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Model Validation for Automated Building Code Compliance Checking

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ABSTRACT

To allow full automation of building code compliance checking with different building design models and codes/regulations, input building design models need to be automatically validated. Automated architecture, engineering, and construction (AEC) object identification with high accuracy is essential for such validation. For example, in order to check egress requirements, exits of a building (and their presence or absence) need to be identified automatically through object identification. To address that, the authors propose a new AEC object identification algorithm that can identify needed code checking concepts from building design models based on the invariant signatures of AEC objects, which consisted of Cartesian points-based geometry, relative location and orientation, and material mechanical properties. Building design models in industry foundation classes (IFC) format are processed into invariant signatures, which can fully represent the model data and convert them into computable representations to support automated compliance reasoning. A systematic implementation of the above invariant signatures-based object identification algorithm can be used to automatically conduct building design model validation for code compliance checking preparation. An experimental testing on Chapters 4 and 8 of the International Building Code 2015 and a convenience store design model showed the model validation using the proposed identification algorithms successfully validated ceiling and interior door concepts. Comparing to the manual validation used in current practice, this new object identification algorithm is more efficient in supporting model validation for automated building code compliance checking.

INTRODUCTION

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Building information modeling (BIM) helps save time and reduce errors compared to the traditional approaches in different tasks in the architecture, engineering, and construction (AEC) domain (Sacks et al. 2018). BIM is believed to be the future of the AEC domain (Azhar 2011). For the task of automated compliance checking (ACC) of building codes, information conversion and communication are expected to be more efficient and effective with BIM. Comparing to the traditional method, where the compliance checking is manually performed by human workers, BIM-based ACC is expected to save time, reduce cost, and generate less errors (Nguyen and Kim 2011). Towards the goal of full automation in ACC, research has been conducted in different sub-tasks. For example, Tan et al. (2010) presented a new method to extend BIM for simulation to support ACC of building envelope design. For knowledge representation of ACC, Yang and Xu (2004) implemented a Java-based system to represent objects in BIM for the purpose of ACC, in a distributed online environment. Zhang and El-Gohary (2016a) proposed to incorporate building code concepts into the industry foundation classes (IFC) schema (BuildingSMART 2018) by extending the IFC standard with concepts from the International Building Code. For information matching, Xu and Cai (2020) proposed to use ontology-based modeling to store information in building information models (BIMs), which are represented by spatial constraints, and then map them to building code requirements.

While significant results have been achieved, the goal of seamless full automation in ACC has not been realized. One of the main challenges is in information extraction, conversion, and matching from BIMs to building codes. As one of the most promising BIM data standards, IFC still does not provide full support for building code information coverage for the task of ACC (Zhang and El-Gohary 2016b). There is a need for seamless linkage to connect the IFC models to the requirements in building codes.

Although there are concepts (e.g., door) that can be found a direct match in IFC standard (e.g., *IfcDoor*), the majority of concepts (e.g., egress, fire door, ceiling) in building codes cannot be directly matched to IFC entities. For the concepts that can be directly matched to IFC, information extraction and mapping can be performed straightforwardly by linking a concept to the corresponding IFC entity. However, for the concepts that cannot be directly matched, a more systematic investigation is needed to enable the automated extraction and mapping of such information. For example, ceiling is a common concept in building codes. While the IfcRoof can be used to represent ceiling objects in a BIM model, some ceilings may not be represented directly, e.g., a two-story building may only have one roof on the second floor, so the ceiling on the first floor is not as directly and explicitly represented. However, based on inference, the underside of the slab can be considered a ceiling, and therefore should be checked with ceiling requirements in building codes. There is a need to identify such information to support ACC.

In this paper, the authors conducted a review of some of the building code concepts that cannot be directly matched to IFC, and proposed a solution for information mapping of those concepts. As a proof of concept, the authors tested their method in the ceiling concept and interior door concept to show the feasibility.

BACKGROUND

Information exchange in BIMs. In many fields such as computer science and transportation engineering, information extraction and exchange serve important roles and are investigated by

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different researchers (Sarawagi 2008; Yang et al. 2019). Recent research has been using an ontology-based approach to generate more satisfying extraction/exchange results comparing to the use of syntactic features only (Fernández et al. 2011, Yehia et al. 2019, Paliouras et al. 2011, and Wimalasuriya and Dou 2010). In the AEC domain, there is also an increased amount of effort in addressing research gap for information exchange in BIMs. For example, Ding et al. (2017) built a real-time quality monitoring system that used the Industrial Foundation Classes-based Inspection Process Model (IFC-IPM) to realize the quality inspection and was tested to perform well on a real model.

