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Knowledge Management in Construction Health and Safety Based on Ontology Modeling

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Abstract: Knowledge management in construction health and safety is an intensive process involving different stakeholders. However, this domain's information is still fragmented and stored in various disordered formats that require systematic structure for reusing and sharing. This study aims to develop a domain ontology, HSM-Onto (Health and Safety Management-Ontology), to construct health and safety knowledge and improve health and safety management decision making. The HSM-Onto could implement the organization, storage and reuse of construction health and safety knowledge. It comprises two primary domain knowledge contexts, including construction project context and risk context. Based on the conducted analyses, the findings show that the HSM-Onto's health and safety knowledge sharing is effective and equips health and safety employees with sound recommendations for decision making.

Keywords: knowledge management; ontology; health and safety; human–computer interaction; decision making

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1. Introduction

Due to several general characteristics of the construction process, including lengthy construction times, distinctive site conditions, multifaceted construction technology and heavy reliance on the environment [1], construction is regarded as one of the most unsafe industries worldwide [2]. Construction accidents on building sites usually lead to casualties and property loss. For this reason, researchers and stakeholders are increasingly focused on health and safety (H&S) management during all stages of the project lifecycle.

In this context, construction H&S management has long been a subject of intense discussion. Typically, H&S information and knowledge are gathered from a range of sources, primarily in unstructured formats. They include expert experience, construction drawings and organization plans, risk case bases and other documents from projects [3]. However, the maintenance of this knowledge has not been sufficiently formalized so far, and this disorganization hampers stakeholders from taking effective H&S management in the following ways:

1. It is unlikely that enough H&S knowledge can be possessed to cover all eventualities during each construction phase. For instance, designers may overlook specific design safety knowledge necessary for the project's success; weak H&S management could be blamed for oversights such as this. Similarly, during the construction phase, risk managers can make bad decisions, particularly if they are new to the role.
2. To support H&S management on a project, the diverse groups involved, which include general contractors and subcontractors, generally design separate knowledge systems that function as support resources for decision making [4]. However, the knowledge required for H&S management is usually stored in unstructured forms and represented in different data formats in these information systems [5]. Therefore,

the same object set could be defined in various hierarchical classifications, with the same concepts expressed by a different party. As a result, the risk reports output of the same project from these systems could be expressed in various forms and without a unified standard.

3. Establishing enhanced H&S management can be accomplished by (i) sharing all relevant information, including the scope and type of project, method of construction, procedures for safety management and onsite data conditions and climate; and (ii) communicating such information across diverse groups and projects. For example, during the construction process, risk managers may require risk information from other sections (and even some data from other projects) to serve as a reference when making decisions. However, the exchange of information among different project sectors is inefficient based on current knowledge systems.

The abovementioned factors trigger concerns about the standardization and formalization of H&S to the demands of highly efficient and effective decision-making for H&S management. Some argue that the development of a unified knowledge model both philosophically and linguistically facilitates H&S knowledge representations; however, this pertains not just to data or hypertext, but to whether this information is exchanged in a machine-interpretable manner. Ontology is clearly defined as a shared concept [6]. Ontology technology has presented knowledge in a structured way by classifying objects and their properties and the analytical correlations between them within a particular domain, thereby enabling information to be amalgamated, accessed and reused [7]. It can facilitate person-to-person communication. Furthermore, it can provide a way to capture and translate human knowledge into a machine-readable environment, which promotes human–computer interactions [8].

In the end, the proposed HSM-Onto becomes a platform for the standardization and formalization of a domain knowledge model of H&S management, which focuses on explicit specification, semantic attributes and unified H&S knowledge.

2. Related Works

2.1. Knowledge Management for Construction Health and Safety

The research suggested that the practical construction of H&S management was often based on previous experience [5], and management of knowledge exchange and reuse in this particular domain is a critical area in construction management research [9]. Management science expert Peter F. Dreucker (2015) endeavored to demonstrate that knowledge is essential to organizations in contemporary society [10]. The most important aspect of knowledge management (KM) is managing the flow of knowledge. This encompasses the sharing and reuse of knowledge. There are five primary steps for processing knowledge in KM: (i) acquiring, (ii) editing and substantiating, (iii) storing, (iv) sharing and (v) creating [11]. KM also refers to managing knowledge-creation procedures and person-to-person knowledge sharing during projects [12].

