-evolving mechanism to determine a proper threshold. In this step, the scores of the triples from the new BIM model to be audited are calculated based on the obtained embeddings and compared with the threshold to determine whether the involved elements in the triples are accepted or rejected. Figure 6 shows the proposed self-evolving mechanism to learn a proper threshold to filter mistake elements. A set of new BIM models to be audited with different mistakes is used to develop the threshold iteratively. Each set of triples from each new BIM model are scored using the scoring function shown in equation (3). A triple is accepted if its score is greater than the current threshold, meaning that the involving elements are classified as correct. Based on the classification results, TP (True Positive, i.e., mistake elements classified as mistaken), FN (False Negative, i.e., mistake elements classified as correct), FP (False Positive, i.e., correct elements classified as mistaken), and TN (True Negative, i.e., correct elements classified as mistaken) are derived. Then, the sensitivity and specificity that measure how many truly mistake and correct elements are classified as mistakes and correct respectively are calculated according to equations (4) - (5). Subsequently, the threshold is iteratively updated with respect to equation (6), as follows:

$$Sensitivity = TP/(TP + FN) \tag{4}$$

$$Specificity = TN/(TN + FP) \tag{5}$$

$$\theta = \theta_0 + \lambda(f(h, r, t)_{max} - f(h, r, t)_{min}) - \gamma(f(h, r, t)_{max} - f(h, r, t)_{min}) \tag{6}$$

$$\lambda = \lambda + \lambda_0(1 - sensitivity) \tag{7}$$

$$\gamma = \gamma + \gamma_0(1 - specificity) \tag{8}$$

where θ is the learned threshold and θ_0 is the initial one, λ is the introduced adjusting factor to increase the threshold to filter mistake elements as much as possible, γ is the introduced penalty factor to decrease the threshold to avoid reporting correct elements as mistake ones, and $f(h, r, t)_{max}$ and $f(h, r, t)_{min}$ are the maximum and minimum scores of the triples from the gold BIM model, respectively. λ and γ are also obtained iteratively and dynamically according to equations (7) – (8), where λ_0 and γ_0 are the initial values, respectively.

Finally, if the average sensitivity and specificity over the BIM models in the development set meet certain criterions, the average threshold is regarded as the final one. Otherwise, another epoch is conducted to further optimize the threshold until the criterions are satisfied or the number of epochs reaches the limit.

3. Illustrative examples

The proposed framework is validated through identifying different kinds of mistake elements in BIM models created by Autodesk Revit 2021. Dynamo 2.10 is utilized to transform BIM data into BIM-KG tiples. The BIM-KG entities and relations are stored in Neo4j Community Edition 4.3.2. The transR model is implemented with Python 3.7.10 and PyKEEN 1.5.1.dev0 [12]. Other BIM modelling auditing mechanisms described in Section 2.2 are also built with Python 3.7.10.

3.1. Configurations of BIM models

As shown in Figure 7 (a), a gold BIM model is prepared with respect to the BIM MIR for QTO, meaning that it contains sufficient semantic information (e.g., type, concrete grade) and consistent modelling style (vertical elements (i.e., columns and walls) take precedence over horizontal elements (i.e., slabs and beams); slabs take precedence over beams). In addition, 6 BIM models are regarded as the new BIM models to be audited, as shown in Figure 7 (b) – (g). They are prepared to cover common types of building structures (i.e., frame structure, shear wall structure, shear wall-frame structure) and different mistakes (i.e., insufficient semantic information, different inconsistent precedencies between elements). Models B – E are used for the development of a proper threshold, while models F and G are for the testing purpose.

