Achieving Model-Based Safety at Construction Sites: BIM and Safety Requirements Representation

Marjan Vakilinezhad, m.vakili@nyu.edu
NYU Tandon School of Engineering, USA

Priscila Dias, priscila@nyu.edu
NYU Tandon School of Engineering, USA

Semiha ERGAN, semiha@nyu.edu
NYU Tandon School of Engineering, USA

Abstract

Due to the one-of-a-type nature of projects, which necessitates setting up of unique production sites, construction industry requires stringent requirements for safety of the workforce and the general public around any job site. Although there are various federal (e.g., OSHA) and local safety regulations (e.g., NYC Department of Buildings codes) to keep construction sites safe and incident free, 20.5% of work fatalities in the private industry were from the construction industry in 2014 (OSHA, 2014). Within the current practice, the requirements listed in these regulations are kept within document based safety plans. The challenge is the large number of safety requirements to be maintained within these regulations. For example, within only Part 1926 of OSHA, there are 29 main topics and 423 sub topics, with several requirements within each sub topic. Given this, manual approach of tracking whether these requirements are within safety plans and then having them proactively in the schedule for implementation are ineffective, contributing to omissions and accidents/incidents.

The research aims to develop a framework for proactive checking of safety requirements of upcoming activities by representing safety requirements as rules within building information models (BIMs). This paper demonstrates the challenges in converting safety regulations into rulesets for automated compliance checks using BIMs and analysis of these rulesets in a set of construction projects. Initial findings suggest that automated inspection of the safety requirements is achievable, given that the BIM model used is a construction model, and model components are decomposable.

Keywords: Model based safety, Building Information Model (BIM), safety regulations, automated inspection

1 Introduction

Being one of the most injury prone industries, construction industry accounted for one in five work fatalities in the private industry in 2014 (BLS 2014). Although there are federal and local regulations to address safety issues, accidents and near misses are still a reality at job sites. In the past two decades, there were more than 26,000 construction worker casualties in U.S., 40% of which involved falls from height, and 30% of the falls were caused by inadequate, removed, or inappropriate use of fall protection equipment (Zhang et al. 2013). Hence, it is necessary to rethink traditional practices, because safety related issues highly affect the progress of the construction work and may create obstacles for quality improvement of construction processes (Zhang & Hu 2011).

The various safety regulations (e.g., OSHA regulations, Department of Buildings safety regulations) dictate the requirements for keeping construction sites and general public free from harm. However, the bottleneck within the current practice is that the requirements listed in regulations are kept within document based safety plans in the form of narratives. As there is a substantial number of safety requirements to be maintained within these regulations (e.g., only Part 1926 of OSHA comprises 29 main topics and 423 sub topics), the traditional approach of manually checking whether construction safety plans are in compliance with regulations and then implementing them proactively for upcoming activities is inefficient, contributing to omissions and accidents/incidents.

Technological improvements in the construction industry provide opportunities to tackle problems faced in the current practices for streamlining or improving traditional methods. Information stored in building information models (BIMs) can be leveraged for proactive job safety at construction sites. This research explores the potential of utilizing BIMs to assist in automated checking of safety requirements. Phased construction models have the potential to be used for looking ahead in the schedule for upcoming activities on job sites and identifying safety flaws. Within the context of this paper, the authors provide a list of challenges identified while converting safety narratives in OSHA into specific rulesets for enabling automated compliance checks using BIMs. The challenges have been demonstrated using a 14 floor construction project currently under construction.

2 Background

This paper builds upon previous research studies that discuss the necessity of improving traditional construction safety approach, through the use of technology and advanced tools, including building information modeling. Thus, a review of the literature on the topic provided a sound point of departure for generating a knowledge base about the potential of using BIMs to assist construction safety analysis and management.

Labors and general public are surrounded by potential hazards at/around construction sites. The Occupational Safety & Health Administration (OSHA) has grouped worker fatalities into five major categories: falls, struck-by, electrocutions, caught in between, and other (Hinze & Teizer 2011). Safety issues – including unprepared workforce, weak execution of safety regulations, and most important, the deficiency of advanced tools that facilitate precise analysis and execution of safety plans – have been limiting the advancement of safety for construction processes (Zhang & Hu 2011).

