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Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)

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ABSTRACT

Construction safety related knowledge and project specific information are scattered and fragmented. Despite technological advancements of information and knowledge management in the building and construction industry, a link between safety management and information models is still missing. The objective of this study is to investigate a new approach to organize, store and re-use construction safety knowledge. A construction safety ontology is proposed to formalize the safety management knowledge. It consists of three main domain ontology models, including Construction Product Model, Construction Process Model, and Construction Safety Model. One-on-one expert interviews were conducted for ontology evaluation. The interaction between safety ontology and Building Information Modeling (BIM) is also explored. A prototype application of ontology-based job hazard analysis (JHA) and visualization is implemented to further illustrate the applicability and effectiveness of the developed ontology. The developed construction safety ontology enables more effective inquiry of safety knowledge, which is the first step towards automated safety planning for JHA using BIM.

1. Introduction

About 90% of workplace injuries can be traced to unsafe work practices and behaviors [1]. As good safety practices and records create a positive, incident free, and productive work environment, planning for safety at the front-end of a project is not only the first but also a fundamental step for managing construction safety and health, and establishing a good safety culture [2].

Planning for safety typically consists of the identification of all potential hazards, as well as the decision on choosing corresponding safety measures [3]. A job hazard analysis (JHA) is a technique that focuses on job tasks as a way to identify hazards before they occur. It focuses on the relationship between the worker, the task, the tools, and the work environment [4]. As a process of identifying potential hazards for each step of an activity and proposing safety rules to prevent potential incidents related to these hazards, the US Occupational Safety and Health Administration (OSHA) recommends performing JHA for construction activities to highlight and react to potential hazards. The basic procedure (see Fig. 1) for conducting a JHA includes (1) identifying all job steps of a given activity; (2) identifying potential hazards related to these different job steps; and (3) proposing action procedures (e.g., safe procedures or precautions) to eliminate, reduce, or control each hazard [5]. Table 1 shows a sample JHA form of an activity "Dismantling Scaffolding". It lists general project and task information, the type and the actions to control the hazards. The JHA form is typically read and explained to workers in a pre-task work meeting. Each participant is required to acknowledge its content by signing the form. This theoretically ensures that each worker is familiar with related work task hazards and mitigation strategies. Beyond such advantages alerting workforce ahead of executing potentially dangerous work tasks, some project stakeholders may use the form for legal purposes.

Because of the complexity and time-consuming nature of JHA, safety personnel need extensive time to acquire the JHA information and then apply the knowledge to perform the analysis. Another factor contributing to the time-consuming nature of JHAs is the one-of-a-kind character of construction projects which makes each JHA unique every time it is required. However, the entire analysis is typically structured in multiple stages containing a number of recurring and similar JHA. Such JHA can be represented and stored as generic reusable patterns that can be standardized and instantiated for many different projects.

With the advancement of information technology in the building and construction industry, a missing link between safety management and information models becomes apparent. The richness of design information offered by Building Information Models (BIM) has helped on the delivery of better quality buildings. The ability to extract construction specific information from a BIM is critical to support productive, safe and healthy construction workplaces and other downstream

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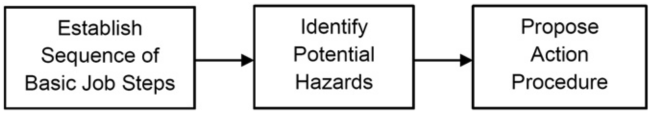


Fig. 1. Basic JHA procedures.

processes [6]. In terms of construction safety, the current construction safety information and knowledge available through mandated safety rules and regulations, existing accident records, and personal safety engineering experience are mostly scattered and fragmented. It currently cannot easily be linked to or represented in project models such as a BIM. Given these circumstances, this research presents the development of a Construction Safety Ontology aiming to integrate safety knowledge with project planning and execution to enable early hazard identification and BIM-based visualization. Considering that there is no "perfect" ontology and no "optimum" classification or concept hierarchy [7], it is important to note that the proposed Construction Safety Ontology is not intended to cover a domain of interest in full detail. Rather, as a domain ontology, it intends to capture the most fundamental concepts in the domain in a structured and extendable format [8].

This study aims to formalize construction safety knowledge and connect it with BIM for automated hazard analysis and safety task scheduling. This paper is structured as follows: Section 2 reviews the current safety practice and existing studies on compliance checking and knowledge modeling in the Architecture, Engineering, and Construction (AEC) industry. Section 3 presents the objective and scope of this study. In Section 4, the research methodology for developing the proposed construction safety ontology is presented along with the system architecture of a proposed ontology-based hazard identification application. The taxonomical structure of the Construction Safety Ontology is defined and explained in Section 5. The first stage of the ontology validation through one-on-one expert interviews is discussed in Section 6. The developed automated JHA in BIM application is demonstrated in a case study as part of the second stage validation in Section 7. A summary of the contributions and suggestions for future research in the final section conclude this paper.

2. Background

2.1. Current construction safety planning and knowledge management practice

The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. Safety planning in construction environments is thus challenging. Traditional JHA requires safety personnel to perform several important tasks, for example, learning from historical documentation to gain safety knowledge and applying it to activities on new construction projects. Often they use their historical documentation or best practices as a template so they do not have to start from scratch. The uniqueness of the construction activities and their contexts can lead to problematic JHA and expose workers to uncontrolled hazards. Hence, JHA is complex, time-consuming, at times inaccurate, and hard to keep up-to-date with changing construction schedules. Safety personnel must perform JHAs often weeks, sometimes even months, before the activity actually is scheduled to be performed [9]. This makes it difficult to quickly react to changes in the construction plans and schedules while appropriately managing the resulting safety concerns.

Table 1
Sample JHA form.

Project title: *Masonry Project XYZ*	Job location: *Third Floor*	Analyst: *Safety Superintendent A*	Date: *Feb. 17, 2014*
Activity name: *Dismantling scaffolding* Job step: *Dismantle scaffolding components from the level above* Hazard type: *Fall* Hazard controls: *1. Provide and use lifelines & harness with fall arrester* *2. Implement buddy system among workers* *3. Display warning signs* *4. Cordon off affected work area* *5. Implement effective communication system to stop work when there is bad weather*			

On the other side, current construction safety information and knowledge are scattered and fragmented across safety regulations, accident records, best practices, and safety experts' experiences. In knowledge management terms, there are two types of knowledge typologies: explicit and tacit knowledge. The explicit knowledge of construction site safety exists in the form of accident records, and safety regulations as well as best practices. Safety hazard recognition is an important actualization of tacit knowledge since it mainly relies on a safety engineer's experience [10]. For this matter, design-for-safety toolbox software was developed by Gambatese et al. [11]. It contains a database of design suggestions or "best practices" that can be implemented during the project planning and design phases. A way to properly document and organize such knowledge and enable quick project-specific inquiry becomes essential to fully leverage existing safety knowledge. A disadvantage of the tool is that it does not consider the specific conditions that exist on a construction site, for example, daily progress or changes of the job site environment. The tool only recommends mitigation strategies at a higher, more general level, for example, what solutions exist when fall hazards are present.

2.2. Information technology supported construction hazard identification

Information and communication technologies (ICT), such as BIM, Virtual Design and Construction technology (VDC) along with Geographic Information Systems (GIS), have become established tools in the AEC industry. The literature shows that VDC has potentials to simulate various stages of the construction process to help engineers, architects, and contractors to detect, visualize, and resolve safety hazards prior to the hazardous conditions arising in the project. A number of research efforts focused on improving construction hazard identification using ICT. Hadikusumo and Rowlinson [10] developed a design-for-safety-process (DFSP) tool to assist a user in identifying safety hazards inherited within construction components and processes. The DFSP database contains object types, possible safety hazards, and accident precautions database. Bansal [3] uses GIS based navigable 3D animation in safety planning for predicting places and activities which have higher potential for accidents; he links the information between the CPM schedule and safety recommendation database. The VTT Technical Research Centre of Finland [12] developed a job safety analysis method with the aid of virtualized construction site using CAVE^{TM} (CAVE Automatic Virtual Environment) [13]. Guo et al. [14] developed a conceptual framework of adopting virtual prototyping technology to aid construction safety management. It consists of three components: modeling and simulation, the identification of unsafe factors, and safety training. Lin et al. [15] developed a 3D video game, Safety Inspector, to provide a comprehensive safety training environment in which students assume the roles of safety inspectors and walk the game site to identify potential hazards.

