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TECHNICAL PAPER

Building information modeling (BIM)-based model checking to ensure occupant safety in institutional buildings

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Abstract
Occupant safety is pivotal in building designs. The present study developed a building information modeling (BIM)-based methodological framework and rule set for occupant safety-focused design checking for institutional building designs in Ontario, Canada. A comprehensive review was conducted to determine safety-related regulations, standards, and best practices included in the Ontario Building Code (OBC) and Canadian Standards Association (CSA) guidelines. Identified safety standards were defined in a BIM model checking software as a ruleset. A case study was conducted to demonstrate the proposed ruleset for an institutional building in Windsor, Ontario, Canada. The case study demonstrated that the intended ruleset did not contain errors and effectively performed the rule check. The proposed rule set prevents safety hazards for building occupants by accurately identifying building elements that do not comply with the safety guidelines and codes. Furthermore, the proposed approach promotes BIM adaptation in the Canadian construction industry.

Keywords Model checkers · Design standards · Building construction · Occupant safety · Design reviews · Design rule checking

Introduction

Construction projects are dynamic and complex, and hence, many building codes, standards, and guidelines were developed to maintain a certain quality in different aspects of the construction sector, such as the level of hazard protection, construction safety, occupant safety, and environmental protection [1–5]. Design engineers should comply with the codes and design guidelines [6]. Noncompliance with building design codes delays preconstruction activities (e.g., building permits) as noncompliant designs pose safety risks to building users.

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Errors in building designs are commonly observed in construction projects [7]. Statistics show that approximately 30% of construction costs are associated with rework [8, 9]. This issue stems from traditional design approaches embedded in the construction sector, such as using 2D drawings to communicate with contractors. The use of 2D drawings forces design engineers to check code compliance manually despite the complexity of the constructed asset [10, 11]. Even though the construction industry has acknowledged 2D drawings as an error-prone and time-consuming process, reluctance to move from the traditional practices has been a roadblock [12, 13]. Building information modeling (BIM)-based rule checking can identify errors in a building model, minimizing the need for corrections and rework during the construction stage [10]. Furthermore, BIM-based rule checking enhances the accuracy and efficiency of compliance checking [10, 14].

BIM-based model checking is defined as a system that considers objects' configuration and relationships to assess a building design without any modifications [2]. BIM-based model checkers automatically evaluate a building design based on a set of functional requirements, which are denoted as rules [1, 15]. The result of the process can be "pass," "fail," "warning," or "unknown" [2]. BIM-based model checking is a four-step process: rule interpretation, building model preparation, rule execution, and rule reporting [16]. Applications and add-ons in the BIM suite, such as BIM Assure, Solibri Model Checker (SMC), Revit Model Review, and SmartReview APR, are used in this process.

Recently, BIM-based rule checking has received the attention of academics. For example, Eastman et al. [2] and Lee [17] applied a logical approach to check occupant circulation rules. Ding et al. [18] and Dimyadi and Amor [19] used an object-based approach for rule interpretation to check disabled access to buildings; Bouzidi et al. [20] applied an ontology-based approach for providing technical guides for tile roofs based on relevant codes; Nguyen and Kim [21] employed an Autodesk Revit model checker to check fire safety requirements, and Chahrour et al. [22] studied BIM-based rule checking for clash detection of a USD 75 million project and concluded that rework could be reduced by USD 15.2 million through rule checking procedure.

Most of the previous studies have developed BIM-based model checking tools using the ruleset from the Occupational Safety and Health Administration (OSHA) guidelines. Though OSHA is renowned throughout the world for safety guidelines, using such generic standards-based model checking tools may not address the specific safety requirements of a country or province. Hence, province or country-specific safety rule sets should be developed for building design review. However, to the best of the authors' knowledge, no approach has dealt with the development of a BIM-based occupant safety rule check for Ontario, Canada.

Hence, this study presents a BIM-based occupant safety ruleset to check institutional building designs for code compliance to prevent safety hazards for building users in Ontario, Canada. Ontario Building Code (OBC) and Canadian Standards Association (CSA) standards were reviewed to obtain safety-related guidelines. Accordingly, a ruleset was developed for use in building model checking. Regardless of the different approaches of this study, this research is more comprehensive in terms of the safety rule checking concept than recent similar research works in Canada [23] or other countries [24, 25] that utilized fire egress codes and focused only on fire-related safety. The outcomes of this research can aid building designers in model checking and ensuring the safety of building users. The rest of the paper's structure is as follows: Relevant literature was reviewed, and a research methodological framework was developed. Then, a case study was conducted, followed by an analysis of the results, discussion, and conclusions.

Literature review

BIM-based rule checking involves rule interpretation, model preparation, rule execution, and rule reporting. These aspects are explained in detail below.

Rule interpretation

Building codes and standards are typically in written texts, tables, and possibly equations. These rules should be translated into a machine-processable format to be used in a model checker [2]. This is performed in two ways. In the first method, rules are translated into computer codes by a programmer [23]. In the second method, rules are formally translated through the logic of human language [26]. Therefore, construction industry experts without any programming background can execute the second method of rule interpretation through software or plugin applications [27].

Programming-based rule interpretation

There are different techniques for interpreting the rules for rule checking development, such as an ontological approach, a logical approach, and an object-based approach [16]. Each method is explained below.

Object-based approach An object-based approach is a technique for organizing knowledge by defining attributes, procedures, rules, and machine learning [28]. Building rules are represented in a three-stage approach. In the first stage, building codes are classified. In the second stage, all relevant building objects and rules are identified. In the third stage, all data and values are stored and maintained in a tabular form to establish a knowledge base [29]. CoreNet e-PlanCheck is an example of an object-based rule checking system that is officially implemented in Singapore [30].

One advantage of this approach is that contextual concept lattice classes can cover the standard scope; therefore, rules can be encapsulated within the classes [31]. Creating and maintaining a complex concept lattice is a time-consuming and error-prone task [32].

