Ontology-Based Semantic Modeling of Safety Management Knowledge

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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, which consists of three main domain ontology models, including Construction Product Model, Construction Process Model and Construction Safety Model. The interaction between safety ontology and Building Information Modeling (BIM) is also explored. A prototype application of ontology-based job hazard analysis and visualization is implemented to further illustrate the applicability and effectiveness of the developed ontology. The developed construction safety ontology is expected to enable more effective inquiry of safety knowledge, which is the first step towards automated safety planning using BIM.

INTRODUCTION

The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. Safety planning and management in such complex and dynamic construction environment is thus more challenging. It also is difficult as 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. 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 processes. In terms of construction safety, safety management information, such as safety hazard information and best practice rules, which enable early hazard identification and BIM-based visualization, currently cannot easily be linked to or represented in project models such as a BIM. 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.

BACKGROUND

In terms of safety knowledge management, explicit knowledge of construction site safety is documented in accident records, and safety regulations as well as best practices. Safety hazard recognition is an important actualization of tacit knowledge and is considered a tacit knowledge because it mainly relies on the safety engineer's experience (Hadikusumo and Rowlinson 2004).

One of the promising directions of BIM applications in the AEC industry is to facilitate rule checking and simulations for evaluating building designs in the earlier phases of a project (Eastman et al. 2011). Along with developing rule-checking software, a domain-specific language has been introduced as a language-driven approach to the rule checking and design analysis (Lee 2011). In terms of construction safety, Zhang et al. (2012 and 2013) explored the integration of construction and safety management based on 4D CAD models and rule-based algorithms. Industry Foundation Classes (IFC)-based solutions have also been explored for fall hazards identification and prevention in construction (Melzner et al. 2013). Solibri Model Checker (2013) is one of the commercial available applications which provide rule checking capability against BIM, however, safety hazards identification isn't realized in such program.

Gruber (1993) defined ontology as "an explicit and formal specification of a conceptualization." 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. Lima et al. (2005) implemented the e-COGNOS platform and proved the benefit of ontology-based semantic systems as these provided adequate search and indexing capabilities. These systems also allowed for a systematic procedure for formally documenting and updating organizational knowledge in knowledge management systems. El-Diraby and Osman (2011) developed a domain ontology for construction concepts in urban infrastructure products. Wang and Boukamp (2011) presented a framework aiming to improve access to a company's Jobsite Hazard Analysis (JHA) knowledge by using ontologies for structuring knowledge about activities, job steps, and hazards using ontologies. The framework also includes an automatic ontological reasoning mechanism for identifying safety rules applicable to given activities. Zhong et al. (2012) explored the ontology-based semantic modeling of regulation constraints aiming to integrate regulation knowledge with the definition and execution of construction processes.

These recent research efforts have paved the way for automated compliance checking and knowledge modeling in construction industry. However, from the existing literature it can be concluded that most of the existing efforts have been mainly focused on domain ontologies for construction concept and model exchange. We currently still lack an ontology to represent construction safety knowledge in a comprehensive way.

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 the safety knowledge. As "masonry construction is one of the specialty trades with high risk of work-related injuries" (Memarian and Mitropoulos 2012), masonry construction was chosen as an area of focus for demonstrating the effectiveness of the developed ontology.

RESEARCH METHODOLOGY

The main reasons for using ontologies for safety knowledge modeling are that ontologies can be shared and used to link information from different knowledge domains together and support consistency checking and reasoning. 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 planned as follows:

1) Define the purpose and the scope of the ontology. The purpose of developing a construction safety ontology is not only to formalize the current knowledge, but also to support safety hazard identification and mitigation in BIM, the development of the ontology should support the integration of the knowledge with building information models. Existing BIM schema, such as the IFCs, are considered.

2) Ontology capturing and coding. The knowledge sources considered for identifying relevant concepts and coding the safety ontology include, among other sources, the Occupational Safety and Health Administration (OSHA) regulation 1926 (OSHA 2013), Occupational Injury and Illness Classification Manual (BLS 1992). 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.

3) Semantic Web Rule Language (SWRL) rule development. Selected OSHA regulation and industry safety best practices are coded in SWRL rule formats, compatible with ontology classes and relationship.

4) Ontology validation. 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, to support safety management.