Although these existing studies share similar objectives with this study, none of them formalize the safety knowledge in a way that can support hazard identification and visualization on the job step level. Further automation of the process and better visualization methods need to be explored.

2.3. Compliance checking in construction

A promising knowledge management direction in construction is the use of BIM applications in the AEC industry to facilitate rule checking and simulations for evaluating building designs in the early phase of a project [16–18]. Numerous studies have focused on developing compliance checking algorithms and applications to ensure design quality. Along with developing rule-checking software, a domain-specific language has been introduced as a language-driven approach to the rule checking and architectural design analysis [19]. Zhang et al. [20] introduced the integration of construction and safety management based on BIMs and rule-based algorithms based on OSHA fall protection regulations. Industry Foundation Classes (IFCs)-based solutions have also been explored for fall hazards identification and prevention in construction [21]. Solibri Model Checker [22] is one of the commercially-available applications which provide rule checking capability against BIMs for architectural design validations. However, construction safety hazards identification is currently not realized either in such program or by existing studies. More advanced and general rule-checking solutions for construction safety need to be explored.

2.4. Ontology-based knowledge modeling in AEC industry

Gruber [23] defined ontology as "an explicit and formal specification of a conceptualization." Ideally, an ontology should (1) capture a shared understanding of a domain of interest and (2) provide a formal and machine readable model of the domain [24]. Ontologies are now central to many applications such as scientific knowledge portals, information management and integration systems, electronic commerce and web services. Ontologies have been used in artificial intelligence to try to capture knowledge, and create a model of the knowledge base. There exist numerous examples of general and specific ontologies, such as medical, transportation, and plant ontologies [25]. In recent years, ontologies have been adopted in many business and scientific communities as a way to share, reuse and process domain knowledge. The main areas, in which ontological modeling is applied, include communication and knowledge sharing, logic inference and reasoning, and knowledge reuse.

Development of a domain ontology in the construction industry has been another crucial step to improve knowledge management and workflow. Venugopal et al. [26] presented a formal classification structure for IFC implementations for the domain of Precast Concrete Industry to improve the interoperability of BIM applications. Lima et al. [27] implemented the e-COGNOS platform and proved the benefits of using semantic systems for adequate search and indexing capabilities. Secondly, the work they presented allows a systematic approach for formally documenting and updating organizational knowledge. Lastly, their work enhances the customization of functions in knowledge management systems. The e-COGNOS platform presented the first comprehensive ontology-based portal for knowledge management in the construction domain. Akinci et al. [28] envisioned that semantic CAD/GIS web services can provide a way to address the lack of interoperability between CAD and GIS platform. El-Diraby and Osman [29] developed a domain ontology for construction concepts in urban infrastructure products. Wang and Boukamp [9] presented a framework aiming to improve access to a company's JHA knowledge by using ontologies for structuring knowledge about activities, job steps, and hazards. Zhang et al. [30] proposed a framework for automated, ontology-based job hazard analysis in building information models. An ontology-based semantic modeling approach of regulation constraints based on proposed CQIEontology and construction process ontology was explored by Zhong et al. [31] aiming to integrate regulation knowledge with the definition and execution of construction processes. They concluded that the proposed regulation-based automated construction quality compliance checking as a parallel activity to construction planning and execution can improve efficiency, reduce errors, and save human resources. Ontology has also been applied to establish the basis of a decision-making tool for analyzing environmental, health and safety risks along project planning and execution phases. Also, it supports to define technical solution and preventive measures [32–34].

Undoubtedly, these research efforts have paved the way towards automated compliance checking and knowledge modeling in the construction industry. However, from the literature review given above, it can be concluded that most of the existing efforts have focused on a domain ontology for construction concepts and model exchange. We currently still lack an ontology to both represent construction safety knowledge and to enable interaction between ontology and BIM.

In terms of knowledge preparation, Natural Language Processing (NLP) techniques have been leveraged to extract information from regulation text. Zhang and El-Gohary [35] explored the effectiveness of utilizing syntactic and semantic features of the text to automatically extract regulatory information from building codes using automated Information Extraction (IE) approach. Chi et al. [36] presented an approach based on text classification to support the automation of JHA. Kim et al. [37] proposed an automated information retrieval system that can search for and provide similar accident cases. The retrieval system extracts BIM objects and composes a query set by combining them with a project management information system. Chi et al. [38] applied ontology-based text classification (TC) to match safe approaches identified in existing resources with unsafe scenarios to assist JHA. However, knowledge extraction and preparation using NLP are beyond the scope of this study.

3. Objective and scope

In this study, we propose a construction safety knowledge ontology to formalize the safety management knowledge, and explore its connection with BIM to advance the interaction between safety management and BIM. The purpose of the ontology is to allow computer applications to easily discover, query, and share construction safety knowledge. Though the ontology aims to be general and extensible, in order to limit the scope of demonstration and validation in this paper, masonry construction was chosen as an area of focus for demonstrating the effectiveness of the developed ontology, as "masonry construction is one of the specialty trades with high risk of work-related injuries" [39]. While the possibility to connect the ontology to BIM is explored, the actual semantic modeling of safety information in the form of building information (e.g. using IFCs) is not investigated in this paper.

4. Research methodology

The reasons for using ontologies for safety knowledge modeling are manifold. First, they can be shared and used to link information from different knowledge domains together. Second, ontologies support consistency checking and reasoning. In addition, concepts used in explicit safety knowledge and their semantic relationships can be represented in the form of classes and properties of the ontology in an intuitive way [31].

Automated reasoning about specifications requires the specifications to be modeled in a computer-interpretable way [40]. In order to make construction safety specification checking an easier and more efficient process for safety managers or superintendents, an ontology-based semantic modeling of safety specifications is explored. The detailed research tasks are shown in Fig. 2 and explained in the following sub-sections.

4.1. Defining the purpose and the scope of the safety ontology

The purpose of developing a construction safety ontology is not only to formalize the current construction safety knowledge, but also to

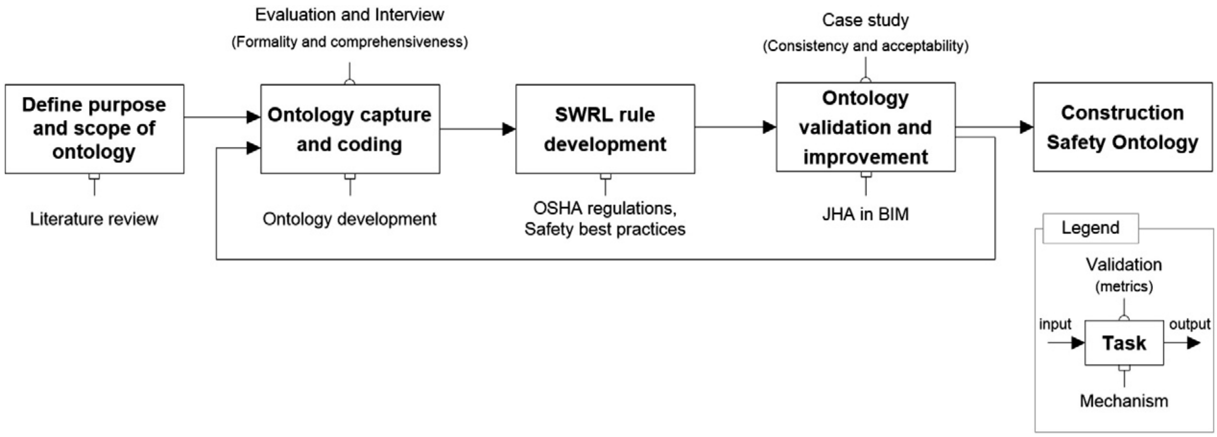


Fig. 2. Research tasks in construction safety ontology development.

support safety hazard identification and mitigation through BIM. An ontology should therefore support the integration of the knowledge with building information models. Existing BIM schema, such as the IFCs, are considered. For example, the data structure for building elements in the safety ontology follows IFC's *IfcBuildingElement*.