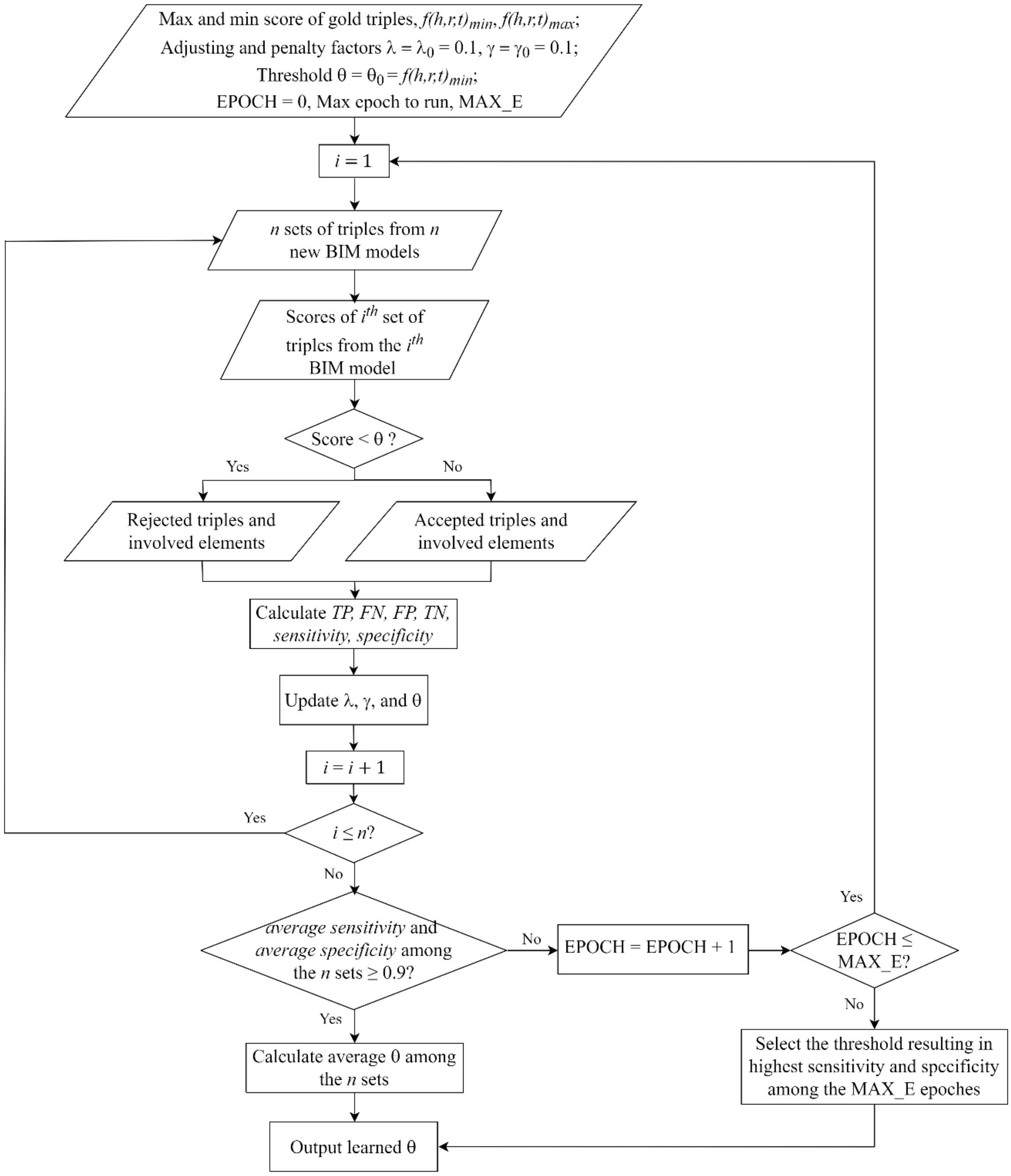
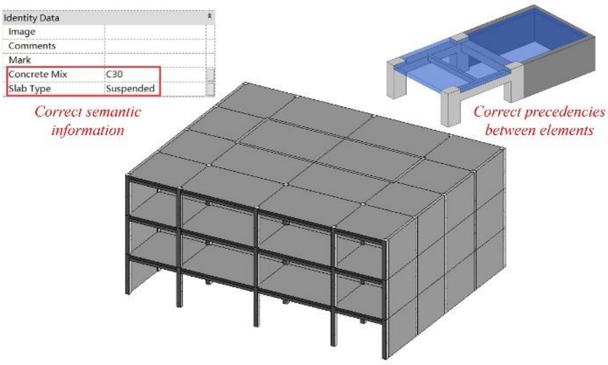
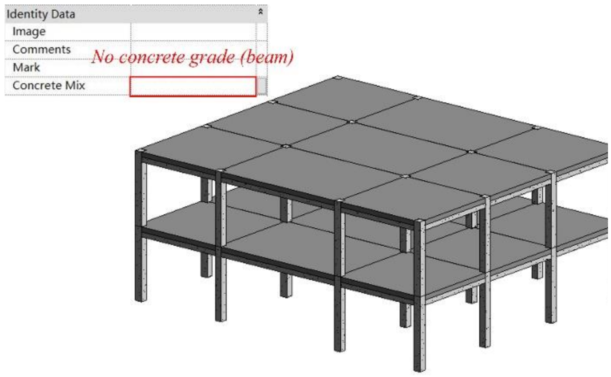