Logic-based approach First-order predicate logic is the most common language and is applied to interpret natural language. This method is common because humans define rules, and interpreting rules can be made by translating logic into human language statements [33]. In this approach, explicit and implicit logical conditions such as "and," "or," and "If–Then" are combined and applied to validate and check a building element [34]. In order to interpret rules into basic logic, a conceptual graph can be employed by rule experts without programming knowledge [35]. There are four stages for translating rules into the conceptual graph:

I. Identification of the main concept of rules
II. Identification of independent sub-rules of each rule
III. Identification of constraints and restrictions
IV. Identification of connections of all elements to develop the proper conceptual graph.

Then, to support the process of compliance code checking in the BIM environment, BIM Rule Language (BIMRL) is developed through Structured Query Language (SQL) [36]. BMRL defines a simplified schema that uses the relational database to facilitate access to the building data. This approach is useful for unidirectional data processing where Industry Foundation Classes (IFC) models are loaded into the simplified schema [37]. The advantage of this approach is that predicate calculus constructions provide a sufficient means for constructing any expression [32]. However, they cannot efficiently represent the different evaluation strategies of data items for object classes of different designs. Thus, the final model of the predicate logic standard is complicated and arduous to create and maintain [38].

Ontology-based approach This approach is based on using a graph that displays objects and their logical relations [39]. The ontological approach involves four aspects, as follows:

I. Developing a construction regulation database
II. Creating a reasoning model
III. Capitalizing the database
IV. Validating the framework by integrating all aspects into a prototype [40].

The advantage of this approach is the effective use of computers in the design process. However, this approach is unable to provide formal language for describing models [41]. Hence, it is difficult to understand how design classifications are achieved. Furthermore, this approach does not explain how evaluation provisions are represented, leading to problems in understanding the compliance checking process [32, 41].

BIM application-based rule interpretation

There are several model checkers currently being used in the market. Solibri Model Checker (SMC) is a popular BIM application used to check the integrity, quality, and safety of BIM models [42]. SMC, which contains built-in geometry-oriented rules, automatically analyzes and checks virtual building models to detect design deficiencies and missing elements [43]. SMC strictly checks model structure requirements [16]. Furthermore, it provides a user-friendly visualization of the building model and permits a virtual walk-through. This feature has been used for checking safety rules related to fall hazard prevention for construction workers [44]. The SMC-based SMART Code system was developed by the International Code Council in North America to check the reliability of rule checking [2]. The advantages of SMC are (i) its ability to read and correctly interpret IFC files exported from a wide range of BIM authoring tools, (ii) a complete set of spatial operations, and (iii) a high level of maturity (widely used by designers) [45]. On the other hand, SMC's disadvantages include a lack of formal and standard schema for the rule definition and rule templates with hard-coded rules [45].

BIM Assure gives users visibility into building data. The features of BIM Assure are cloud-based model viewing (2D/3D), the support for IFC file format, the ability for element classification and data viewing, and the ability for editing and rule analysis [45]. The advantages of BIM Assure are ease of defining rules, low requirements for programming constructs, minimum domain knowledge required, and proper performance indication [46]. On the other hand, the disadvantages of this tool have no standard schema for the rule definition, low support for complex rules, no integrated geometry engine, and low interface to other languages and systems [45, 46].

There are plug-ins for BIM applications, such as the Autodesk Revit plug-in, that enable rule checking. Nguyen and Kim used this possibility to check openings in firewalls, fire resistance ratings, and horizontal continuity of the firewalls based on the International Building Code (IBC) in the USA [21]. Although the Revit Model Review requires a low level of logic or programming constructs, it has no integrated geometry engine, no standard schema for the rule definition, low support for complex rules, and low interface to other languages or rule checking systems.

Table 1 shows the BIM-based approaches and techniques for developing automated compliance checking. As shown in this table, different rule interpretation techniques have been used by previous researchers. However, no previous research has interpreted BIM-based safety rules according to OBC and CSA standards.

Model preparation

The steps that should be undertaken in preparing the building model for rule checking include (i) creating a model view to derive the required data for a specific type of rule checking and to extract subsets of an overall building model, (ii) extracting implicit properties using enhanced objects to derive new information and compute complex properties, (iii) obtaining the new model to make an evaluation

Table 1 Approaches and techniques for a rule interpretation

Study	Country	Rule checking	Approach and techniques				
			BIM application-based		Programming-based		
			SMC	Plugin	OBB	LB	ONB
[47]	Singapore	Technical requirements for household and story shelters			✓		
[2]	Norway	Building accessibility rules	✓				
[17]	The U.S	Circulation rule checking				✓	
[48]	Italy	Health and safety code checking					
[36]	The U.S. & Singapore	Fire safety and accessibility rules				✓	
[20]	France	Technical guides of tile roofs					✓
[49]–[51]	Australia	Disabled access code			✓		
[21]	The U.S	Fire safety requirements		✓			
[30]	Singapore	Building service rules			✓		
[52]	Korea	Building permit requirements				✓	
[25]	Turkey	Fire safety requirements			✓		
[53]	The U.S	Environmental requirements					✓
[54]	The U.K	Fire safety requirements			✓		
[44]	The U.S	Fall hazard protection rules	✓		✓	✓	
[55]	Bangladesh	Construction safety tracking					
[56]	Portugal	Water system regulations				✓	
[57]	Australia	Fire safety requirements					✓
[58, 59]	Norway and the U.S	Accessibility, building habitable spaces					✓
[60]	China	Construction quality inspection					✓
[61]	The U.K	Sustainability requirements				✓	✓
[62]	Germany	Secure data-flow compliance checks		✓		✓	
[23]	Canada	Fire safety in timber buildings		✓	✓		
[63]	Brazil	Fire fighting in a BIM environment		✓			
[64]	China	Green construction requirements		✓		✓	
[65]	Korea	Fire safety requirements			✓	✓	
[66]	Hong Kong	Building envelope energy efficiency				✓	
[67]	The U.K	Compliance checking in healthcare building					
[68]	Norway	Compliance checking in building construction projects					
[69]	Egypt	Emergency egress of building designs					
[70]	Spain	Healthcare facility design regulations					

of certain implicit relations and properties easier, (iv) performance-based analysis to check rule adequacy, and (v) checking layout rule parameters to check the building model layout types [71].