The system architecture of our ontology-based hazard identification application includes ontology editor, reasoner, rule engine, and BIM platform. We use *Protégé*, a free, open-source platform enabling the development of domain models and knowledge-based applications with ontologies (Stanford Center for Biomedical Informatics Research 2013). The safety ontology is first modeled and edited using Protégé to define classes, relationships and axioms. Then, the resulting *Construction Safety Ontology* is checked to ensure its consistency using an ontology reasoner. Next, based on this Construction Safety Ontology, SWRL rules are then developed to represent OSHA regulations. These rules can also be customized and added by subject matter experts according to their specific requirements. After connecting the ontology with a BIM 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, will be also obtained through BIM. Thus, the facts including the knowledge base and individuals generated from BIM will be passed to a rule engine to be checked against the SWRL rules defined earlier. Once new knowledge has been inferred by the rule-checking process, it updates the ontology. This then allows the BIM platform to access and visualizes the inferred knowledge, such as required safety protective systems and protective safety zones. Finally, a project specific JHA report, including a 4D building model, is generated to support site level project safety planning and inspection.

IMPLEMENTATION AND RESULTS

The goal and intention is to formalize construction safety planning knowledge by developing a construction safety ontology. As shown in Figure 1, 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 component information such as column, slab, and wall information, and provides the main interface for connecting the ontology and a BIM platform. The *Construction Process Model* includes the construction plan of the project along with construction resources, such as equipment, material and labor. Finally, the *Construction Safety Model* contains construction safety related knowledge such as potential hazard, specification from regulations, mitigation recommendation, and safety resource. The resulting construction safety ontology aims to integrate safety planning and construction execution planning by linking safety knowledge to construction processes and products.

In order to test the effectiveness of the ontology, a BIM-based automated JHA application was developed. The application leverages the ontology as described in the following sub chapters.

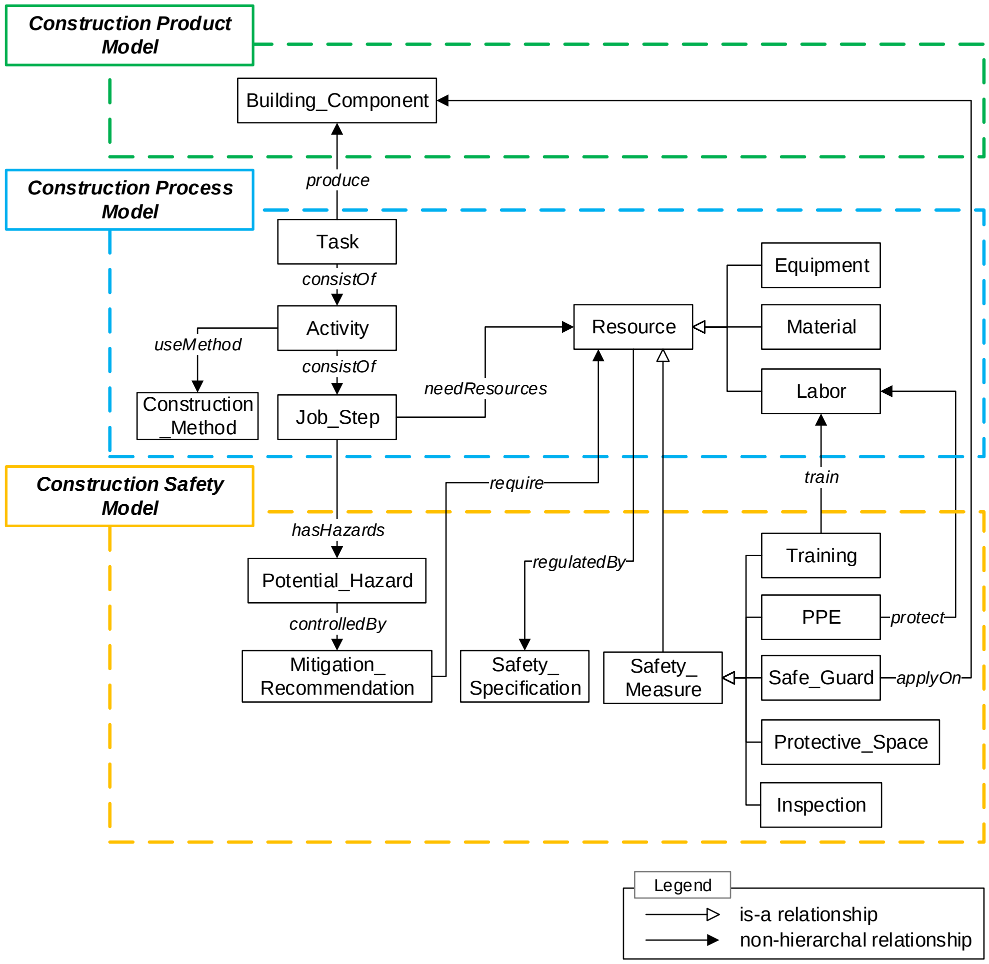


Figure 1. Construction Safety Ontology

1) SWRL Rule Development. The OSHA regulation of masonry construction (OSHA 2013) 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 bracing system if the height of the wall is greater than 8 feet for *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.