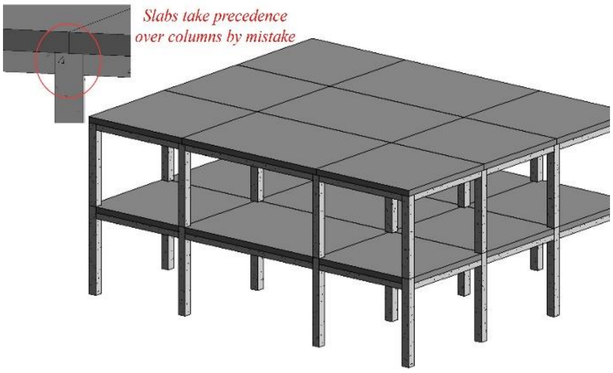
Figure 6. Mechanism to determine a proper threshold



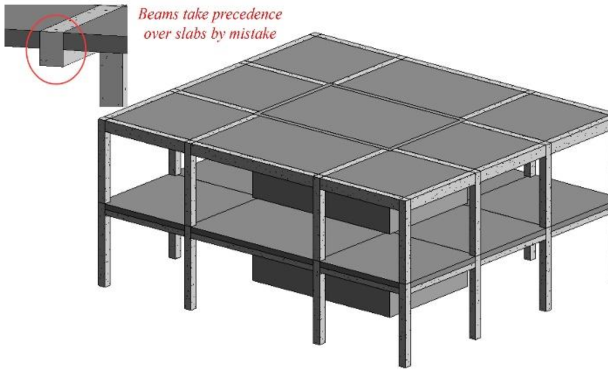
(a) Model A – Gold BIM model



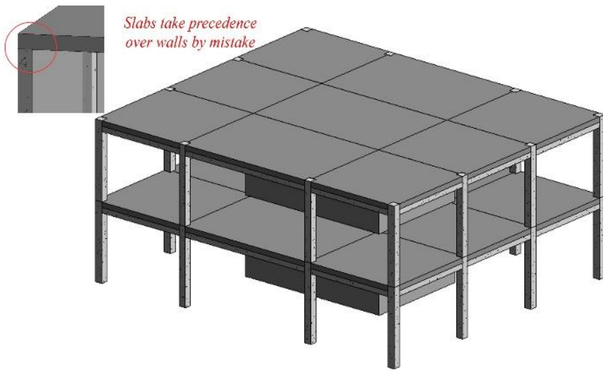
(b) Model B



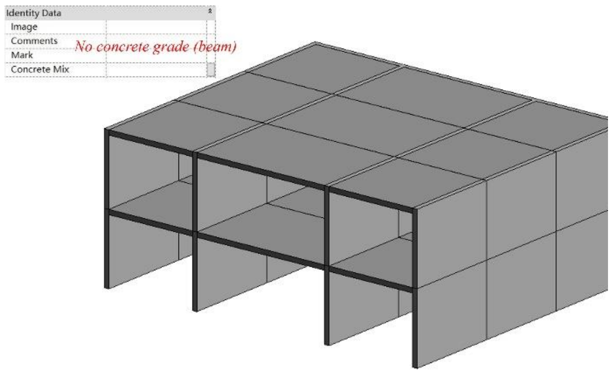
(c) Model C



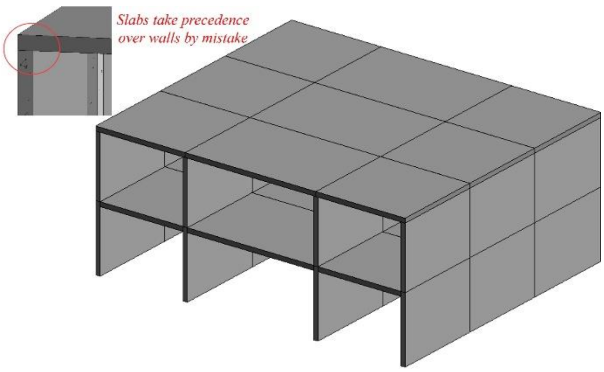
(d) Model D



(e) Model E



(f) Model F



(g) Model G

Figure 7. BIM model configurations

3.2. Automatic transformation from BIM to KG representations

A Dynamo program was developed to examine the BIM-KG transformation mechanism in Section 2.2. As shown in Figure 8, BIM-KG fact triples in the form of <*head*, *relation*, *tail*> are obtained from the gold BIM model automatically, whose embeddings are trained for the computation of mistake elements in the subsequent step.