Rule execution

Rule execution brings the BIM model and the corresponding rules together [2]. The BIM model should be validated before performing the rule check to ensure properties, names, and objects are available [72]. Moreover, in the rule execution stage, a management system is required to coordinate the application of rule modules and their results. This system checks the completeness of the rule checking and model version consistency [73].

Rule reporting

Rule reporting validates whether design conditions are satisfactory according to the ruleset. A rule checking report also provides a graphical representation of each element of the BIM model in reference to the source rule [7].

Methodology

Figure 1 illustrates the methodological framework of this research. The four-step process proposed by Eastman et al. [2] for BIM-based rule checking was considered in this research. This research was performed in 5 interrelated steps, which are explained in detail below:

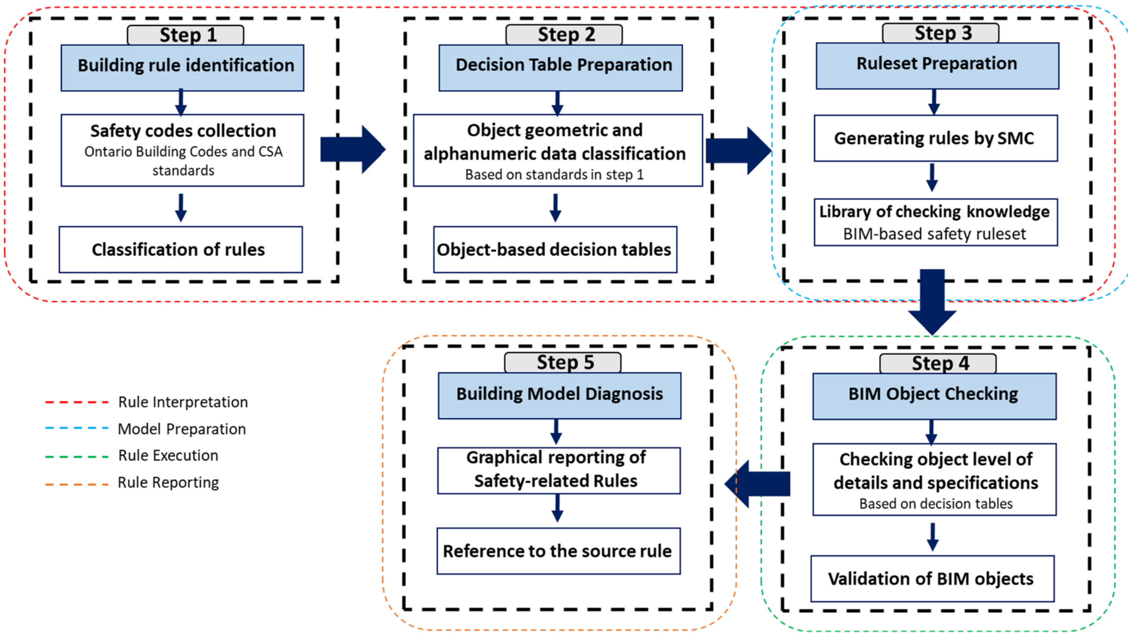

Fig. 1 Research methodological framework

Step 1. Building safety rule identification

OBC and CSA Standards were reviewed to identify safety-related guidelines. The approach used by Solihin [36] and Nguyen and Kim [21] in finding safety-related was used in this study. The list of used codes and standards in this study are as follows: OBC and CSA A500-16 (building guards), guidelines in CSA Z1002-12 (occupational health and safety, hazard identification and elimination, and risk assessment and control), CSA Z259.2.4:15 (fall arresters and rigid vertical rails), CSA Z259.13–16 (manufactured horizontal lifeline systems), CSA Z1000:14 (occupational health and safety management), and CSA Z45001:19 (occupational health and safety management system, requirements with guidance for use included safety-related guidelines).

The safety-based rules and standards used in this study are classified as follows: (i) egress analysis, which deals with issues such as the number and location of means of egress, (ii) stairs and steps, to check stairs and step dimensions and configuration, (iii) ramps, to check the slope and dimension of ramps, (iv) landings, to deals with the location and dimension of landings in a building model, and (v) handrails and guards, to check the existence and height of building guards (if they exist).

Step 2. Decision table preparation

The object-based decision table was developed to show the geometric information of objects based on the relevant rules from the OBC and CSA standards (Table 2). Overall, there are 64 parameters, which can be organized into five categories: (1) stairs, (2) ramps, (3) guards, (4) Egress analysis, and (5) ceiling height.

Step 3. Ruleset preparation

The customized parametric ruleset file (BIM-based safety rules) was created using a model checking application (SMC). First, available rule templates in SMC were reviewed to identify the appropriate template related to each rule in the decision table (Table 2). Second, based on the rules identified in step 1, safety classes for rule checking were defined in SMC. Finally, the ruleset classes were customized based on the 64 rules in the decision table.

Step 4. BIM object checking

BIM model objects were validated by focusing on the level of detail and specifications required by decision tables. Object validations include the correctness of the required attribute value, the correctness of embedding an attribute within a BIM object, and the definition of relationships between objects within a building model.