4.2. Ontology capturing and coding

The knowledge sources considered for identifying relevant concepts and coding the safety ontology include the OSHA regulation 1926 [41], the Occupational Injury and Illness Classification Manual [42], and Construction Solutions Database [43]. These include construction safety regulations and industry safety best practice reports. In order to design and maintain a meaningful, correct, and minimally redundant ontology, the consistency of the ontology is checked and verified using an automated reasoner. A Description Logic (DL) reasoner is able to perform various automated inferencing services on the developed OWL-based ontology, such as determining whether or not the ontology includes inconsistent classes. Automated consistency checking is crucial as manual checking would be highly time-intensive. It helps in assessing the overall consistency of the ontology. In addition, interviews with domain experts were conducted to further evaluate the ontology content.

4.3. Semantic Web Rule Language (SWRL) rule development

The Semantic Web Rule Language (SWRL) is a language that can be used to express rules as well as logic, combining OWL DL or OWL Lite with a subset of the Rule Markup Language [44]. Selected OSHA regulations and industry safety best practices are coded in SWRL rule formats, compatible with ontology classes and relationship. This enables automated reasoning to test the applicability of safety rules and regulations for different projects. An additional objective was to have rules that can be configured and adjusted by a user. As the rules will likely be applied to projects with unique circumstances, user-friendliness to reflect advantages of competing construction methods and other accepted best safety practices as well as human involvement are key concerns in the traditionally risk-averse construction industry. It is therefore possible to have industry subject experts to adjust existing SWRL rules or to create new rules in Protégé; however, it may require some additional training if Protégé is new to them.

4.4. Ontology validation and improvement

A BIM-based JHA application is developed to automatically identify work activity related safety hazards, suggest mitigation methods, and visualize relevant safety information, such as hazard zones. All support safety management in advancing decision making at the front-end, before any work tasks start. The feedback from the application (i.e. users provide verbal or written comments on the reliability and accurateness of the new approach) then goes back to ontology development to make further improvement. The Construction Safety Ontology then becomes the final output.

The system architecture of our ontology-based hazard identification application includes ontology editor, reasoner, rule engine, and BIM platform (see Fig. 3):

1) *Protégé* is an open-source platform to construct domain models and knowledge-based applications with ontologies [45]. The OWL-based safety ontology is first modeled and edited using *Protégé* to define its classes, relationships and axioms.
2) *Pellet* is an OWL 2 reasoner providing OWL DL reasoning services for OWL ontologies. It is used to check the consistency of the developed Construction Safety Ontology.
3) Based on the Construction Safety Ontology, SWRL rules are then developed to represent OSHA regulations. Also, the rule set can be customized and rules can be added by subject matter experts according to their specific requirements.
4) After connecting the ontology with *Tekla*, a commercial BIM software platform, individuals/instances of the safety concepts defined in the ontology are generated using BIM project information. Properties of each individual, such as geometry information, are obtained through BIM.
5) Facts including the knowledge base and individuals generated from BIM are passed to the *Jess* rule engine to be checked against SWRL rules defined earlier by a *safety manager*.
6) Once new knowledge has been inferred by the rule-checking process, *Jess* updates the ontology.
7) The updated OWL ontology is then linked with the BIM platform to visualize inferred knowledge, such as required safety protective systems and protective safety zones.
8) Finally, project specific JHA along with a 4D building model visualizing safety information are generated to support site level project safety planning and inspection.

5. Taxonomical structure of the construction safety ontology

The goal and intention of this research are to formalize construction safety planning knowledge by developing a Construction Safety Ontology. As shown in Fig. 4, our Construction Safety Ontology consists of three main domain ontology models including: *Construction Product Model*, *Construction Process Model*, and *Construction Safety Model*.

The *Construction Product Model* contains building element information such as column, slab, and wall information, and provides the main interface for connecting the ontology and a BIM platform. It

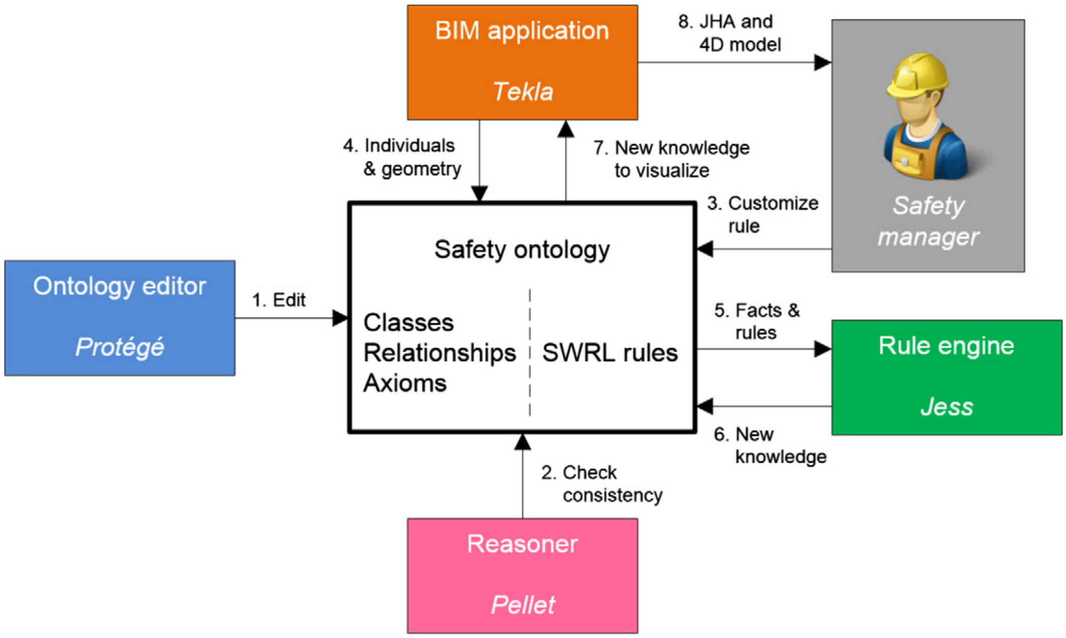


Fig. 3. System architecture of the ontology-based hazard identification application in BIM.

follows the structure of the IFC schema and mainly includes subtypes of IfcBuildingElement. This building element includes major functional parts of a building; examples are foundation, floor, roof, and wall [46].

The *Construction Process Model* includes the construction plan of the project along with construction resources, such as equipment, material and labor. The model used in this study was based on several existing studies on construction process modeling. Specifically, it leveraged models proposed by Benevolenskiy et al. [47] and Wang and Boukamp [9] and modified these to fit to the construction safety domain. *Task*, *Activity*, and *Job_Step* represent the hierarchical breakdown of the construction process. *Task* is related to *Building Component* through the "produce" property. For instance, *Task_Masonry_Wall* produces *Masonry_Wall*. Each of the tasks consists of a set of activities, and each activity consists of different job steps. The construction method is associated with the activity and construction resources are related to each of the activity's job steps.

The *Construction Safety Model* contains construction safety related knowledge, such as potential hazard, specification from regulations, mitigation recommendation, and safety resource. Each *Job_Step* is associated with multiple *Potential_Hazard* instances through the "hasHazards" property. Then, each *Potential_Hazard* is controlled by some *Mitigation_Recommendation* to eliminate or reduce the safety risk. Some of the *Mitigation_Recommendation* requires additional *Resource* instances such as safety protective systems or equipment. "hasHazards" and "needResoruces" are determined using conventional hazard recognition (hazards) and mitigation (resources) strategies. These resources are regulated by *Safety_Specification* instances derived from safety regulation or best safety practices. The type and classification of potential hazards follow the Occupational Injury and Illness Classification Manual [43]. The connections between *Job_Step* and *Potential_Hazard* are established based on industry safety database such as the Construction Solutions Database [42].