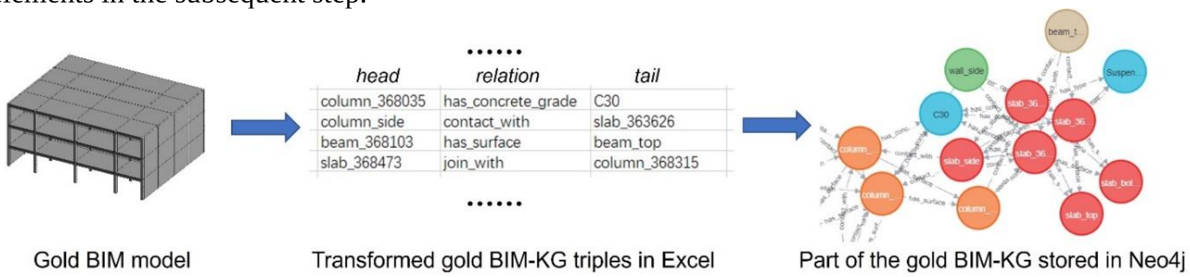


Figure 8. Examples of BIM-KG transformation

3.3. Automatic BIM model auditing based on the KG representations

The TransR model in Section 2.3.1 is utilized to train the gold BIM-KG fact triples to obtain the embeddings of the entities and relations. Figure 9 presents examples of the obtained embeddings.

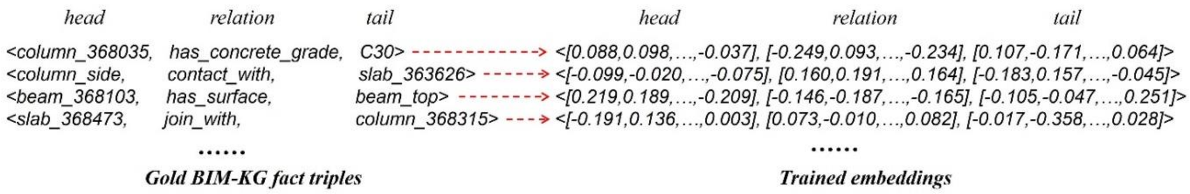


Figure 9. Examples of trained embeddings

Then, models B – G are utilized to learn a proper threshold. The threshold finally converges to -2.6169 through updating in iterations according to the mechanism in Section 2.3.3. Afterwards, the comparison between the triple score and the threshold shown in Figure 10 can be undertaken to identify mistake elements.