Step 5. Building model diagnosis

The building model was checked in this step, and the design errors were determined. The graphical report (i.e., output) indicated building elements that did not comply with standards and building codes after the rule execution. Based on

Table 2 Summary of object-based decisions

Rule no	Checking objects	Checking points or condition	Premise	Required data	Reference
Stairs					
1	Stairs	Include	True	Stair property	O. Reg. 332/12: BC (9.8)
2	Stairs	Stair width	900 mm < Width	Stair width measured between wall faces or guards	O. Reg. 332/12: BC (9.8.2.1)
3	Stairs	Over-stair height	1950 mm < Height	The clear height over the stairs	O. Reg. 332/12: BC (9.8.2.2)
4	Stairs	Number of step risers	Count > 3	Nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.3.2)
5	Stairs	Height of stairs	3.7 m < Height	The vertical height between any landings	O. Reg. 332/12: BC (9.8.3.3)
6	Stairs	Length of step riser	125 mm < length < 200 mm	Nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.4.1) (Private stairs)
7	Stairs	Step tread depth	235 mm < depth < 355 mm	Nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.4.1) (Private and rectangular stairs)
8	Stairs	Stair winders	90° < Winder turn angle	Winders that converge to a center point	O. Reg. 332/12: BC (9.8.4.5)
9	Stairs	Stair winders	30° < Tread turn angle < 45°	Winders that converge to a center point	O. Reg. 332/12: BC (9.8.4.5)
10	Stairs	Include landing	True	At the top and bottom of each flight of interior and exterior stairs	O. Reg. 332/12: BC (9.8.6.2)
11	Stairs	Width of landing	Width of stair < Width	In straight-run stairs, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
12	Stairs	Length of landing	860 mm < Length	In straight-run stairs, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
13	Stairs	Width of landing	Width of stair < Width	In straight-run exterior stairs, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
14	Stairs	Length of landing	900 mm < Length	In straight-run exterior stairs, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
15	Stairs	Width of landing	Width of stair < Width	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
16	Stairs	Length of landing	230 mm < Length	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
17	Stairs	Width of landing	Width of stair < Width	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
18	Stairs	Length of landing	Width of stair < Length	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
19	Stairs	Height over landing	1950 mm > Height	The clear height over the landing	O. Reg. 332/12: BC (9.8.6.4.)
20	Railings (Handrail)	Include	True	One handrail is required for each stair	CSA (A500-16–4.8.2) O. Reg. 332/12: BC (9.8.7.1)
21	Railings (Handrail)	Continuity of handrail	True	Where not interrupted by doors	O. Reg. 332/12: BC (9.8.7.2)
22	Railings (Handrail)	Include	False	Where obstructed pedestrian travels	O. Reg. 332/12: BC (9.8.7.3)
23	Railings (Handrail)	Height of handrail	865 mm < Height < 965 mm	Where guards are not required	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.7.4)
Ramps					
24	Ramps	Ramp width	Width < 860 mm	Pedestrian ramps	O. Reg. 332/12: BC (9.8.5.2)
25	Ramps	Height over ramp	Height < 1950 mm	The clear height over the ramp	O. Reg. 332/12: BC (9.8.5.3)
26	Ramps	Exterior ramp slope	Slope < 1 in 10	Ramp slope	O. Reg. 332/12: BC (9.8.5.4)
27	Ramps	Interior ramp slope	Slope < 1 in 10	Ramp slope	O. Reg. 332/12: BC (9.8.5.4)

Table 2 (continued)

Rule no	Checking objects	Checking points or condition	Premise	Required data	Reference
28	Ramps	Rise of ramp	Rise between floors or landings < 1500 mm	Where the slope of the ramp is greater than 1 in 12	O. Reg. 332/12: BC (9.8.5.5)
29	Ramps	Include landing	True	At the top and bottom of every ramp with a slope greater than 1 in 50	O. Reg. 332/12: BC (9.8.6.2)
30	Ramps	Include landing	True	Where a doorway opens onto a ramp	O. Reg. 332/12: BC (9.8.6.2)
31	Ramps	Width of landing	Width of ramp < Width	In a straight-run ramp, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
32	Ramps	Length of landing	860 mm < Length	In a straight-run ramp, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
33	Ramps	Width of landing	Width of ramp < Width	In a straight-run exterior ramp, its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
34	Ramps	Length of landing	900 mm < Length	In a straight-run exterior ramp, its landing turning through less than 30	O. Reg. 332/12: BC (9.8.6.3)
35	Ramps	Width of landing	Width of ramp < Width	30° < Landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
36	Ramps	Length of landing	230 mm < Length	30° < Landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
37	Ramps	Width of landing	Width of ramp < Width	90° < Landing turning through	O. Reg. 332/12: BC (9.8.6.3)
38	Ramps	Length of landing	Width of ramp < Length	90° < Landing turning through	O. Reg. 332/12: BC (9.8.6.3)
39	Ramps	Height over landing	1950 mm > Height	The clear height over the landing	O. Reg. 332/12: BC (9.8.6.4)
40	Railings (Handrail)	Include	True	Where ramp width < 1100 mm	CSA (A500-16–4.8.2) O. Reg. 332/12: BC (9.8.7.1)
41	Railings (Handrail)	Handrail number	Count = 2	Where ramp width > 1100 mm	CSA (A500-16–4.8.2) O. Reg. 332/12: BC (9.8.7.1)
42	Railings (Handrail)	Continuity of handrails	True	Where not interrupted by doors	O. Reg. 332/12: BC (9.8.7.2)
43	Railings (Handrail)	Include	False	Where obstruct pedestrian travel	O. Reg. 332/12: BC (9.8.7.3)
Guards					
44	Railings (Guardrail)	Include	True	The surface elevation difference between the walking surface and the adjacent surface is > 600 mm	CSA (A500-16–4) O. Reg. 332/12: BC (9.8.8.1)
45	Railings (Guardrail)	Include	True	The elevation difference between the two sides of the door is > 600 mm	CSA (A500-16–4) O. Reg. 332/12: BC (9.8.8.1)
46	Railings (Guardrail)	Include	True	Interior stair risers > 2	CSA (A500-16–4) O. Reg. 332/12: BC (9.8.8.1)
47	Railings (Guardrail)	Include	True	The elevation difference between the openable window sill and the finished floor is > 480 mm	CSA (A500-16–4) O. Reg. 332/12: BC (9.8.8.1)
48	Railings (Guardrail)	Include	True	The elevation difference between the two sides of the window is < 1800 mm	CSA (A500-16–4) O. Reg. 332/12: BC (9.8.8.1)
49	Railings (Guardrail)	Height of guards	Height > 900 mm	The clear height	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)