The *Resource* class hierarchy is further explained in Fig. 5 using the same annotation as Fig. 4. It contains four resource subclasses, namely *Equipment*, *Material*, *Labor* and *Safety_Measure*. The *Safety_Measure* has five subclasses: (1) *Training* to train workers to conduct the job in a safe manner, (2) *Personal_Protective_Equipment,* such as gloves and lifelines, (3) *Safe_guard*, for example guardrail systems which are applied on instances of *Building_Element*, (4) *Protective_Space*, for instance a limited access zone for masonry wall construction to avoid unneeded personnel entering a dangerous area, and (5) *Inspection*, if the job activity needs to be inspected by safety personnel.

The resulting construction safety ontology allows for the integration of safety planning and construction execution planning by linking safety knowledge to construction processes and products.

6. Construction safety ontology evaluation

Generally, ontology evaluation is roughly classified into two kinds: form-based (syntax) evaluation and content-based (semantic) evaluation. The developed ontology has been checked to ensure its consistency using the *Pellet* reasoner. Such a form-based evaluation as to whether the ontology being constructed is written properly in terms of its form/syntax is required to enable automatic reasoning. However, content-based evaluation is needed to evaluate whether the ontology properly represents the target domain [48].

Two types of content-based evaluation methods were considered in this study: agreement-based and task-based. Agreement-based evaluation is measured through the proportion of agreement that experts have with respect to ontology elements and structure. Task-based evaluation assesses what domain tasks have to be supported by an ontology and how well that ontology supports these tasks [49]. It measures an ontology according to its fitness to goals, preconditions, post conditions, constraints and options. The developed ontology is evaluated through interviews with subject experts and then tested through the developed JHA application as a task-based evaluation, which will be discussed in the next section.

One-on-one interviews were conducted with construction safety experts to evaluate the content and structure of the ontology. 11 professionals completed the survey whose time in the industry accumulates to about 117 years of practical work experience (Table 2). The evaluation process consists of three major sections: 1) the taxonomy, relations, and axioms of the construction safety ontology were first presented to the safety professional, then 2) an open discussion was held to explain the details of the ontology and also to receive constructive feedback, and 3) the participant was asked to evaluate the ontology through an online survey after the interview.

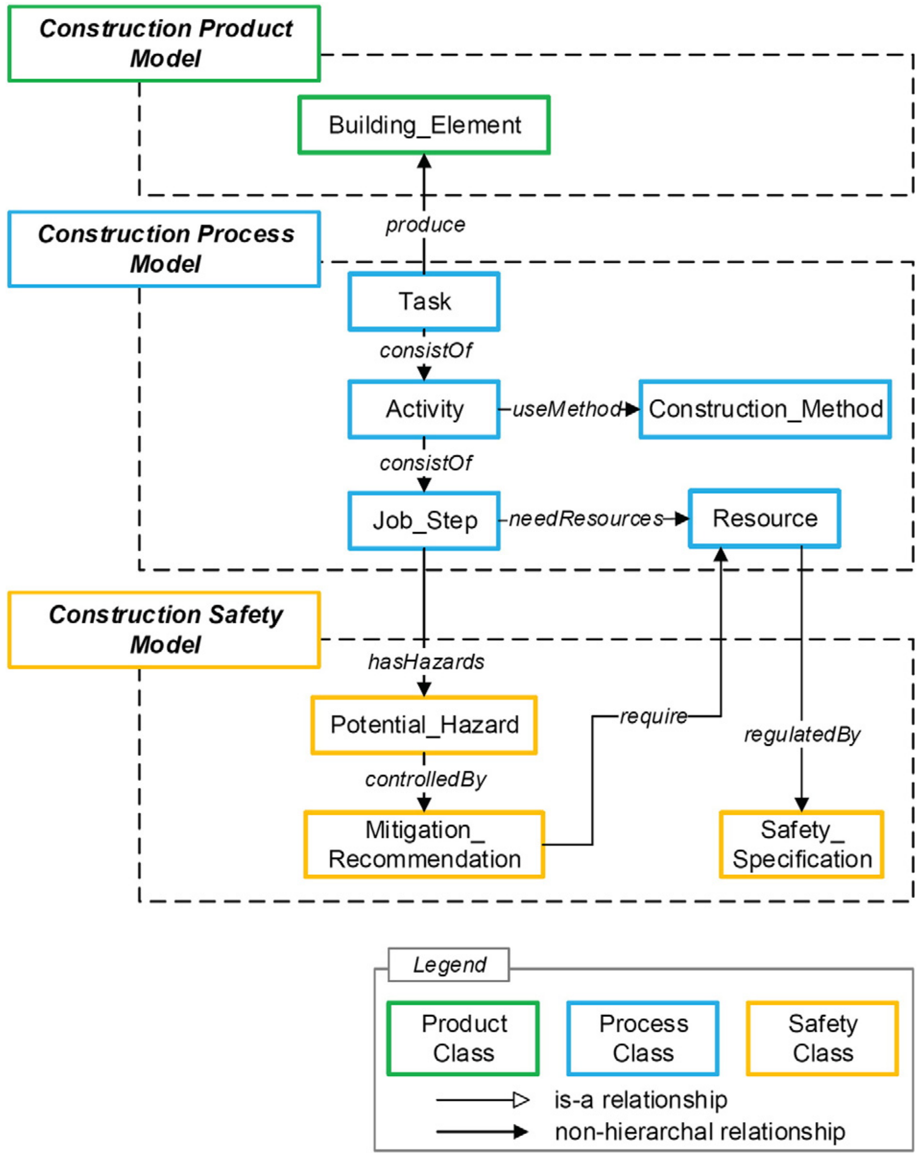


Fig. 4. The Construction Safety Ontology.

The survey used a Likert six-point scale to record the responses of experts, with 1 being the most favorable (see Table 3). The results indicate that:

- Participants find the concepts used to be in the range of "very familiar" to "familiar."
- Participants find the concepts and relations used in the ontology are "representative" of construction safety knowledge.
- Participants find the navigation through the ontology to be "easy".
- Participants "agree" that the ontology covers the main concepts and relations within the construction safety domain.

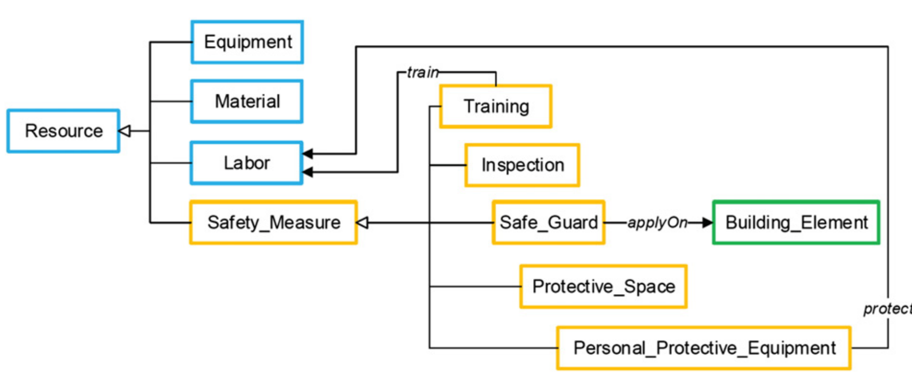


Fig. 5. Resource class in the Construction Safety Ontology.

Table 2
Industry safety professional participants.

Participant	Years of experience	Job title
1	20	Safety Engineering Supervisor
2	9	OSHA Inspector and Industrial Hygienist
3	35	Construction Project Manager
4	15	Safety Professional
5	10	Safety Director
6	5	Assistant Superintendent
7	5	Safety Engineer
8	1	Project Safety Coordinator
9	9	HSE Manager
10	6	Projects HSE Consultant
11	2	Project Safety Advisor

Table 3
Survey results.