Construction H&S management has benefitted from the combination of the KM method and IT tools. The construction industry has developed a range of approaches for risk analysis and modeling, including Fault Tree Analysis (FTA) diagrams, the Check List, What-If rule, Failure Mode and Effects Analysis (FMEA) tables. For instance, Hillson [13] classified risks into groups as the checklist for H&S through a risk breakdown structure. To enhance safety performance, several knowledge-based H&S management applications have been constructed. For instance, SimSAFE was developed by Wang et al. [14]. This advanced model uses simulation to calculate the risk and cost of predicted accident assessments and can be applied to every scheduled activity. A proposed strategy is to employ a risk-based safety impact assessment to further the "design-for-safety" avenue [15]. Alanen et al. [16] introduces a model-based framework for safety and security risk assessment management that uses ontology and data analysis model to demonstrate the tools' feasibility. Collinge et al. [17] developed tools and a Risk library to assist designers in H&S

work in digital environments. This includes risk scenarios integrated with management processes and uses ontology to improve knowledge sharing.

The available reused H&S knowledge consists of explicit and tacit knowledge. The interdependencies are modeled in the database system following the previously discussed literature review. However, these database systems are based on multisource information stored in unstructured documentation, while semantics relations are not explicitly expressed. Hence, it is necessary to represent H&S information semantically in a model explicitly: doing so could avoid expression ambiguities among stakeholders.

2.2. A study of Ontology

Philosophy is the foundation of ontology. Ontology refers to expressing a specific worldview from the perspective of a group of people at a particular time based on a particular viewpoint; this is typically referred to as "epistemology" [18]. Unlike common belief, ontology is temporal and indicates the perspective of the developer in many cases. As such, epistemology limits the scope of ontology.

In the context of an informatics system, ontology is a clear, structured description of a shared concept [6]. Ontology encompasses vocabulary and an explanation of the links between classes. It can be concluded that ontology has two main elements: concepts and semantic relations. Hence, ontology could enable advanced knowledge representation that is more than simply data or information; it can be employed within the artificial intelligence (AI) field and applied to semantic web and problem-solving methods [19]. However, it should be remembered that ontology here is also bound by the same limitations philosophical ontologies face. Ontology scoping is an essential task during the development process. Domain ontology refers to the basic conceptualization of the knowledge within a particular domain. In the construction management area, ontology has already been applied for knowledge representation [20], decision making [21] and information integration [22]. Additionally, compared to AI, ontology is closer to linguistic, communication and cognitive science than it is to reasoning about domain knowledge. In this way, ontology is more likely to facilitate human-to-machine information conversion, which funnels human mental constructs into a computer-readable format. For example, a specific ontology was used for query expansion by combining the semantic algorithms and the result of knowledge extraction [21]. The related link-data approach was also conducted in the previous research work [23–25]; in this way, a more integrated reasoning environment could be used for comprehensive information query and management.

Lastly, it is essential to emphasize that ontology centers knowledge rather than raw information or data. The H&S knowledge of a specific domain has already been analyzed before the ontology was developed. Now, a domain ontology could be developed to organize all this information into a logical semantic expression and computer-interpretable format. In this way, structured and unified H&S knowledge can be exchanged and reused among various parties and computer applications to support H&S decision-making based on human–computer interaction.

2.3. Ontology for Health and Safety Management in the Construction Industry

To enhance knowledge management, a diverse array of industries, including medicine [26], computer science [27] and biology [28], have developed their own ontologies. In the construction field, projects typically involve large-scale collaborative efforts from many specialists (such as ventilation, heating and design), stakeholders (such as contractors, designers and owners) and phases (including design, construction and operation), and ontology is hugely significant [29]. For example, Pauwels et al. [30] introduced semantic web technologies to aspects of interoperability, linking information and logic inference.

Based on the above research, ontology can facilitate information sharing and reuse via structured information. As such, there is research concentrating on the application of ontology in H&S management. A framework employing ontologies to formalize knowledge about activities, job stages and risks was developed by Wang et al. [31]. It encompasses an ontological reasoning tool that enables the safety regulations for specific activities to be determined. This framework could make for quicker and more accurate decision making in responding to hazards. In addition, Chi et al. [32] used ontology-based text classification (TC) to connect unsafe situations with current resources' safety techniques. These safety approaches could serve for H&S decision-making when performing JHA. Three primary domain ontology models were created by Zhang et al. [33]: (i) Construction Product Model, (ii) Construction Process Model and (iii) Construction Safety Model for JHA. The purpose was to align safety knowledge and construction processes designed in BIM to combine H&S decision making with construction execution decision-making.

Other researchers use ontology as an H&S knowledge base for safety checking. Another development was the Construction Safety Checking Ontology (CSCOntology) by Lu et al., a meta-model that checks construction safety. This model is formalized using ontological languages and the constraints of safety checking, which can be extracted from safety regulations. The system implements construction-safety-checking processes and transfers ontology safety knowledge and SWRL into a JESS rule engine. Therefore, this ontology-based safety checking system could result in better H&S decision making. Tseng et al. [10] developed the ontology-based risk management (ORM) framework in a bid to carry out knowledge extraction via project risk ontology as part of construction-stage risk management (RM). The framework improved the risk management performance by enabling project risks to be identified, analyzed and addressed. This framework was able to apply to the RM workflow so contractors could manage safety issues on site. Fang et al. [34] integrated computer vision algorithms with ontology models and developed the knowledge graph that identifies hazards associated with high failure as an example of safety regulations. Li et al. [35] developed an ontological logic-based domain model for construction safety that includes hazard and safety concepts, first-order rules and tools that links with construction sites.