Table 2 (continued)

Rule no	Checking objects	Checking points or condition	Premise	Required data	Reference
50	Railings (Guardrail)	Height of guards	Height > 920 mm	For required exit stairs	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4.)
51	Railings (Guardrail)	Height of guards	Height > 1070 mm	Around landings	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
52	Railings (Guardrail)	Height of guards	Height > 1500 mm	Where the elevation difference between exterior stairs and above adjacent level > 10 m	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
53	Railings (Guardrail)	Height of guards	Height > 1500 mm	Where the elevation difference between landings and above adjacent level > 10 m	CSA (A500-16–4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
54	Railings (Guardrail)	Opening in guards	Diameter < 100 mm	Railing (guardrail) opening	CSA (A500-16–4.8.3.1) O. Reg. 332/12: BC (9.8.8.5)
Egress analysis (Means of egress)					
55	Doors (Exit)	Include	True	If the space is set to be a fire exit space, it must have a fire exit door	O. Reg. 332/12: BC (9.9.2.1)
56	Doors (Exit)	Exit width	Width > 900 mm	Emergency exit doors	O. Reg. 332/12: BC (9.9.3.2)
57	Doors (Exit)	Exit width	Width > 800 mm	Where there is only one door leaf or multiple-leaf with one active leaf	O. Reg. 332/12: BC (9.9.6.3)
58	Doors (Exit)	Exit width	Width > 1210 mm	Where multiple-leaf doors are installed with two active leaves	O. Reg. 332/12: BC (9.9.6.3)
59	Corridors	Corridor width	Width > 1100 mm	Corridor used by the public, and the exit corridor	O. Reg. 332/12: BC (9.9.3.3)
60	Doors (Exit)	Door height	Height > 2100 mm	The clear height in exits and access to exits	O. Reg. 332/12: BC (9.9.3.4)
61	Floors	Floor height	Height > 2030 mm	The clear opening height of doorways	O. Reg. 332/12: BC (9.9.6.2)
Ceiling height					
62	Ceilings	Ceiling height	Height > 2100 mm	Ceilings in the passage, hall, or main entrance	O. Reg. 332/12: BC (9.5.3.1)
63	Ceilings	Ceiling height	Height > 2000 mm	The clear height in a storage garage	O. Reg. 332/12: BC (9.5.3.3)
64	Ceilings	Above ceilings	Height > 400 mm	Clearance above suspended ceilings	O. Reg. 332/12: BC (9.5.3.3)

the model checking, each element was defined as accepted, rejected, critical severity (major), moderate severity (normal), and low severity (minor).

Case study: the method implementation

The proposed rule set was implemented as a case study for the Center for Automotive Research and Education (CARE) building of the University of Windsor located in Windsor, Ontario, Canada. This 2-story building was renovated in 2014. The building is classified as an educational building. The BIM model of the CARE building was created based on the 2D construction drawings (Fig. 2). Autodesk Revit was used to create the building model.

An Industry Foundation Class (IFC) file was used to transfer building data to the SMC. The exported IFC file from the BIM model includes all details with a high level of specificity. In this transfer, it is important to ensure the required elements for safety rule checking are available in the IFC file. This measure was performed to verify that the IFC file contains all required elements for the rule checking process.

The BIM-based safety ruleset file was coded in SMC. As presented in Table 1, SMC has been used by previous researchers to check safety rules in building evaluation, such as building evacuation, fall protection for workers, building safety design, and accessibility. SMC is capable of creating specific rules identified in Table 2. This file was imported into the rule checking section of SMC to execute rules and report the result of code checking. Table 3 provides a summary of the model checking report. This report determines whether each component meets the rules identified in Table 2. The detailed report informs designers of each problematic element and compares the designed value with the standard value of that parameter identified in Table 2. In this case study, there is no "rejected" or "major" error. Therefore, it shows that this case study does not need to be entirely redesigned. However, several "normal" errors indicate the need for a major revision in the parameters of the "means of egress" section.

SMC graphically illustrates the errors in the building design. Figure 3 indicates three instances of the graphical report. After the rule execution step, SMC highlights elements with errors. SMC categorizes errors, and users can click on the intended element in the report section of SMC to observe the element in the BIM model.

Discussion

This study proposed a BIM-based occupant safety ruleset for institutional buildings in Ontario, Canada. A BIM ruleset enables accurate and fast evaluation of building designs to ensure compliance with building codes, standards, and guidelines [74]. The application of the proposed ruleset was demonstrated by using an existing building. The rule check returned no elements rejected or with major errors. A building design should comply with building codes and guidelines to receive construction approval. Hence, this validates the proposed rule set and its application. The theoretical and practical implications are discussed below.

Fig. 2 The CARE building used for the case study

Table 3 Summary of safety code checking report

BIM-based safety standards	Accepted	Rejected	Major	Normal	Minor
Stairs				x	x
The model should have stairs					x
The model should have stairs					x
Stair width	OK				
Height over stairs	OK				
Maximum height of stairs	OK				
Stair winders	OK				
Step riser height				x	
Step tread length				x	x
Minimum number of risers	OK				
Ramp width				x	
Ramp-ramp intersections	OK				
Height over ramps				x	
Ramp slope				x	
Staircase landings					x
Required handrail (ramp)	OK				
Continuity of handrails (ramp)	OK				
Required handrail (stair)	OK				
Continuity of handrails (stair)	OK				
Required handrail (ramp2)	OK				
Height of handrails (stair)	OK				
Height of handrails (ramp)	OK				
Guards				x	
Required guards 1				x	
Required guards 2				x	
Required guard 3	OK				
Egress analysis (means of egress)				x	
Escape route analysis				x	
Escape route analysis from office spaces				x	
If the space is set to be a fire exit space, it has to have a fire exit door					x
The model should have exits	OK				
Large spaces must have more than one door				x	
The fire compartment area must be within the limits				x	
Firewalls must have the correct wall, door, and window types				x	
Spaces must be included in fire compartments				x	
The model should have stairs				x	
The model should have exits				x	
Spaces must be connected to doors				x	
The model should have spaces	OK				
Ceiling heights	OK				
Suspended ceiling-suspended ceiling intersections					x
Suspended ceiling intersections					x
Floor heights	OK				
Clearance above suspended ceilings	OK				
Doorway					x
Door width					x
Door height	OK				
Clearance in front of doors					x
Spaces must have doors					x