Previous research studies have investigated the use of BIM tools and 4D applications to assist managers to analyze the dynamics of construction from a safety perspective (e.g., Zhang & Hu 2011). In addition, research studies looked at automated safety rule checking using BIMs for improving the ineffective approaches currently used to manually track the compliance of safety plans with safety regulations. Towards this, research studies focused on certain aspects of safety regulations (e.g., fall protection) to automatically identify safety threats in building information models (Zhang et al. 2013).

Background literature suggests that there are research efforts investigating ways of applying BIMs to improve the safety level at construction sites. This paper complements the research work performed in this area, however differs from the existing body of knowledge by documenting specific challenges faced while converting the bulk number of safety regulations into rules and integrating them with model components in BIMs.

3 Research Method

In order to identify the challenges inherent in the process of representing and checking safety requirements from regulations in a model-based process, two major tasks were conducted: (1) analyzing major local and federal safety regulations for representing safety requirements and converting them to implementable rulesets, (2) conducting experiments with model-checking tools to link identified safety requirements to testbed building information models. While defining the rule sets and linking models with rule sets, the authors documented the challenges faced that hindered effective linkage of safety requirements to BIMs. For this purpose, the research team selected a building as the case project. The testbed building was a 14 floor office and educational building, located in NY with approximately 460,000 sf area. The complete model (Architectural, Structural, Mechanical, Electrical, and Plumbing) was accessible to the research team. In order to simplify the model to conduct the experiments, only the first 4 floors model along with the activities and construction methods related to these four floors were utilized.

Analysis of safety regulations included the screening and detailed analysis of the major federal safety regulation, which is Occupational Safety and Health Association (OSHA) "Safety and Health Regulations for Construction" (Part 1926). All the safety requirements listed in OSHA Part 1926 were screened through to identify safety requirements that can be linked to building information models. A total of 423 sub topics within Part 1926 of OSHA were evaluated (e.g., 1926.250: General requirements for storage, 1926.502: Fall protection systems criteria and practices, etc.). Initial screening showed that 48 of these subtopics (corresponding to 332 narratives) include OSHA safety requirements that can be represented as rule sets. So far, the research team worked on 38 subtopics (corresponding to 206 of narratives) to work on them to identify the process challenges observed. The list of these sections is provided in Table 1.

Table 1: List of the sections from OSHA that are analyzed so far

Section	Title	Section	Title
1926.25	Housekeeping	1926.452	Additional requirements applicable to specific types of scaffolds
1926.34	Means of egress	1926 L App A	Scaffold Specifications
1926.104	Safety belts, lifelines, and lanyards	1926.502	Fall protection systems criteria and practices
1926.105	Safety nets	1928 M App B	Guardrail Systems - Non-Mandatory Guidelines for Complying with 1926.502(b)
1926.106	Working over or near water	1926.651	Specific Excavation Requirements
1926.150	Fire protection	1926.652	Requirements for protective systems
1926.151	Fire prevention	1926.701	General requirements
1926.152	Flammable liquids	1926.702	Requirements for equipment and tools
1926.154	Temporary heating devices	1926.703	Requirements for cast-in-place Concrete
1926.250	General requirements for storage	1926.754	Structural steel assembly
1926.252	Disposal of waste materials	1926.755	Column anchorage
1926.302	Power-operated hand tools	1926.757	Open web steel joists
1926.307	Mechanical power-transmission apparatus	1926.758	Systems-engineered metal buildings
1926.403	General requirements (Electrical)	1926.760	Fall protection
1926.404	Wiring design and protection	1926.852	Chutes

1926.405	Wiring methods, components, and equipment for general use	1926.958	Materials handling and storage
1926.406	Specific purpose equipment and installations	1926.1052	Stairways
1926.408	Special systems	1926.1053	Ladders
1926.451	General requirements	1926.1435	Tower cranes

In order to convert the narrative to an implementable ruleset, if needed, the narrative is first decomposed into simpler rules to decrease the complexity. Then these simple rules are converted to implementable and machine readable rulesets in the form of pseudo codes. The rules are later checked against the components in a BIM using a model checking environment (Figure1). There are tools available in the industry that enables automated code checking or hazard detection (e.g., VICO, Solibri Model Checker, and Navisworks) (Ku 2010). Such tools can be leveraged to support phase-based safety requirements checking using BIM, given that the safety requirements are represented as rule sets. This workflow has been used to convert an initial set of OSHA Part 1926 subtopics to rulesets and challenges faced while implementing this workflow have been documented. This paper provides an overview of these challenges using the testbed BIM.