Question	Mean	Median	Standard deviation	Result
Are you familiar with the concepts used in the ontology?	1.45	1	0.5	"Very familiar" to "familiar"
Do you think the concepts and relations used in the ontology are representative?	1.64	2	0.48	"Representative"
How easy was it to understand and navigate through the ontology?	1.82	2	0.54	"Easy"
Does the ontology cover the main concepts and relations within the Construction Safety domain?	1.91	2	0.51	"Agree"

7. Automated JHA in BIM: a case study

7.1. SWRL rule development

The OSHA regulation of masonry construction [41] was first interpreted into SWRL rules using the ontology's concepts. The following examples show (1) the requirement of limited access zone for masonry wall and (2) the requirement of having a bracing system, if the height of the wall is greater than 8 ft for a *Placing_Brick* job step. It should be noted that other job steps related to constructing the masonry wall also need to establish such SWRL rules. All units were converted from U.S. standard to metric in the SWRL rules. The concepts and attributes in these two SWRL rules are illustrated in Fig. 6, which also shows their correspondence with the Construction Safety Ontology in Fig. 4.

OSHA Regulation 1:

> *1926.706(a)* A limited access zone shall be established whenever a masonry wall is being constructed.
> *1926.706(a)(2)* The limited access zone shall be equal to the height of the wall to be constructed plus four feet, and shall run the entire length of the wall.

SWRL Rule 1:

Masonry_Wall(?mw) ∧ hasHeight(?mw, ?h) ∧ Task_Masonry_Wall(?act) ∧ produce(?act, ?mw) ∧ consistOf(?act, ?sub) ∧ Masonry_Operation(?sub) ∧ consistOf(?sub, ?pb) ∧ Placing_Brick(?pb) ∧ needResources(?pb, ?laz) ∧ Limited_Access_Zone(?laz) ∧ hasHeight(?mw, ?h) ∧ hasLength(?mw, ?l) ∧ swrlb:add(?x, ?h, 1219.2) → hasWidth(?laz, ?x) ∧ hasLength(?laz, ?l) ∧ hasHeight(?laz, ?h)

OSHA Regulation 2:

> *1926.706(b)* All masonry walls over eight feet in height shall be adequately braced to prevent overturning and to prevent collapse unless the wall is adequately supported so that it will not overturn or collapse. The bracing shall remain in place until permanent supporting elements of the structure are in place.

SWRL Rule 2:

Masonry_Wall(?mw) ∧ hasHeight(?mw, ?h) ∧ Task_Masonry_Wall(?act) ∧ produce(?act, ?mw) ∧ consistOf(?act, ?sub) ∧ Masonry_Operation(?sub) ∧ consistOf(?sub, ?pb) ∧ Placing_Brick(?pb) ∧ swrlb:greaterThan(?h, 2438.4) → needResources(?pb, Masonry_Wall_Bracing)

7.2. Individual generation

The individual generation is the process to create ontology instances based on model items in BIM, and the process is illustrated in Fig. 7 as an example. Individuals are generated based on the information both from the safety ontology and BIM. In Fig. 7, *Masonry_Wall_362* is generated as an individual of *Masonry_Wall*. Related classes are also generated to the instance level as shown from the snippet of OWL RDF/XML of this individual in Fig. 8 including activity, task, resource, potential hazard, etc. In addition, information such as geometry and schedule obtained from BIM are attached to the individual.

7.3. Individual update and visualization

In this example, dimensions of an inferred *Limited_Access_Zone* are computed by running the rule engine and evaluating the SWRL rule. In Fig. 9, the height, length and width of the individual *Limited_Access_Zone_362* are computed based on the geometry of the masonry wall, and displayed in Protégé. Fig. 10 shows the snippet of the *Limited_Access_Zone_362* in OWL RDF/XM format. Hence, the BIM is updated to visualize the limited access zone for masonry construction.

Limited_Access_Zone has been created and visualized in the model (see Fig. 11a). In addition, since the height for this masonry wall is larger than 8 ft, *Masonry_Wall_Bracing* task has been automatically inserted into schedule with a link to the wall object in BIM (see Fig. 11b). The limited access zone is generated on one side of the wall, and usually scaffolding will be erected at the other side. Since it is a layout issue, side for limited access zone is first randomly picked by the program and the user can switch the two sides if needed afterwards.

7.4. Automated JHA and reporting

A JHA prototype was developed using Microsoft Visual C# to implement the ontology-based hazard identification application (Fig. 12). The JHA Advisor user interface is designed to leverage different sets of BIM and the Construction Safety Ontology. The general steps of applying the prototype are listed as follows:

1) Load construction schedule from the building model
2) Load construction safety ontology as OWL format
3) Generate individuals based on both project schedule and ontology
4) Output individuals into new OWL file
5) Use *Jess* rule engine to check individuals and infer new knowledge
6) Re-load individuals from updated OWL file to visualize protective zones and to update schedule to include safety tasks
7) Review the construction sequence according to 4D model simulation
8) Generate the JHA report including the JHA results and also the snapshot of the simulated 3D building model

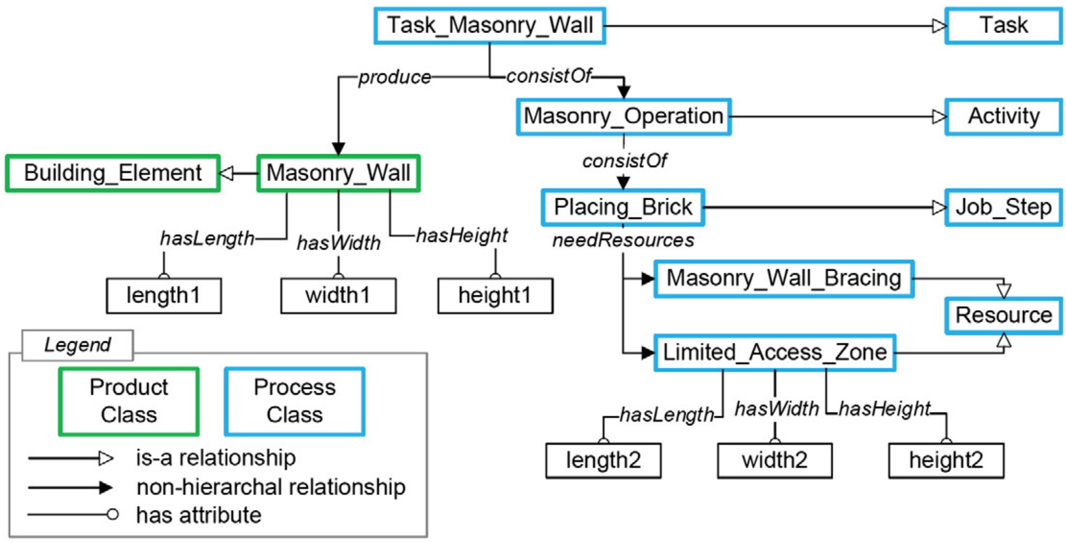


Fig. 6. Masonry wall task related classes and attributes used in SWRL rule 1 and 2.