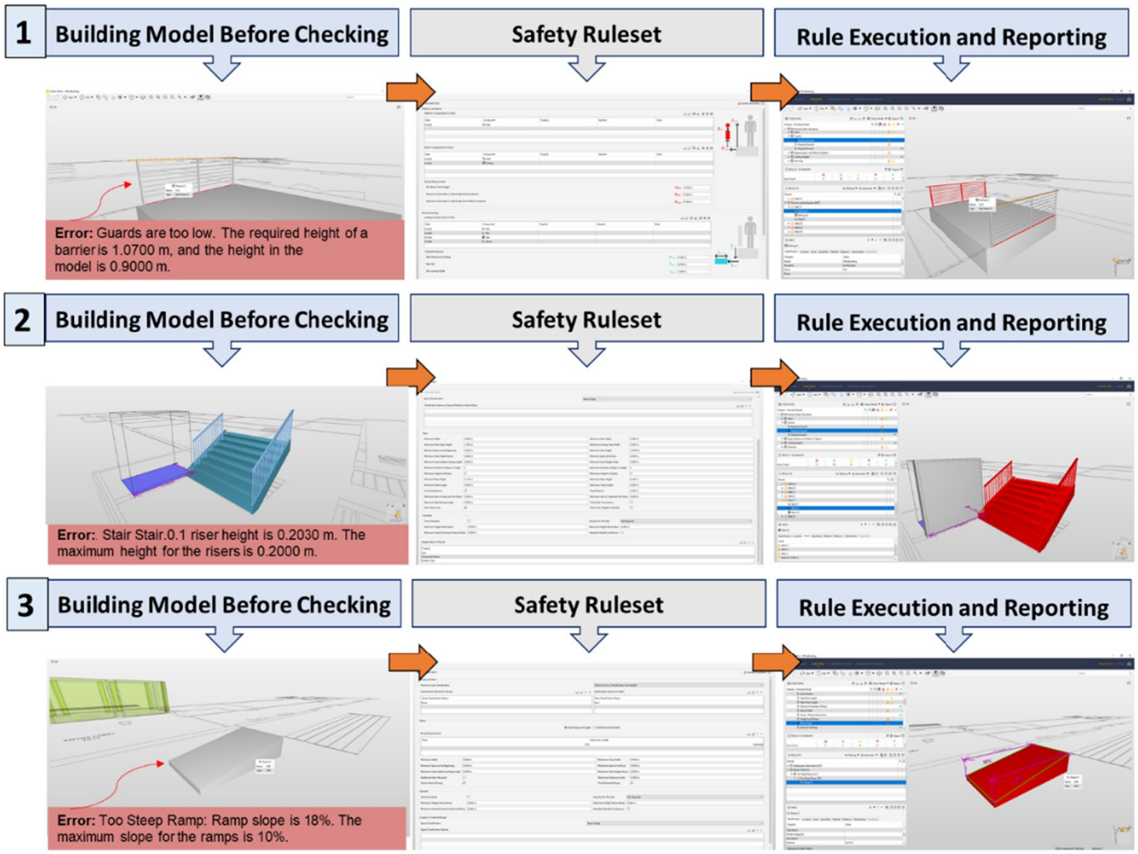

Fig. 3 Graphical report

Theoretical implications

The study developed a comprehensive database comprising occupant safety-based rules for buildings in Ontario, Canada. The guidelines available in the OBC, CSA A500-16 (building guards), CSA Z1002-12 (occupational health and safety—hazard identification and elimination and risk assessment and control), CSA Z259.2.4:15 (fall arresters and rigid vertical rails), CSA Z259.13–16 (manufactured horizontal lifeline systems), CSA Z1000:14 (occupational health and safety management), and CSA Z45001:19 (occupational health and safety management system—requirements with guidance for use included safety-related guidelines) were used in developing the aforementioned database. SMC was used to define the ruleset.

SMC generates a detailed report with the causes of errors, enabling building designers to revise the building model accordingly. The severity parameters defined in step 5 of the proposed framework were used to interpret the report generated by SMC. Therefore, the integration of the proposed ruleset and the rule result severity tables provided by SMC (refer to Table A1) interprets the generated report for designers.

Practical implications

The present study aids in preventing safety incidents for building occupants by identifying elements that don't comply with safety regulations in Ontario, Canada. The proposed ruleset can be extended to enhance the efficiency and accuracy of the building permit review and approval. It is important to point out that the proposed method requires the building design to be developed as a BIM model, which requires additional effort. The graphical and detailed reports enable designers to know the standard and correct value to edit the BIM model. Thus, the proposed framework allows designers to reduce model errors and prevent safety hazards for building occupants.

The proposed rule set was developed for occupant safety in Ontario, Canada. However, this ruleset can be customized to suit building codes in other provinces. Furthermore, additional safety rules can be identified and programmed into the present ruleset using the same approach or by using an application programming interface. The Architectural Engineering and Construction (AEC) industry should spearhead this cause by standardizing further safety.

Limitations

Several limitations have been identified in the proposed model checking tool. Since SMC does not allow users to freely manipulate data for generating new properties, using the proposed ruleset in SMC prevents the system from adequately covering some elements, such as passive fire protection. Furthermore, SMC software utilizes hard-coded rules. Hence, the individual steps of the checking processes are not visible and consequently limit the users' ability to alter them.