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 reconstructed 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) ∧ needResource(?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) → needResource(?pb, Masonry_Wall_Bracing)

2) Individual generation. The individual generation process is illustrated in Figure 2. Individuals (in green) are generated based on the information both from the *Construction Safety Ontology* (in yellow) and BIM (in blue). In Figure 2, *Masonry_Wall_362* is generated as an individual of "Masonry_Wall". Properties, such as related safety hazards, are also generated to the instance level. In addition, information such as the geometry and the schedule from a BIM are attached to the individual element.

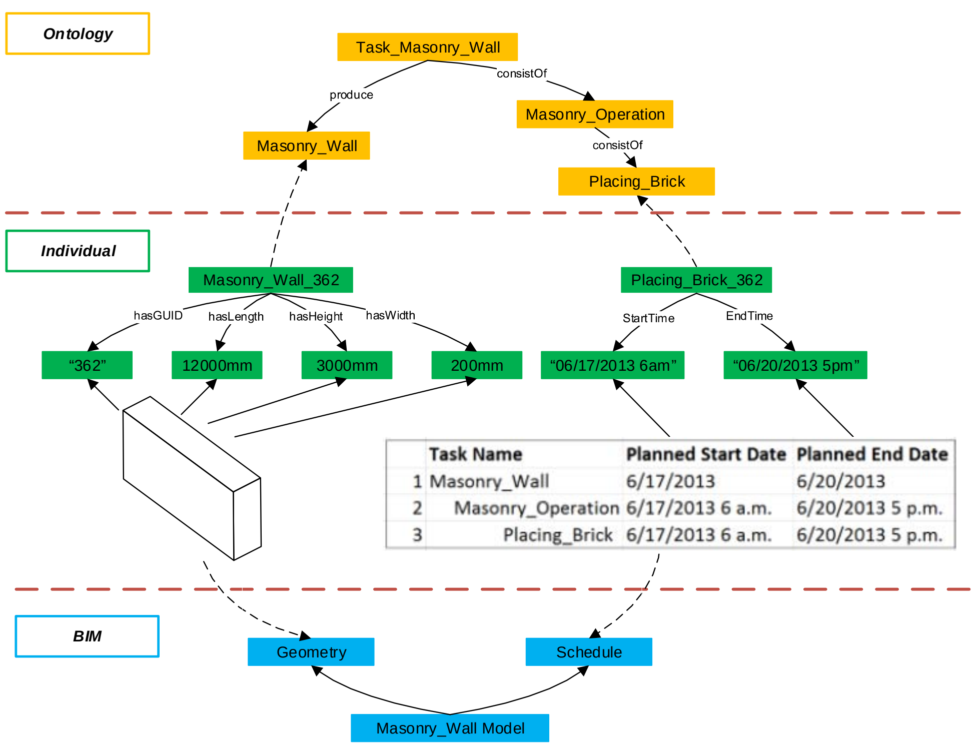


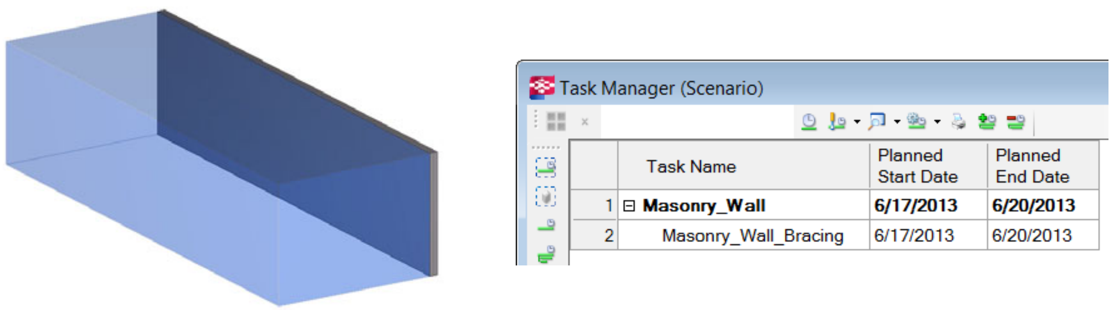
Figure 2. Individual generation based on both ontology and BIM.