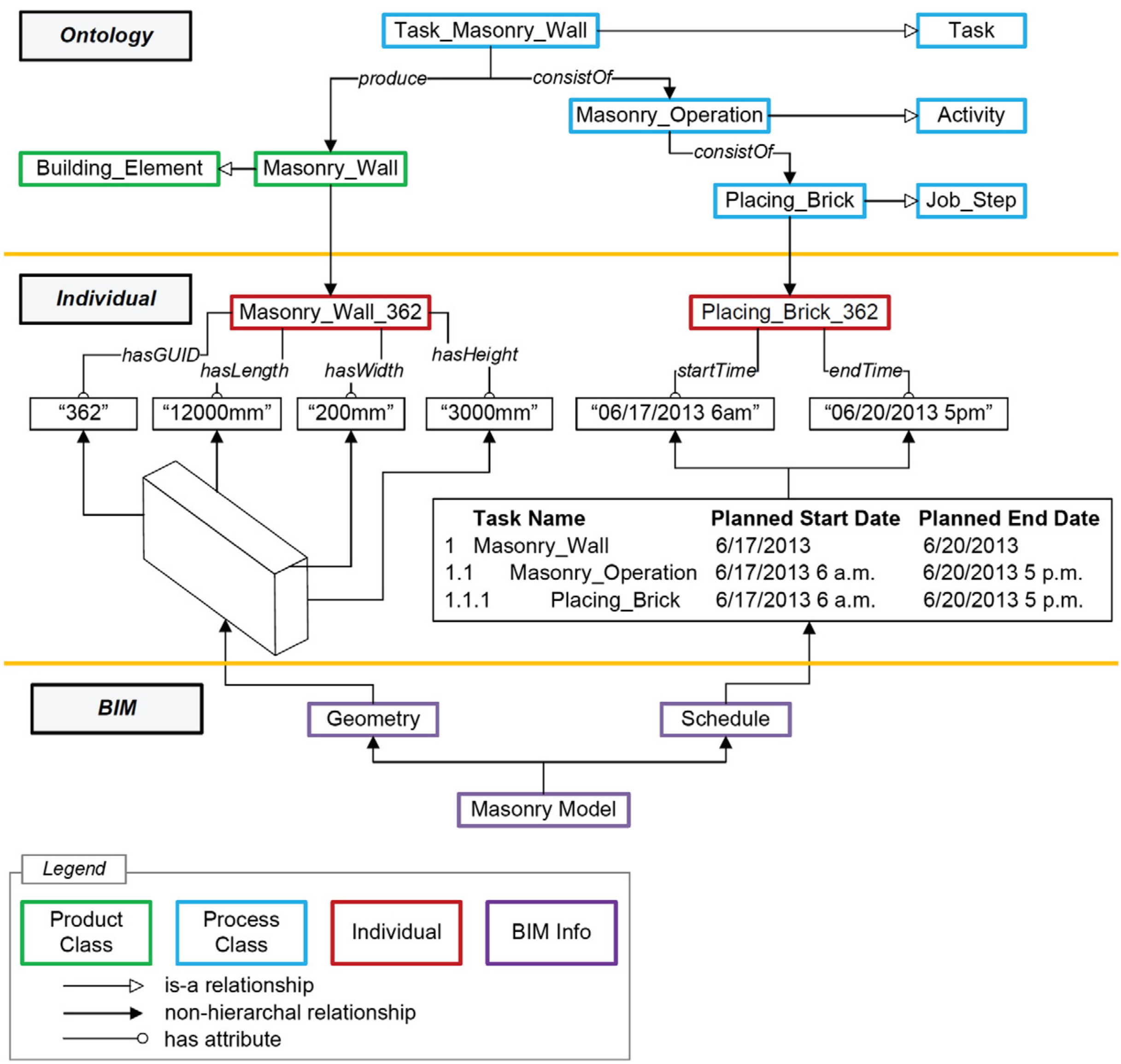


Fig. 7. Individual generation based on both ontology and BIM.

```
<Task_Masonry_Wall rdf:ID="Task_Masonry_Wall_362">
    <produce>
      <Masonry_Wall rdf:ID="Masonry_Wall_362">
        <hasHeight rdf:datatype="http://www.w3.org/2001/XMLSchema#float">12000.0</hasHeight>
        <hasGUID rdf:datatype="http://www.w3.org/2001/XMLSchema#int">362</hasGUID>
        <hasLength rdf:datatype="http://www.w3.org/2001/XMLSchema#float">200.0</hasLength>
        <hasWidth rdf:datatype="http://www.w3.org/2001/XMLSchema#float">3000</hasWidth>
      </Masonry_Wall>
    </produce>
    <consistOf>
      <Dismantling_Scaffolding rdf:ID="Dismantling_Scaffolding_362">
    </consistOf>
    <consistOf>
      <Masonry_Operation rdf:ID="Masonry_Operation_362">
        <consistOf>
        <consistOf>
          <Placing_Brick rdf:ID="Placing_Brick_362">
            <needResources rdf:resource="#Limited_Access_Zone_362"/>
            <hasHazards rdf:resource="#Sharp_Edges_362"/>
            <hasHazards rdf:resource="#Overexertion_362"/>
            <hasHazards rdf:resource="#Fall_362"/>
            <hasHazards rdf:resource="#Struck_By_Falling_Object_Or_Equipment_362"/>
          </Placing_Brick>
        </consistOf>
        <consistOf>
        <consistOf>
        <consistOf>
      </Masonry_Operation>
    </consistOf>
    <consistOf>
      <Setting_Up_Scaffolding rdf:ID="Setting_Up_Scaffolding_362">
    </consistOf>
  </Task_Masonry_Wall>
```

Fig. 8. Snippet of OWL RDF/XML showing an individual of Task_Masonry_Wall.

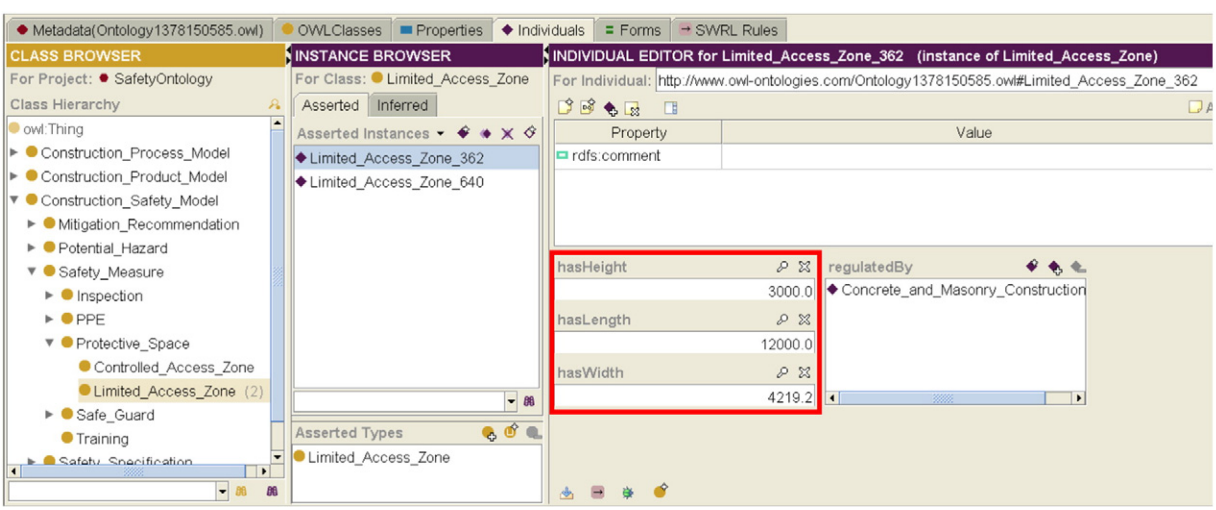


Fig. 9. Computed dimensions of Limited_Access_Zone_362 in Protégé.

```
<Limited_Access_Zone rdf:ID="Limited_Access_Zone_362">
  <hasHeight rdf:datatype="http://www.w3.org/2001/XMLSchema#float"
  >3000.0</hasHeight>
  <hasLength rdf:datatype="http://www.w3.org/2001/XMLSchema#float"
  >12000.0</hasLength>
  <hasWidth rdf:datatype="http://www.w3.org/2001/XMLSchema#float"
  >4219.2</hasWidth>
</Limited_Access_Zone>
```

Fig. 10. Snippet of OWL RDF/XML showing an individual of Limited_Access_Zone.