Conclusions

This study presented a BIM-based rule checking approach to reduce the safety risk for building occupants in Ontario, Canada. A comprehensive review was first conducted to provide up-to-date information regarding available rule checking techniques and systems. Then, OBC and CSA guidelines were used to develop a methodological framework that checks compliance with safety guidelines. The CARE building at the University of Windsor in Ontario, Canada, was chosen to test the framework. The goal of the case study was to see if the established ruleset was error-free and appropriately reflected the research's content. The case study's findings revealed that the intended rulesets were all included without errors and were easily utilized for rule checking, confirming the validity of the proposed framework. The case study further demonstrated the ability of this system to identify safety errors in a building design, informing the designers whether the building design requires a redesign, major revision, or minor revision. Moreover, due to the object-based classification of the ruleset, graphical and detailed reports can be generated that indicate the specific model elements with errors.

Overall, the outcomes of this study aid in preventing safety incidents for building occupants by identifying design elements that do not comply with standard safety regulations in Ontario, Canada. The outcomes of this research can be further extended to enhance the efficiency of the building permit review and approval. This study also promotes BIM adaptation in the Canadian construction industry.

Model checkers cannot make modifications to a design. Artificial intelligence (AI) can be used to modify the model based on identified errors. Hence, future research should look at developing an AI-based model checking interface for BIM applications. Moreover, this study focused on the architectural aspect of a building. Future studies can develop rulesets and automated safety rule checking systems for structural, plumbing, or mechanical sections.

Appendix

See Table 4.

Table 4 Rule result severities

Tag	Rule	Auto	Components	Results category	Severity
SOL/208	Accessible door rule		Doors, openings, and spaces	Wrong door opening direction	Moderate
				Not enough space behind door	
				Not enough space in front of door	
				Not enough space next to door	
				Too close doors	
				Missing parameter data	
				Unclassified spaces	
				Revolving door not accompanied by swing door	
				Too narrow door	*DoorDimension-Ratio
				Too low door	
				Too low glazing ratio	
				Too high threshold	
SOL/208	Accessible ramp rule		Ramps	Not enough space at the beginning	Moderate
				Not enough space at the end	
				Too long ramp	
				Too steep ramp	
				No additional stairs	
				Not checked	
				Too narrow ramp	*DimensionRatio
				Too narrow ramp, clear width	
				Too short intermediate landing	

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/210	Accessible stair rule	Use Automatic Severities	Stairs	Not connected to slab at beginning	Critical
				Not connected to slab at end	
				Not enough space at beginning	Moderate
				Not enough space at the end	
				Open risers	
				Not checked	
				Under not shielded	*Low*
				Too many steps in stair flight	*StairMaxSteps
				Too high stair flight	*DimensionRatio
				Too high stair	
				Too short intermediate landing	
				Too narrow stair	
				Too narrow stair, clear width	
				Non-uniform step at beginning	
				Non-uniform step at the end	
				Too long nosing	
				Not enough clear space above	
				Too high riser	
				Too low riser	
				Too long tread	
				Too short tread	
				Too high sum of tread and two risers	
				Too low sum of tread and two risers	
		Unmarked	Stairs	All	Moderate
SOL/211	Accessible window rule		Windows	Windows at the end of the corridor	Moderate
				Too high sill	*DimensionRatio
SOL/209	Free floor space		Space	All	Moderate
SOL/233	Allowed beam intersection		Beams	All	Moderate
SOL/215	Allowed profiles		Beams and columns	All	Moderate

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/224	Architectural components are filled		Any non-container components	Horizontally differing components	*DifferingPercent
				Vertically differing components	
				Laterally differing components	
				No corresponding components	Moderate
SOL/212	Building envelope validation		Building	No building envelope elements	Critical
			Walls	Building envelope elements around spaces	Moderate
				Building envelope elements around space groups	
				Walls around space groups and spaces differ	*Low*
SOL/231	Comparison between property values		Any	Non-matching properties	Moderate
				Missing information	*Low*
SOL/222	Component distance		Any non-container component	Too few components in space/space group	Critical
				No spaces	Moderate
				No space groups	
				No components close enough	
				Components too close	
				Too few close components	
SOL/171	Component property values must be consistent		Any	All	Moderate
SOL/25	Components must be connected to spaces		Windows, doors, and openings	Without connection to any space	Moderate
				With connections to space groups	
				With connections to spaces side or far away	
				No external walls	
				With only one connection to a space	Low
				In external walls with connections to two spaces	
				Connections to spaces only on one side	
				With more than two connected spaces	

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/21	Components must have unique identifier		Any	Components without unique identifier Spaces and space groups without unique identifier	Critical
				Components without identifier	Moderate
				Components with non-matching identifier	
				Spaces and space groups with non-matching identifier	
				Different first numbers	
				Non-consecutive numbers	
SOL/23	Components must touch other components		Any non-container component	Unchecked components	Moderate
				Components touch partially	*CoveredAreaRatio
				Components don't touch	*NearestDistance
SOL/161	Distances between spaces		Spaces	No direct access	Critical
				Spaces too far	*MaxDistance
				Spaces too near	*MinDistance
				Missing spaces	Moderate
SOL/218	Element hole validation rule		Beams, columns, and members	All	Moderate
SOL/179	Escape route analysis		Spaces	No routes to the exits	Critical
				Not enough routes to exits	
			Projects	Exits are not specified	
				No fire compartments	Moderate
			Spaces and doors	The exit passageway is too low	
				The exit passageway is too narrow	
			Projects	Travel distance not specified	
				Occupancy not specified	
			Spaces	Travel distance is too long	
				Wrong door opening direction	
			Buildings	Exit classification is not loaded	
				Space grouping classification is not loaded	
			Doors	Cannot check the door opening direction	Low
SOL/190	Fire compartment area must be within limits		Fire compartments: No severity parameters	Too large fire compartments	Critical
				Inadequate information	Moderate