3) Individual update and visualization. In this example, dimensions of an inferred *Limited_Access_Zone* are computed by running a rule engine (see Figure 3) and evaluating the SWRL rule. The BIM is then updated to visualize the limited access zone for masonry construction.

```
<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>
```

Figure 3. OWL RDF/XML of an individual of *Limited Access Zone*.

In Figure 4, a *Limited Access Zone* has been created automatically. It is visualized in blue with 50% transparency. In addition, since the height for this masonry wall is larger than 8 feet, *Masonry Wall Bracing* task has been automatically inserted into the schedule with a link to the wall object in the BIM (Figure 4(b)).



(a) (b)

Figure 4. (a) Generated *Limited Access Zone* for masonry wall; (b) Inserted *Masonry Wall Bracing* task in the schedule.

DISCUSSIONS AND CONCLUSIONS

An ontology-based semantic modeling of construction safety knowledge was explored in this research. A construction safety ontology was developed to formalize the construction safety management knowledge. It provides a reasoning opportunity to support safer and healthier construction project execution while linking to BIM. Initial tests deliver promising results that lead us to believe that the proposed approach can eventually support a more comprehensive project safety management using BIM technology. However, it is acknowledged that comprehensive testing of the framework and extensive application to a wider construction domain will be required to help validate both the model and the framework.

REFERENCES

Bureau of Labor Statistics. (1992). "Occupational Injury and Illnesses Classification Manual." http://www.bls.gov/iif/oshwc/oiicm.pdf. Accessed November 2013.

Eastman, C., Lee, J. M., Jeong, Y. S., and Lee, J. K. (2009). Automatic rule-based checking of building designs. *Automation in Construction*, 18(8), 1011-1033.

El-Diraby, T. E., and Osman, H. (2011). A domain ontology for construction concepts in urban infrastructure products. *Automation in Construction*, *20*(8), 1120-1132.

Gruber, T. R. (1993). A translation approach to portable ontology specifications. Knowl. Acquis., 5(2), 199 –220 .

Hadikusumo, B. H. W., and Rowlinson, S. (2004). Capturing safety knowledge using design-for-safety-process tool. *Journal of Construction Engineering and Management*, 130(2), 281-289.

Lee, J. K. (2011). Building environment rule and analysis (BERA) language and its application for evaluating building circulation and spatial program, Ph.D. dissertation, Georgia Institute of Technology, 2011.

Lima, C., El-Diraby, T., and Stephens, J. (2005). Ontology-based optimization of knowledge management in e-construction. *Journal of IT in Construction*, 10, 305-327.

Melzner, J., Zhang, S., Teizer, J., and Bargstädt, H. J. (2013). A case study on automated safety compliance checking to assist fall protection design and planning in building information models. *Construction Management and* Economics, 31(6), 661-674.

Memarian, B. and Mitropoulos, P. (2012) Safety Incidents and High-Risk Activities of Masonry Construction. Construction Research Congress 2012: pp. 2510-2519.

OSHA, Requirements for masonry construction. Accessed Dec 2013, https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10785

Solibri, 2013. http://www.solibri.com/solibri-model-checker.html (Sep. 30, 2013)

Stanford Center for Biomedical Informatics Research, The Protégé Ontology Editor and Knowledge Acquisition System, http://protege.stanford.edu/.

Wang, H. H., and Boukamp, F. (2011). Ontology-based representation and reasoning framework for supporting job hazard analysis. *Journal of Computing in Civil Engineering*, 25(6), 442-456.

Zhang, S., Teizer, J., and Boukamp, F. (2012). "Automated Ontology-based Job Hazard Analysis in Building Information Models (BIM)", Proceedings of CIB W099, Singapore, September 10-11, 2012, 74-81.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., and Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction*, 29, 183-195.

Zhong, B. T., Ding, L. Y., Luo, H. B., Zhou, Y., Hu, Y. Z., and Hu, H. M. (2012). Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking. *Automation in Construction*, 28, 58-70.