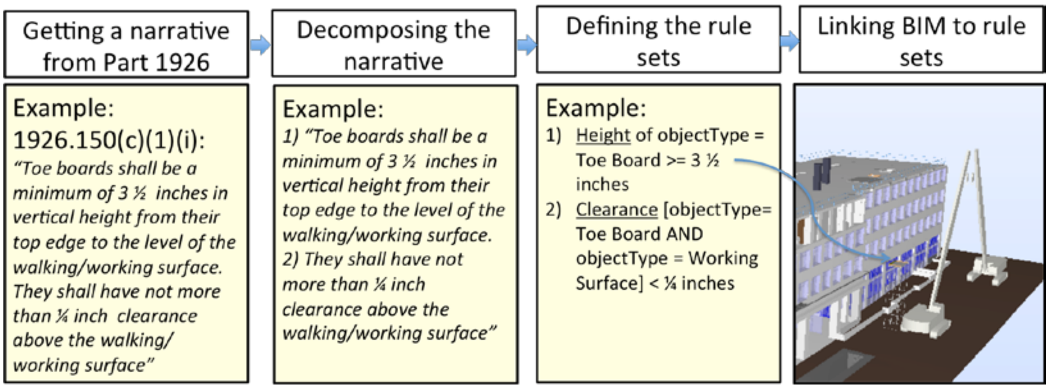

Figure 1 An overview of the workflow

4 Research Findings and Challenges

This section provides the results obtained from the tasks performed, and overviews the set of challenges that authors identified during research. These challenges are essential to know and address in order to heave a streamlined process for model-based safety requirements checking at construction job sites. So far, the research team identified seven major challenges as discussed below with examples demonstrated in the test bed building.

4.1 Vagueness of the narratives

Model-based checking of safety requirements requires clear and specific language without any ambiguity. This requires that narratives are clear in language without any vagueness in the wording that would result in subjective interpretations. An example is from subpart 1926.1053(a)(5) of OSHA (Ladders): "*The rungs of individual-rung/step ladders shall be shaped such that employees' feet cannot slide off the end of the rungs.*" This requirement is vague and uninformative in terms of describing a clear width or shape for the ladder rung to implement as a rule. The missing necessary information makes it impossible to link the rule to the model.

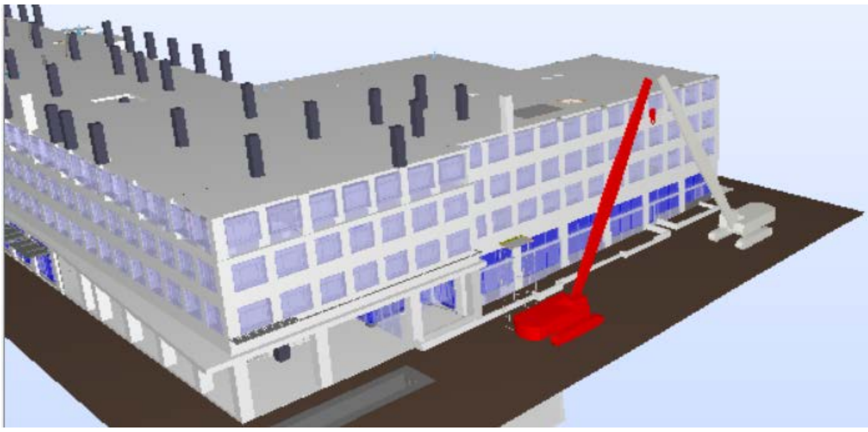

Figure 2 A visual representation of a violated rule, component highlighted in red: This rule checks that Minimum distance between all objects classified as a "Crane" = 2* length of crane boom as an example

A similar example included OSHA subpart 1926.1435 (b) (6) (Tower Cranes) says: "*Multiple tower crane jobsites. On jobsites where more than one fixed jib (hammerhead) tower crane is installed, the cranes must be located such that no crane can come in contact with the structure of another crane. Cranes are permitted to pass over one another*". In order to implement this rule, a specific distance between two objects in the building model should be defined (Figure 2). So far, four such narratives were found within the implemented narratives. Such narratives, even if the corresponding components are in the model, are not possible to accurately represent and check in any process.