A masonry model along with scaffolding was built as shown in Fig. 13. All building elements were linked to a corresponding construction schedule (see Fig. 14). The scaffolding models were generated semi-automatically using algorithms developed in Kim and Teizer [50]. These temporary structures match the masonry model and comply with OSHA rules. Construction schedules in BIM typically do not show high levels of detail. For example, detailed activities, such as a wall erection activity for every instance of a wall, are often not listed in the Gantt chart. Instead, the schedule usually represents these through a summary activity, e.g. one activity that represents all wall erection activities on a given level. The developed JHA program is capable of populating the

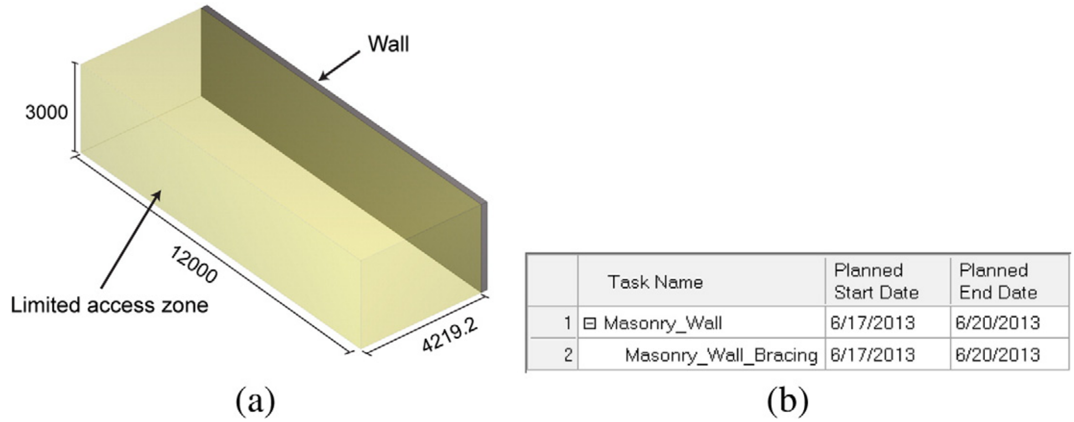


Fig. 11. (a) Generated Limited Access Zone for masonry wall and (b) Inserted Masonry_Wall_Bracing task in the schedule.

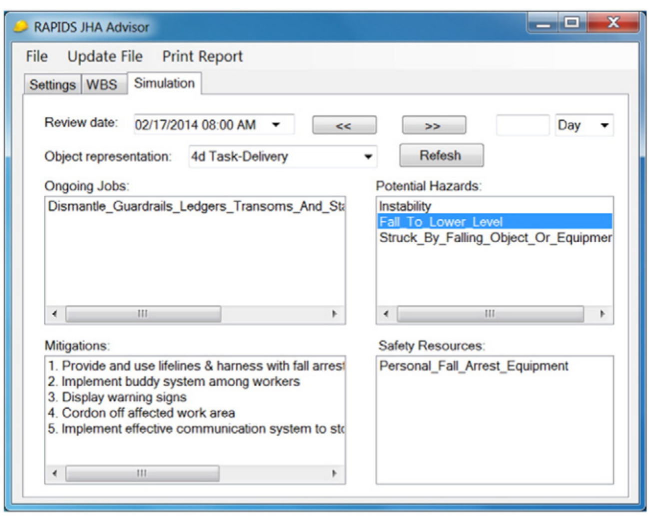


Fig. 12. RAPIDS JHA advisor interface.

detailed construction schedule depending on pre-allocated percentage of the time for each activity and job step. The time percentage used for each activity and job step is stored in the ontology as an attribute, which then will also be generated for each individual during the individual generation process. At the same time, relevant safety information is also retrieved. Such activity level based construction simulation is helpful to practitioners as it communicates where and when safety equipment is needed and needs to be removed. Thus, the developed user interface provides a valuable tool that may find popular application in the field as it increases communication among project stakeholders. The smallest time step for the purpose of the simulation was set to a minute in the developed program to allow for micro-level analysis of the activities.

For each task in the schedule, the corresponding *Activity*, *Job_Step*, *Potential_Hazard* and *Mitigation* are shown (see Fig. 12). An informative report (see Fig. 15) was automatically generated by the system as an Excel™ sheet. As can be seen in this example, the JHA template of Table 1 is applied to the "Dismantle guardrails, ledgers, transoms, and standards from the level above" job step and its related safety resources, and supplemented with the view of the simulated BIM according to schedule. According to the review time of the 4D simulation of the project, the JHA related elements are shown in orange to be distinguished from other ongoing tasks that are shown in blue. Such JHA reports can not only provide safety analysis in a time-efficient manner, but it can also become a useful safety training tool for improving worker's safety awareness and their understanding of the surrounding working environment.

8. Discussions and conclusions

8.1. Limitations and future study

The initial implementation and test show that the proposed approach can support a more comprehensive project safety management leveraging BIM technology. However, it is acknowledged that comprehensive testing of the framework and extensive application to a wider construction domain will be required to further help validate both the

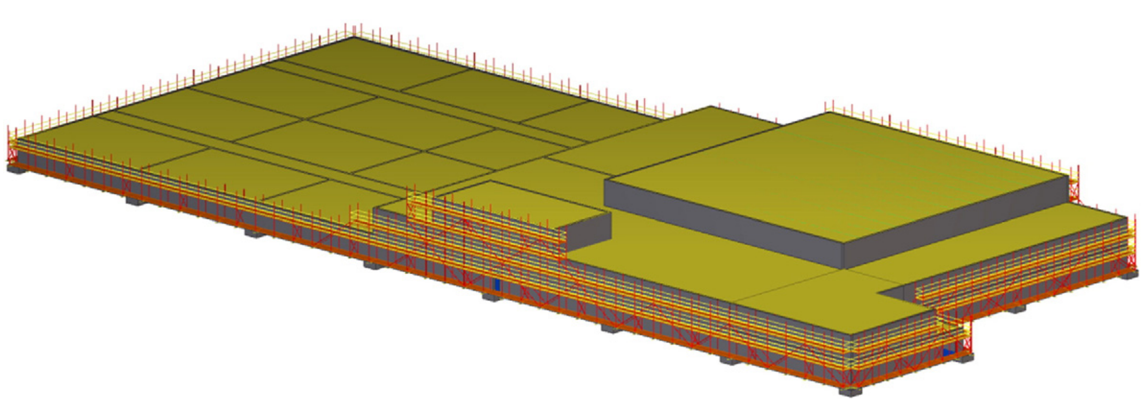
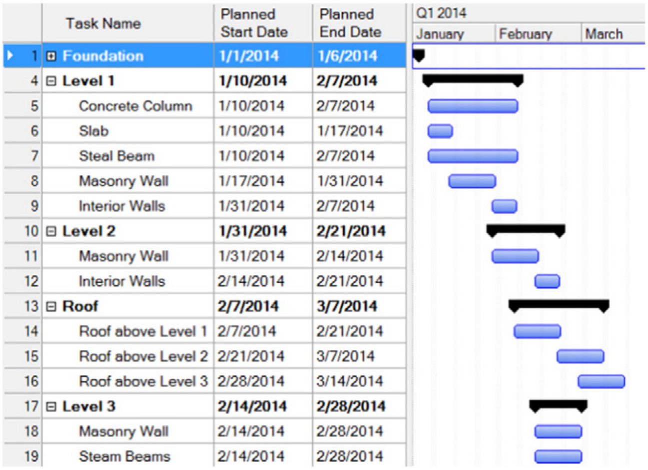


Fig. 13. Masonry model with scaffolding.



	Task Name	Planned Start Date	Planned End Date
1	⊞ Foundation	1/1/2014	1/6/2014
4	⊟ Level 1	1/10/2014	2/7/2014
5	Concrete Column	1/10/2014	2/7/2014
6	Slab	1/10/2014	1/17/2014
7	Steal Beam	1/10/2014	2/7/2014
8	Masonry Wall	1/17/2014	1/31/2014
9	Interior Walls	1/31/2014	2/7/2014
10	⊟ Level 2	1/31/2014	2/21/2014
11	Masonry Wall	1/31/2014	2/14/2014
12	Interior Walls	2/14/2014	2/21/2014
13	⊟ Roof	2/7/2014	3/7/2014
14	Roof above Level 1	2/7/2014	2/21/2014
15	Roof above Level 2	2/21/2014	3/7/2014
16	Roof above Level 3	2/28/2014	3/14/2014
17	⊟ Level 3	2/14/2014	2/28/2014
18	Masonry Wall	2/14/2014	2/28/2014
19	Steam Beams	2/14/2014	2/28/2014