Information exchange plays an even more important role in ACC of building design with building codes, as the whole process relies on information extraction, mapping, and comparison from building design and building code, respectively. For information exchange between building codes and IFC models, Zhang and El-Gohary (2019) used machine learning to map building code concepts and relations to IFC elements and relations. Their result showed an accuracy of 77% in the matching of elements and an accuracy of 78% in the matching of relations, which is representing the state of the art. However, for the goal of full automation in ACC, further improvements in performance are needed. Furthermore, according to the authors' analysis, the direct mapping may only provide limited coverage as many building code concepts do not have a one-to-one direct mapping to IFC entities, instead, a one-to-many, many-to-one, or many-to-many mapping may occur in practical scenarios. New methods need to be investigated to overcome these obstacles to fill the gap of information exchange (extraction and mapping) between building codes and BIMs.

Identification of building components. The information exchange for ACC requires the analysis of code requirements and building components at the instance level. In automated identification of building components, efforts have been made extensively for as-built models. For example, to detect the secondary building components, such as MEP components, Adán et al. (2018) proposed a 6D approach (XYZ+RGB) to recognize objects such as sockets and extinguishers by analyzing the dense 3D points, to identify objects according to color and geometry. The identified objects are positioned into the background model in their last step to create the enriched 3D model. Their method showed a high recognition rate and high position accuracy of the secondary objects. For road tunnel luminary identification, Puente et al. (2014) proposed a four-step automated method using mobile Light Detection and Ranging (LiDAR) technologies. They tested their method in a highway tunnel and achieved 100% accuracy for light detection. For interior partition components detection, Hamledari et al. (2017) proposed a computer vision-based method to process 2D digital images. With four branches of vision-based component detection algorithms according to stud and insulation, they achieved robust results (on average close to 90%) in three image databases.

These existing research efforts have shown extensive and in-depth analysis on the identification of building components for as-built models, where practical results were achieved. However, for as-designed models, there is a lack of similar research efforts, especially in the reasoning of detecting semantic information for inferable building code concepts (e.g., fire door, egress). In contrast to the detection of as-built models, the identification of building code concepts to support ACC has to rely on the information from as-designed BIMs. Nonetheless it can use any information in the as-designed BIMs such as those from other objects, e.g., the relative position between different objects. To achieve full automation, the identification method also needs to produce consistent results across different scenarios.

PROPOSED METHOD

To help achieve seamless information mapping from BIMs to building codes, the authors propose an indirect mapping method by introducing intermediate data representation to improve the mapping process. Instead of (and in addition to) direct mapping, which has limited accuracy and coverage, and is error-prone for many-to-many mappings, the authors' proposed method establishes the intermediate data representation using information from BIMs. Then the mapping is finished using the intermediate data, which contains more information than the original BIMs and can follow a one-to-one mapping approach from there to building code concepts (Figure 1). With this new method, more contextual information is generated through inference, into the intermediate data representation, i.e., the information is extended based on the needs of matching to building codes, and the needs are satisfied by developing rule-based reasoning algorithms. In addition, the new method does not need to extend the IFC schema, which would require modification of the IFC standard that may introduce interoperability problems. It provides a simpler and more practical solution for information mapping compared to extending the IFC schema.

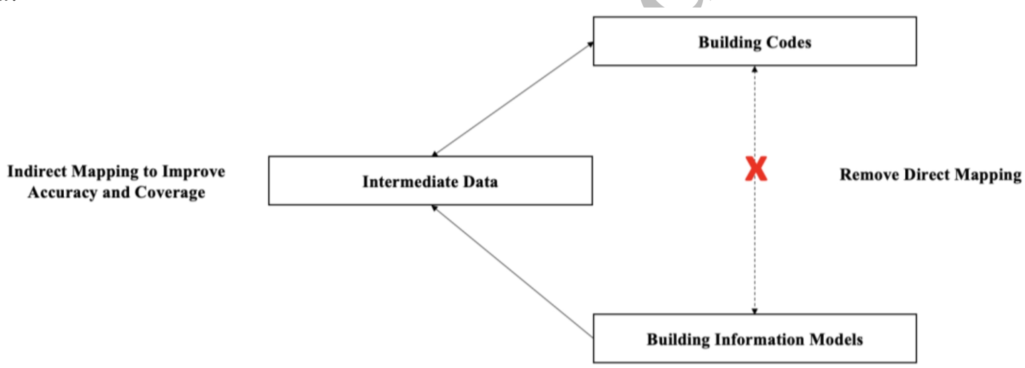

Figure 1. Idea illustration of the proposed method.