4.2 Size of the narratives

Another challenge faced was that narratives contained too many details that required several rules to fully represent them. For example, subpart 1926.502(j) of OSHA requires that, "*Toe boards shall be a minimum of 3-1/2 inches in vertical height from their top edge to the level of the walking/working surface. They shall have not more than 1/4-inch clearance above the walking/working surface.*" This requirement has to be broken down into two separate rules: (1) the height of any object type = "toe board" shall be more than or equal to 3 ½ inches, and (2) the allowed clearance between the object type = "toe board" and the object type = "working surface" should be less than or equal to ¼ inches (Figure 3). The authors performed a detailed analysis of each narrative in OSHA Part 1926 that can be automatically checked in a BIM. 12 of such narratives were identified within the narratives that the research team focused on. As a result, the number of requirements to be implemented becomes even larger than the OSHA narratives. This indicates that when a model based process is adopted, the number of rules to check will be larger, however with an expectation that it will take a shorter time to check their compliance then the current manual practice.

Narrative from OSHA	**Implemented ruleset**
1926.502 (j)(3): "Toe boards shall be a minimum of 3 ½ inches in vertical height from their top edge to the level of the walking/working surface. They shall have not more than ¼ inch clearance above the walking/working surface."	Height of object [Type] = Toe Board ≥ 3 ½ inches Clearance object [Type] = Toe Board AND object [Type] = Working Surface] ≤ ¼ inch

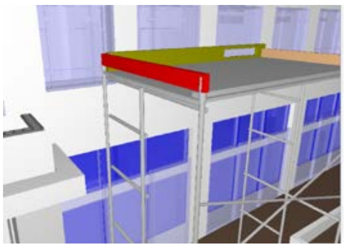

Figure 3 A visual representation of a violated rule, component highlighted in red: The narrative from OSHA and the converted/implemented rules regarding the toe board height

4.3 Using a consistent and recognizable mapping terminology

The narratives in OSHA typically refer to specific components and their properties. In order to implement these requirements, it is essential that the component types referred in machine readable rules correctly map to the component types modeled in a BIM authoring tool. For example, if there is no family in the BIM authoring tool to define a "safety net" or the data exchange format (e.g., IFC) does not define that component, then modelers can use different types of components (e.g., a mesh) to represent a safety net. It will not be possible to identify and check the compliance of the safety nets that are modeled as a "mesh" in a given model. So, it is critical to populate a mapping of possible component types/names for the components that are not typically seen in a model.

Table 2 Examples from OSHA to define the mapping process

Narrative from OSHA	Components	Mapping terminology
1926.105(c) (1): *"Nets shall extend 8 feet beyond the edge of the work surface where employees are exposed and shall be installed as close under the work surface as practical but in no case more than 25 feet below such work surface."*	Safety net Working surface	Any component [type] = Safety net and any slab type= Working surface, will be included in this rule.
1926.152(b)(3): *"...No more than three storage cabinets maybe located in a single storage area. Quantities in excess of this shall be stored in an inside storage room."*	Storage cabinet Storage room	Any component [type] = Storage cabinet and any space type = storage room, will be included in this rule.

Such components are typically the temporary structures and require a consistent mapping terminology to minimize mismatches. The research team identified 30 of such narratives within the scope focused. The required components were defined and assigned certain names/ types that could be recognized by the rulesets. Those names/types were used as a selectable property of the components when applicable rules were defined. A set of components that fall in this category, corresponding OSHA numbers that require the components, and the mapping terminology are provided in Table 2 as examples.