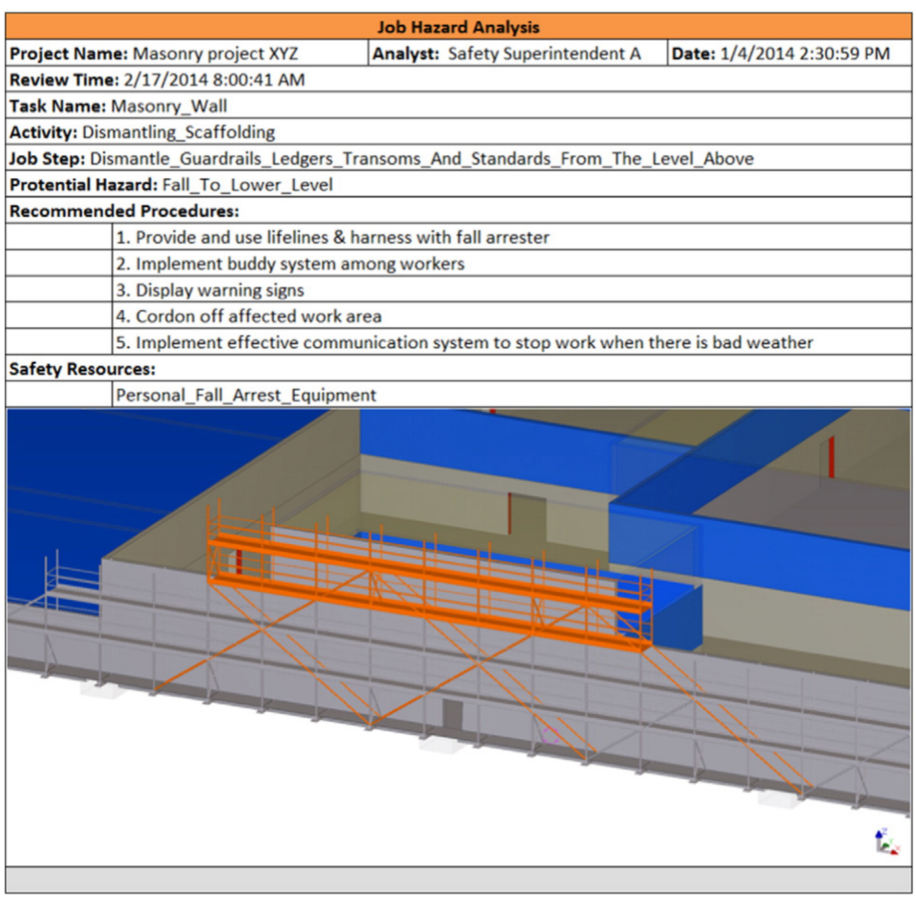
Fig. 14. The project building model schedule.

model and the framework. The identified main limitation is that the JHA knowledge would not be able to consider construction site layout issues, since information such as terrain, site logistics, and construction equipment operation is currently not included and represented in BIM. Some examples include power line proximity issue, struck-by hazard led by heavy equipment operations, and cave-in hazard. Secondly, since it may currently not be possible to update BIM model frequently to reflect current construction site condition and schedule, which will largely affect the JHA results using the developed system. In addition, the developed prototype intends to assist human decision-making; it is recommended to have a safety expert audit the results generated by the automated system and also provide his/her input.

The developed Construction Safety Ontology intends to be extendable. Two new safety management aspects are being considered to be included into the ontology:

(1) Safety risk factors [51] can be integrated into the ontology schema and be used to assess and compare different construction methods and sequences. This assists construction managers to select the safest solution. In addition, the risk assessment results can be visualized in BIM using a color code. This becomes a useful tool for safety inspectors who need to identify and resolve hazards on the construction site. Preliminary results can be found in Collins et al. [52].
(2) Construction workspace conflict detection [53–56] has the potential to be solved in BIM if workspace information and parameters can be included in the Construction Safety Ontology. Fig. 16 shows an extension of Construction Safety Ontology with workspace information included.

Technology-based safety solutions need to be developed [57] taking advantage of computer-aided approaches that replace or assist in traditional management practices. In terms of the IFC exchange format, the current scope of *IfcConstructionMgmtDomain* schema focuses on schedule, cost and quantities of the project without considering construction safety aspect. Since safety is an important aspect of construction management, it is crucial to extend the existing IFC schema to include safety prevention methods, requirement, and risk factors in the long run for creating an integrated safety management system. In addition to



Job Hazard Analysis		
Project Name: Masonry project XYZ	**Analyst:** Safety Superintendent A	**Date:** 1/4/2014 2:30:59 PM
Review Time: 2/17/2014 8:00:41 AM		
Task Name: Masonry_Wall		
Activity: Dismantling_Scaffolding		
Job Step: Dismantle_Guardrails_Ledgers_Transoms_And_Standards_From_The_Level_Above		
Protential Hazard: Fall_To_Lower_Level		
Recommended Procedures:		
	1. Provide and use lifelines & harness with fall arrester	
	2. Implement buddy system among workers	
	3. Display warning signs	
	4. Cordon off affected work area	
	5. Implement effective communication system to stop work when there is bad weather	
Safety Resources:		
	Personal_Fall_Arrest_Equipment	

Fig. 15. Sample JHA report generated by JHA Advisor automatically (grey—finished, orange—ongoing task in review, blue—other ongoing task).

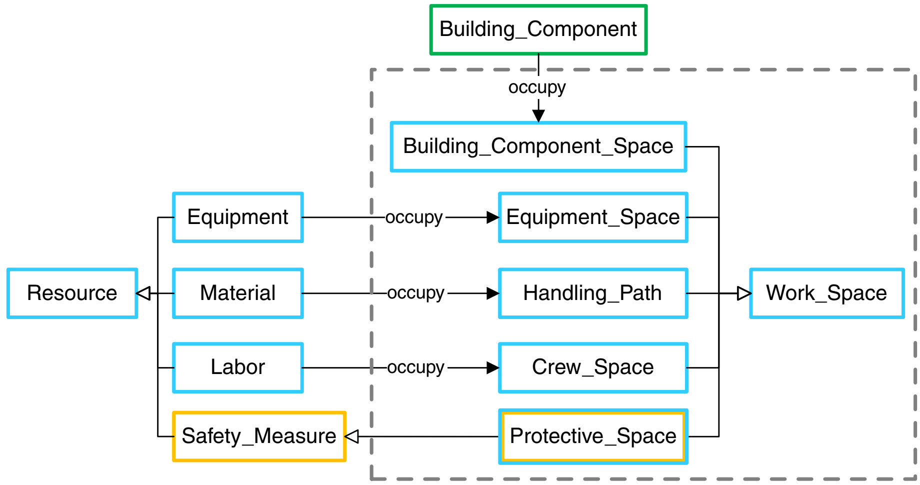


Fig. 16. Extended Construction Safety Ontology to include workspace information.

conducting hazard analysis in BIM, future research may also explore BIM as an interface for safety knowledge acquisition, transfer, and reasoning, which will then fully integrate safety with project lifecycle through BIM.

8.2. Conclusions

This paper presents ontology-based semantic modeling of a construction safety knowledge framework. A Construction Safety Ontology was developed to formalize the construction safety management knowledge. Interviews and surveys with construction experts were conducted to evaluate the ontology structure and content. Also, it supports safer and healthier construction project execution while linking the developed ontology to BIM. Based on the developed framework, a prototype was developed that supports automated ontology-based JHA in BIM to further test the ontology. The prototype introduces significant automation in existing manual/experience-based JHA processes, allowing a user to apply different sets of JHA on building information models. Simulation of safety and visualization of models with safety resources becomes possible. The developed knowledge or best practice can be transferred and applied by safety and field staff on construction sites. This may include individuals with limited safety knowledge and different levels of safety experience. The prototype supports a safety engineer or manager to plan for safety at the front-end of a project more efficiently. It further assists in decision making that will be made by humans. In addition, the construction safety ontology is expected to be able to provide other benefits, if leveraged in safety planning tools. For example, when the schedule of a project changes, the user can re-run the program and quickly receive updated results of the hazard analysis. Further goals of future research and implementation must be to use such tools just prior to conducting work and for that purpose, readily available as-built BIMs are necessary that the developed prototype can use. These can then eventually aid in preventing so called house-keeping issues and conditions related to human behavior that lead to accidents on construction sites, e.g., power cords laying on floor causing tripping or falling accidents and general unsafe behavior caused by absence of mind or missing instructions or infrequent occupational safety and health education and training, respectively. These need to be addressed at same priority as safety regulations suggested by OSHA regulations.

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