The authors proposed three steps in this new method to validate the input IFC-based BIM instance model, which include: (1) Construct invariant signatures from BIMs - extract the information from BIMs and represent this information using invariant signatures, as the intermediate data representation, (2) Generate intermediate data using inference - based on the information need from matching with building code requirements, develop algorithms to conduct logic-based reasoning for extending the information in the intermediate data towards selected concepts in building codes, and (3) Generate logic facts to store information - map the intermediate data to building code concepts and store the mapping result by generating logic facts for each mapped piece.

For Step (1), the state-of-the-art invariant signature analysis algorithms (Wu et al. 2021) can be used to extract and represent information from BIMs. For Step (2), new rule-based identification algorithms are developed to match the target concepts extracted from building codes. For Step (3), algorithms are developed to convert the intermediate information to logic facts in

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form of first order logic (FOL) clauses to store the information, because FOL is commonly used for computer-based logic reasoning.

Through the use of intermediate data and rule-based algorithms, the original building design information is extended with more inferred information, to enable direct validation of BIMs for a better support of information mapping to building codes.

EXPERIMENT

To test the proposed method, the authors collected a model from a real project of a convenience store, a commercial project located in Texas. The project is a one-story building over a slab on grade, with a floor area of 266.56 m^2 and contains 12 rooms and 37 walls. This model was selected because it is simple and therefore suitable for initial testing whereas it is complete, meaning it covers multiple types of building elements, which can satisfy our experimental need. A visualization of the model is shown in Figure 2. For building code, the authors selected International Building Code (IBC) 2015 (International Code Council 2015) as the testing building code, which is the most widely used code base across the United States. The authors used Java language for algorithm implementation, which has a rich set of existing utilities such as Java toolboxes of IFC for extracting information from an IFC model.

Figure 2. Visualization of the convenience store.

During the experiment, the authors randomly selected Chapter 4 and 8 of the IBC 2015 for use. After careful inspection, the authors found that for Chapter 8, one of the most important concepts is the ceiling, which is the upper and interior surface of a room and is also different from a roof that is the upper covering of a building. For the current implementation of IFC, the direct mapping of ceiling is not yet supported. In addition, the flexibility of IFC provides multiple ways to represent a ceiling object. For example, *IfcRoof* provides a straightforward solution for representing ceilings at the top level of a building (i.e., the bottom surface of it needs to be further located), and *IfcCovering* is also used to represent ceiling objects. Another source of the ceiling object is from floor objects that are not on the ground, i.e., for a multi-floor model, all the floors except the lowest one are also carrying ceilings for the stories below them. In short, the concept of ceiling cannot be directly matched to IFC entities and therefore requires further development for identification and mapping.

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Following the three steps in the proposed method, the authors finished Step (1) using the start-of-the-art iterative feature extraction algorithms of Wu et al. (2021) to extract 36 invariant signatures for each object, including geometric, locational, and metadata features based on the sub-algorithms for each IFC object representation. These 36 invariant signatures of an object can fully represent the information provided by that object for the identification of common building code concepts. Yet, the set of features in the invariant signatures can be extended to cover more complex concepts when there is a need, whereas the existing features would remain unchanged (Wu et al. 2021). This information was used as the basis of intermediate data to represent all the information from BIMs and was further extended in Step (2).

For Step (2), the authors developed algorithms for making inferences on existing explicit information encoded in the invariant signatures. To illustrate the idea, the authors used a rule-based algorithm to identify ceiling objects as an example. The assumption was that all the information used from the IFC models were correct, i.e., there were no IFC entity misuses in the model. A high-level description of the developed algorithm for ceiling identification is as follows (Figure 3):

(a) identify ceiling object candidates from roof (*IfcRoof*) objects.

(b) identify ceiling object candidates from all floor (*IfcSlab*) objects. Eliminate the floor objects that do not have a level below it, i.e., eliminate the floor objects on the first floor.

(c) identify ceiling object candidates from all covering (*IfcCovering*) objects. Verify the objects to be at the top of rooms.

(d) delete possible repetition of ceiling object candidates from the above three sources.

(e) conduct final check by algorithmically verifying the geometric and locational information, i.e., the ceilings should satisfy one (and only one) condition of (a)-(c) without repetition.