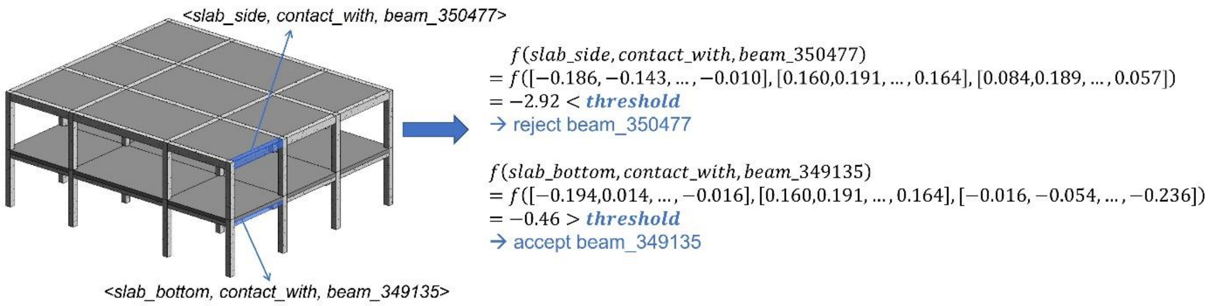


Figure 10. Examples of scoring BIM-KG triples to obtain auditing results

Finally, the unseen models F and G are used to for evaluation. Similarly, BIM-KG triples are first obtained from these testing models. The embeddings for the new entities and relations are derived and then utilized to compute triple scores, which are compared with the learned threshold (i.e., -2.6169) to classify the mistake and correct elements. On average, 100% sensitivity and specificity are achieved over the two testing BIM models, indicating that all the mistake and correct elements are identified successfully. In this case, BIM model designers can be effectively informed of all the mistake elements before delivering the models.

4. Conclusion

In this paper, the information requirements of BIM model auditing for QTO purposes are identified in order to establish a BIM-KG definition, based on which a transformation mechanism is developed to obtain BIM-KG triples from BIM models automatically. A knowledge graph embedding model is utilized to determine embeddings of the BIM-KG entities and relations. A scoring function is used to score the embeddings of the triples from new BIM models to be audited. A self-evolving mechanism is developed to learn a proper threshold so that the scores are comparable to accept or reject elements without human intervention. Six BIM models are used for illustration. The results validate the effectiveness of the approaches through automatically and successfully identifying mistake elements in BIM models with different kinds of errors. Overall, this study contributes to the following:

• This study utilizes BIM models as training sources to obtain computable embeddings so that the underlying patterns among BIM data can be captured. Such a data-driven manner enables automatic and efficient identification of mistake elements without human intervention.

• This study brings insights on improving the efficiency of auditing BIM models for QTO in a fundamental way, through BIM data representation (i.e., the design of BIM-KG representation and transformation mechanisms) and manipulation (i.e., the development of BIM-KG utilization mechanisms to get auditing results). The basic principles are generalizable on this problem and thus this study provides a reliable foundation.

This study is not free from limitation. The adopted knowledge graph embedding model ignores the imbalance of relations (i.e., numbers of triples/entities connected by different relations differ significantly) in the BIM-KG. For example, the relation *contact_with* connects at least three times as many triples/entities as *has_type* does in this paper. Further improvements for it are needed to consider such BIM-KG characteristics so that the obtained embeddings have higher quality to better distinguish correct and mistake BIM-KG triples and elements before this study is applied to more complex BIM models. In addition, this study only covers the requirements on semantic information and modelling style for a limited number of BIM models. Auditing other kinds of requirements and more BIM models can be considered in future work to make the proposed methods more comprehensive.

5. References

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