4.4 Narratives not related to BIM

This challenge is related to model-based safety checking process in general. No matter what is done, certain narratives are not possible to link in a model, as it is not possible to represent such items in a BIM. Such rules were either related to human activities (e.g., the activities of the construction workers, inspections, equipment condition, etc.) or there would be no corresponding component in BIMs for those items (e.g., OSHA subpart 1926.35: Employee emergency action plans.). A total of 325 narratives within OSHA are found not possible to represent in BIMs. Implementers should be aware of such narratives.

4.5 Missing components in BIMs that are required by a safety ruleset

BIMs should be complete and well defined from a safety perspective. However, typically design models are available to the construction teams, and model-based safety requires a construction model. Construction models would require representation of equipment (e.g., cranes, containers) and temporary structures (e.g., trenches, ladders, scaffoldings) that are typically tied to safety narratives. The safety requirements implemented by the research team so far are related to these components that are temporarily located on the construction site, and require specification of their locations, minimum/ maximum distance between them, and their properties. Table 3 provides examples about safety requirements regarding those components.

Table 3 Example narratives requiring temporary components in the models

Narratives from OSHA	Required components
1926.151(c)(5): "*... No combustible material shall be stored outdoors within 10 feet of a building or structure.*"	Combustible Material
1926.451(b)(2): *"... Each scaffold platform and walkway shall be at least 18 inches (46 cm) wide."*	Scaffolding
1926.1053 (b)(5)(ii): *"Wood job-made ladders with spliced*	Ladders with material defined as

side rails shall be used at an angle such that the horizontal distance is one-eighth the working length of the ladder."	"Wood".
1926.152(i)(2)(ii)(a): "*The distance between any two flammable liquid storage tanks shall not be less than 3' (0.91 m)*"	Flammable liquid storage tanks

4.6 Missing attributes of components that are required by a rule set

Another area that introduced a challenge was the missing attributes of the components that were checked by the corresponding rule set. Examples of attributes that are typically missing from a typical model component are the radius of a fire extinguisher, opening dimensions of a safety net, mid-rail height of the railings, etc. Since these attributes are typically not represented in a BIM, it was a challenge to run the corresponding rulesets and highlight the problematic safety implementations at a job site. For example, subpart 1926.152(b)(3) requires that "*Not more than 60 gallons of Category 1, 2 and/or 3 flammable liquids or 120 gallons of Category 4 flammable liquids shall be stored in any one storage cabinet.*" However, the volume of the flammable liquid container was not recognized and could not be selected as a controlling parameter for the component. To solve this problem, modelers should be aware of required attributes.

4.7 Inflexibility of the tools to define required rulesets

It is possible that the tool used to check the rules is limited in flexibility to define new rule sets. There are possibilities to leverage the built-in rule sets in the library of the tool, however they were not adequate to check the required safety topics for this case. Another inflexibility with the off-the-shelf checking tools is the limited range of logical operators and conditional statements that can be combined together. As a result, additional division of the topics and subtopics was required in order to implement them as rules. For example, OSHA sub part 1926.651(c) (2) requires that "*Means of egress from trench excavations. A stairway, ladder, ramp or other safe means of egress shall be located in trench excavations that are 4 feet (1.22 m) or more in depth so as to require no more than 25 feet (7.62 m) of lateral travel for employees*". The common method for converting this requirement to a rule would be: if the depth of object Type = "Trench" > 4' then object Type= "Trench" contain an object Type = "Ladder" or "Stairway" or "Ramp" and the maximum distance between the two = 25'. However, this narrative was broken down into three different rule sets as it was not possible to combine multiple operators and if statements in the model checking environment used. 12 of the implemented rule sets by the research team belong to this category. In addition to creating more rules, this limitation resulted in more false negatives when the BIM model was checked for the safety requirements. The model-based safety process would necessitate tools that are more flexible to define new rulesets or in-house prototypes need to be developed that parse information exchanged for a BIM and check the necessary components.