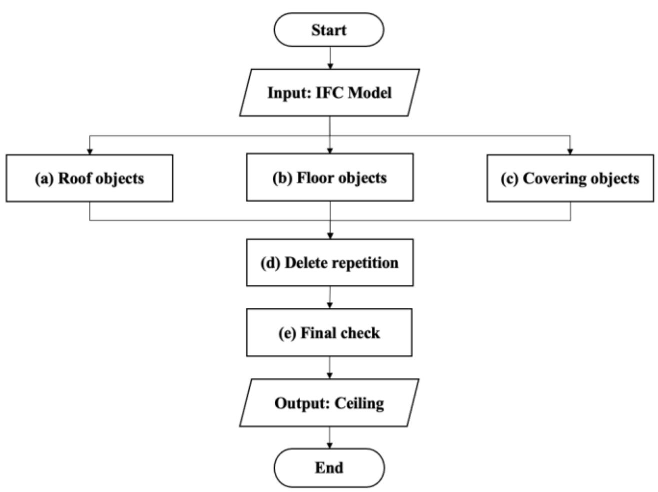

Figure 3. Ceiling identification algorithm.

Testing of the proposed algorithm was conducted on the convenience store model. Figure 4(a) shows the candidate object identified from algorithm step (a), Figure 4(b) shows the candidate objects identified from algorithm step (b), and Figure 4(c) shows the candidate objects identified from algorithm step (c).

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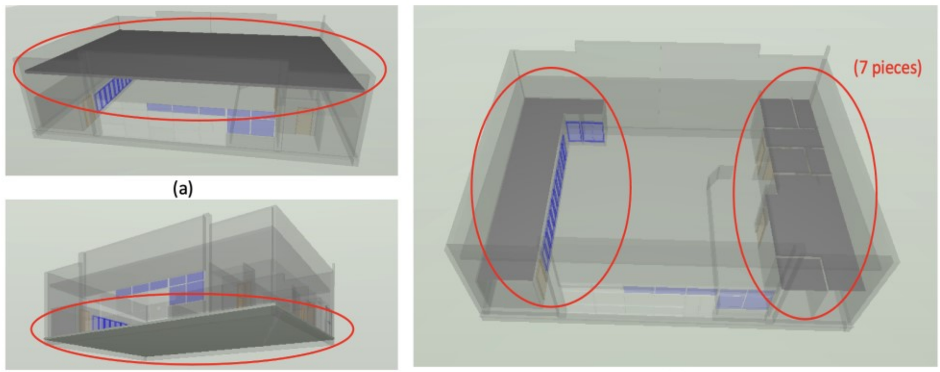

Figure 4. Visualization of the (a) roof object, (b) floor object, and (c) covering object as a candidate that carries a ceiling.

The roof object from step (a) satisfied all conditions in the algorithm; the floor object from step (b) was eliminated because it is the ground floor without rooms below it; the covering objects from step (c) satisfied the conditions and all eight objects became candidates for ceiling objects. The step (d) then checked the positions of the candidates and found no repetitions. As a result, all the nine candidates remained for final verification at step (e). For the final checking in step (e), the shape and locational information were checked, and all the nine candidates were validated to be depicting ceiling objects. That information was added to the intermediate data to map to building code concepts.

With the identification of the ceilings in Step (2), Step (3) can be performed by mapping these information to building code concepts and storing the information in the form of logic facts. For example, the identified ceiling object with ID *2v217OMpjFlOKx_YinYS0a* (the highlighted component on the left in Figure 4(c)) was stored as "*ceiling(ceiling3). area(area3). has(ceiling3, area3). has_value(area3, 439). has_unit(area3, sq_ft). …*" "*ceiling3*" was used because it was the third identified ceiling. The area of the ceiling was 439 sq.ft. To represent such information, an area instance was declared as "*area3*", because there was one instance of area information declared for other objects before this object. The "*has_value(area3, 439)" and "has_unit(area3, sq_ft)*" were used to define the value and unit information, respectively. Following a similar approach, other information about the object can be stored, including the geometry, facing direction, and the count.

In addition to the ceiling concept from Chapter 8, the authors also developed an algorithm for the interior door concept from Chapter 4, with the following two steps: For each door, (a) calculate the center of the door, (b) check if the center of the door is on the boundary of the building. Figure 5 shows some examples for the algorithmic identification results of interior doors.