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/172	Fire walls must have the correct wall, door, and window types		Wall	No fire wall components	Critical
			Door	No fire door components	
			Window	No fire window components	
			Openings and walls	Openings in fire walls	
			Building	No fire compartments	Moderate
			Wall	Needless fire wall components	Low
			Door	Needless fire door components	
			Window	Needless fire window components	
SOL/111	Floor and gross area analysis		Building	No gross area compartments	Critical
				No gross area space groups	
				No gross areas nor compartments	
			Floors	Areas differ	
				Floors without external walls	Moderate
				Floors without components	
				Ungrouped spaces	
				Heights of floors differ	
				Too large external wall area	
				Too large window area	
				Gross area height differs from floor height	Low
			Spaces	Space intersections	*IntersectingArea
				Too high empty area ratio	*AreaRatioDiff
				Too low space area ratio	
SOL/220	Floor distance		Floors	All	Moderate
SOL/228	Floor names must be consecutive		Floor	All	Moderate
SOL/226	Free area in front of components		Any non-container component	All	*DepthPercent
SOL/1	General intersection rule	Duplicates & inside critical	Any non-container component	Duplicates inside	Critical
		Unmarked		All	Moderate
		Dimensions & components Determine severity		Overlapping	*Intersection
SOL/17	The layer of component must be from the agreed list		Any non-container components	Unknown layer	Critical
				No layers	Moderate
SOL/232	Manual checking rule		Any	All	Moderate

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/206	Model comparison		No severity parameters	Incorrect model timestamps	Critical
			Any	Added	Moderate
				Removed	
				Modified	
SOL/11	The model should have components		No severity parameters	All	Moderate
SOL/176	Model structure		Any	Duplicate guids	Critical
			Plates, coverings, roofs, slab, wall	Material thickness differs from component thickness	
			Spaces	Space boundary problems	
			Sites	The site does not have a geometry	Moderate
				More than one site exists	
			Projects	More than one project exists	
			Buildings	No floors	
			No severity parameters	No building	
			Doors	Door components aren't related to wall	
				Invalid door opening direction	
			Windows	Window components aren't related to wall	
			Doors and walls	Door components related to different floor than wall components	
			Windows and walls	Window components related to different floor than wall components	
			Floors	Floors aren't related to building	
				Floors related to multiple buildings	
			Any non-container component	Components aren't related to floors	
				Components related to multiple floors	
			Doors	Undefined door operation type	Low
			Floors	Floors with the same name	
				Floors without name	
				Floors in the same elevation	
				Floors without components	
			Any non-container component	Too many polygons	*PolygonMax

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/225	Number of components in space		Any non-container component	No components	Critical
				Not enough components	*NotEnough
				Too many components	*TooMany
SOL/230	Property rule template with component filters		Any	All	Moderate
SOL/9	Property values must be from the agreed list		Any	All	Moderate
SOL/203	Required property sets		Any non-container component	Missing property values	Moderate
				Properties with values	
				Not acceptable property values	
				Missing property sets	*MissingProperty
				Missing properties	
SOL/213	Shelf running meter rule		Spaces	No required spaces	Critical
				Too low spaces	*TooLowSpaces
				Not enough shelves	*NotEnoughShelves
SOL/132	Space area		Spaces	No limit values	Low
				Too small spaces	*SpaceAreaDifference
				Too large spaces	
SOL/38	Space count on each floor		Floors	Extra spaces	Critical
				No spaces	
				Not enough spaces	
				Too many spaces	
SOL/175	Space group containment		Spaces	Not enough spaces	Critical
				Too many spaces	Moderate
				Spaces outside space groups	Low
				Space groups without requirements	
				Missing space groups	
SOL/36	Space requirements		Spaces	The total area of spaces differs from the required target area	Critical
				Not enough spaces	
				No spaces	
				Spaces with the wrong size	Moderate
				Too many spaces	Low
			No severity parameters	Insufficient data	
SOL/202	Space validation		Space	Not touching at all (top/bottom)	Critical
			Building	No slab or roof components	Low
			Space	Partially touching roof/slab above/below	*PartiallyTouching
				Intersection	*SpaceIntersection
				Space height	*SpaceHeight
				Space perimeter not aligned with bounding components	*SpacePerimeter
			Floors	Unallocated area	*UnallocatedArea

Table 4 (continued)

Tag	Rule	Auto	Components	Results category	Severity
SOL/191	Spaces must be included in fire compartments		Buildings	No fire compartments	Moderate
			Floors	No fire compartments on level	
			Spaces	Spaces outside fire compartments	
SOL/162	Spaces must be included in space groups		Spaces	Spaces not included in space groups	Moderate
SOL/19	Spaces must have enough windows area		Windows	The light opening area is too large	Critical
			Spaces	Too small window area ratios	
				Too large window area ratios	Moderate
				Spaces without windows	
				Spaces without classification	Low
			Windows	Missing light opening area data	
SOL/223	Structural components fit in architectural ones		Any non-container components	No corresponding components	Moderate
				Horizontally and vertically exceeding components	*ExceedingPercentage
				Horizontally exceeding components	
				Vertically exceeding components	
SOL/37	Total space area on each floor		Buildings	Non-existing floors	Moderate
			Floors	No area limits specified	Low
			Floors	Area exceeds the given maximum area	*SpaceAreaDiffPercent
			Floors	Area falls below the given minimum area	
SOL/221	Wall distance		Buildings	The table should have only wall or beam components	Critical
			Floors and walls	The distance between wall components is too large	Moderate
			Walls	The distance between wall components is too small	
				Cannot check	Low
			Floors	Gross area space missing	
SOL/216	Wall validation		Walls	Doesn't fulfill the dimensioning requirements	Moderate
				Unknown geometry types	
				Missing space boundaries	
				Wrong extrusion direction	
				Inconsistent wall areas	*WallAreaDiff

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Informed consent For this type of study, formal consent is not required.

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