4.8 Missing component decompositions

The challenge in this category was due to rulesets that pertained to certain parts of the corresponding components. For example, OSHA subpart 1926.105(d) states that:" *The mesh size of nets shall not exceed 6 inches by 6 inches*", or OSHA 1926.451(e) (2) (iii) states that: "*When hook-on and attachable ladders are used on a supported scaffold more than 35 feet (10.7 m) high, they shall have rest platforms at 35-foot (10.7 m) maximum vertical intervals*". A similar example was the toe-board example for the scaffoldings. These rulesets require getting access to "mesh size" or "rest platform" of corresponding components, such information is not always available in a BIM. Since the subparts of the components like ladders and scaffolds are not recognized, the requirements addressing those component parts were problematic. 14 such narratives were identified so far. This limitation resulted in a constraint, which requires the components to be decomposable in order to make it possible to check the safety requirements for corresponding parts. This requires an extra effort to define parts of such components as separate objects with the object hierarchy maintained.

In this section the challenges observed during the implementation of the rulesets in BIM validation software was presented. These challenges could be divided into two main groups: (1) Narrative-related challenges which include the large size and vagueness of the narratives, keeping a constant and recognizable mapping terminology and rules that could not be checked in BIM. (2) Limitations of BIM editing and validating tools. Missing components, missing attributes of components, missing component decomposition and, having multiple rulesets for one statement as well as the inflexibility of the model checking tool to define rulesets belong to this group. In order to enable the model based safety representation, improvements in both groups is essential. The narratives could contain more specific requirements and should be edited and simplified to easily implementable rules. On the other hand, the BIM editing tools could be improved in terms of including properly modeled detailed components and families with recognizable attributes. Finally, the BIM checking tools could be enhanced to include the necessary tools to easily recognize the modeled objects and related attributes and to provide the built-in rules to check the safety requirements.

5 Conclusion

The large number of safety requirements and the traditional manual approach of tracking them on construction site make it difficult to efficiently check the implementation of these requirements in schedule, resulting in various incident/accidents in construction industry. Building information models can assist the construction site safety, and enable proactive checking of required safety precautions for upcoming activities. Towards this aim, this paper provided the challenges identified for enabling model-based safety checking at job sites on a 12 story case building.

The primary objective of this study was to identify the challenges through the analysis of rule sets in a specific construction project where model is available. The initial challenges identified can be grouped under three as: (1) challenges in converting the safety requirements to simple and implementable rules, (2) challenges in modeling the required component clearly and properly in BIM, and (3) challenges regarding the inflexibility/ limitation of the model checking tool. The initial findings suggest that further actions should be taken in all three fronts to comprehensively check models for safety.

References

Bureau of Labor Statistics [BLS] (2014). *Census of Fatal Occupational Injuries Summary, 2014.* Retrieved from: <http://www.bls.gov/news.release/cfoi.nr0.htm> on March 5th 2016.

Hinze, J., and Teizer, J. (2011). Visibility-related fatalities related to construction equipment. *Safety Science.* 49. pp. 709-718.

Ku, K. (2010). Research needs for Building Information Modeling for Construction Safety. *PhD dissertation*, Virginia Technical University, Blacksburg, VA.

NYC Department of Buildings [DoB] (2014). *Building Code – Safeguards during Construction or Demolition (Chapter 33). In: "2014 Construction Codes".* Retrieved from: <http://www1.nyc.gov/site/buildings/codes/2014-construction-codes.page#bldgs> on March 10th 2016.

Occupational Safety and Health Administration [OSHA]. *29 C.F.R. 1926 OSHA Construction Regulations.* Retrieved from: <https://www.osha.gov/pls/oshaweb/owastand.display_standard_group?p_toc_level=1&p_part_number=1926> on February 26th 2016.

Occupational Safety and Health Administration [OSHA]. *Commonly Used Statistics.* Retrieved from: <http://www.osha.gov/oshstats/commonstats.html> on March 28th 2016.

Smith, D. (2007). An Introduction to BIM. *Journal of Building Information Modeling.* Fall 2007. pp.12-14.

Zhang, J., and Hu, Z. (2011). BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in Construction.* 20(2). pp. 155-166.

Zhang, S., Teizer, J., Lee, J., Eastman, C., and Venugopal, M. (2012). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction.* 29. pp. 183-195.