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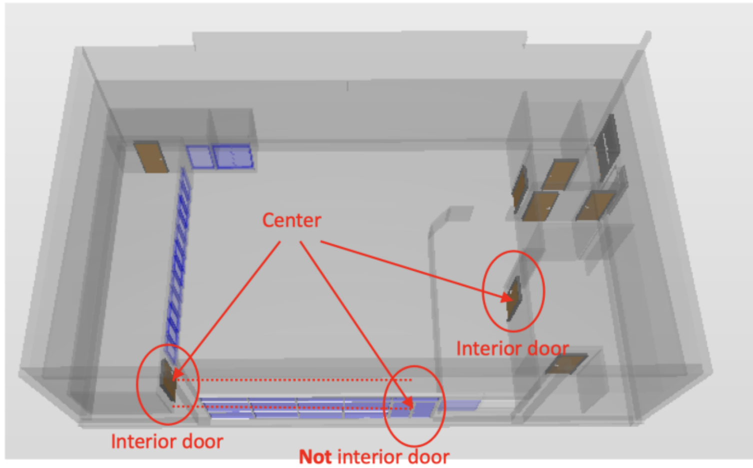

Figure 5. Visualization of example algorithmic interior door identification results.

RESULTS

The experiment was successfully conducted on the convenience store following the three-step method. As a result, all nine ceilings were correctly identified, and 117 logic facts were correctly generated for these nine ceilings (with 100% precision and recall). Table 1 shows the statistics of the nine identified ceilings using the proposed algorithm. The authors conducted a simple comparison between manually generating logic facts and automatic generation using our proposed method. For manual analysis, mapping, and conversion, it took 48.4 minutes. In contrast, the developed system was able to process the model and generate the logic facts in 6.1 seconds, which saved 99.8% of the time spent in the pure manual process.

For the identification of interior doors, all 8 interior doors in the convenience store were successfully identified (100% precision), and all three exterior doors were successfully eliminated (100% recall).

Similar to ceilings and interior doors, many other building code concepts can be identified by their relative location, relationships with other objects in a model, and associated semantic information. For example, egresses can be identified by their relative locations in the building (i.e., doors located at the boundaries of the building that connect interior and exterior), and fire doors can be identified using semantic information (i.e., material) associated with the door objects.

Table 1. Results of the ceiling concept and logic facts.

Ceiling Source	No. Candidates	No. Ceilings	No. Logic Facts
Roof (*IfcRoof*)	1	1	13
Floor (*IfcFloor*)	1	0	0
Covering (*IfcCovering*)	8	8	104
Total	10	9	117

CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

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There are three main contributions to the body of knowledge. First of all, the authors investigated the feasibility of conducting logic-based reasoning on none explicitly represented objects in IFC-based BIMs to support building design information mapping to building code concepts. The preliminary experiment showed that some building code concepts could be derived based on the collected information from BIMs. Second, the authors demonstrated rule-based algorithms for identifying ceiling and interior door objects which were robust enough to cover all possible sources in the experiment. Last but not least, the authors proposed a new method to help information mapping from BIMs to building codes. Compared to the state-of-the-art direct mapping method, this method has higher accuracy (improved from ~78% to ~100%, Zhang and El-Gohary 2019). It also has the potential to cover all concepts that are inferable with well-developed algorithms. Compared to manual identification, the method is much more efficient (99.8% time saving). It also does not need arduous work involved in extending the IFC schema. In summary, the proposed method can better support information exchange and therefore made a solid step towards supporting full automation of automated building code compliance checking.

CONCLUSION

The authors proposed a new method to support information mapping from BIMs to building codes. The method was able to cover concepts that cannot be directly matched between BIMs and building codes. Using the proposed method, the BIMs can be validated to generate intermediate data, which contains the results of rule-based concept inference and identification algorithms. Such method extends the information of BIMs to support indirect mapping of information unfeasible for direct mapping otherwise. The experiment on IBC 2015 and a convenience store model resulted in successful ceiling and interior door identification and logic facts generation. This research demonstrates a solid step in addressing the research gap of information mapping and BIMs validation to support automated building code compliance checking.

LIMITATIONS AND FUTURE WORK

Four limitations are acknowledged as follows: (1) The authors tested two concepts (i.e., the ceiling and interior door) from the IBC 2015. While the method is expected to work on other similar concepts, such as egresses and fire doors, more testing is needed for demonstrating its robustness. (2) The authors only tested the method on one model (i.e., the convenience store). While the method is expected to work on other models, further testing is needed to investigate the strengths and weaknesses in dealing with different types of models. (3) The authors assumed that the building code concepts can be mapped to BIMs, which may not always be true. In other words, not all buildings code concepts can be mapped to BIMs, which is not addressed in the scope of this paper. (4) The resulting logic facts were only compared with manually developed gold standards and need to be further tested by integrating into a complete automated building code compliance checking system. For future research, the above-mentioned limitations shall be addressed. In addition, based on the identification results, the building code requirements encoded in logic rules can be applied to the instances of these identified concepts, in a way similar to those presented by Zhang and El-Gohary (2017a,b). The results shall then be integrated into automated building code compliance checking systems for ultimate testing.

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