The abovementioned research employed ontology as the foundation for examining H&S risks and determining the best approach to address them. As such, they reflect the potential value of ontology in the context of H&S management. Therefore, the ontology presented in this research attempts to formalize construction concepts related to H&S issues, providing the standardization and formalization of H&S knowledge.

3. Development of Ontology Model for Construction Health and Safety

3.1. Objectives and Methods

This study aims to develop domain knowledge for construction safety management. The author reviewed relevant studies about health and safety management and ontology development in the first phase of the research. Based on the literature review [36,37], the study aims to adopt the following process in developing the HSM-Onto, including six steps: (1) Determining the domain and scope of ontology—the requirement analysis could be conducted here, and serves as the basis of establishing competency questions. (2) Considering the reuse of existing ontologies—the relevant existing models could be analyzed for the possibility of reuse. (3) Defining the class and the class hierarchy. (4) Defining properties. (5) Representing the facets. (6) Creating the instance. It should be noted here that the aforementioned steps were conducted in an iterative manner. Protégé is an unrestricted, open-source ontology editor that offers a visual environment in which OWL (W3C Web Ontology Language)-based ontology (standard semantic language, logic-based) can be created, edited and saved [38]. Therefore, the HSM-Onto is created in Protégé 4.1 platform in this research.

3.2. Ontology Scope and Knowledge Sources

As demonstrated in the literature review, the ontology scope is an important aspect that impacts ontology quality. The brand-new ontology is built to achieve standardization and formalization of construction H&S domain knowledge to help stakeholders carry out highly efficient H&S management and to keep them apprised of multidomain knowledge related to H&S management. The domains of this ontology cover construction product (building element, the foundation pit), construction process (task, activity), construction personnel (designers, supervisors, constructors) and construction safety (potential risk, risk level, risk consequence, risk mitigation and risk precursor). The knowledge sources referenced in this ontology are shown as follows:

(1) Concerning standards and technical manuals, the most significant are domestic and international design, construction and management regulations. Thirty-four standards and technical manuals are referenced in this research, including the Construction Design and Management (CDM) regulation, the Manual Handling Operations Regulations (MHOR), the Confined Spaces Regulations and the Working at Height Regulations, etc. (summarized in Table 1).

Table 1. Knowledge Sources of HSM-Onto.

Knowledge Source	Type
The Construction (Design and Management) Regulation	British Regulation
Design of concrete structures to Eurocode 2	Design Guide
The Health and Safety at Work Act	British Regulation
The Construction Head Protection Regulations	British Regulation
The Personal Protective Equipment Regulation	British Regulation
Occupational Safety and Health Administration Regulations	United States Regulation
The Reporting of Injuries, Diseases and Dangerous Occurrence	Technical Report
The Working at Height Regulations	British Regulation
The Confined Spaces Regulations	British Regulation
The Control of Vibration at Work Regulations	British Regulation
The Manual Handling Operations Regulations	British Regulation
The Electricity at Work Regulations	British Regulation
The Control of Noise at Work Regulations	British Regulation
The Control of Substances Hazardous to Health	British Regulation
Health and safety in roof work HSG33	Guidance
Avoiding danger from underground services HSG47	Guidance
The Safe Use of Vehicles on construction site HSG144	Guidance
Construction Solutions	Online Database

(2) The case set with related risk research reports: UK construction accident statistics were used to examine the types of reported accidents to determine the accident scope. Table 2 provides an overview of the prevalence of accidents in each category. This offers a range of reference sources for the previously mentioned projects, including construction plans, risk reports and risk identification checklists.

Table 2. Accident types and hazard scenarios identified in the typical building project.

Accident Types	Description	Selected Hazard Scenarios
Fall from height	Due to lack of proper scaffolding, fragile roofs, unprotected edges, unstable equipment, etc., leading causes of falling from a height	Unprotected outside edge of a slab or balcony Unprotected shaft or hole fixed scaffold without adequate fall protection Improvised platform Ladder propped against a wall
Slips, trips or falls on the same level	This is defined as a slip, trip or fall in which the worker impacts an object or floor at the same level when standing	Low wall or beam Loose plank or block lying where workers pass Oil Spill
Struck by a moving object	At construction sites, workers handle tools or use equipment to move heavy loads that can fall and injure	Missing footboards on a scaffold Moving crane with a load where workers are present Work with materials at height Work with façade element on a scaffold at a height Work with unsecured hand tools at height Moving construction equipment
Injured while handling, lifting or carrying	Lifting heavy materials while loading, unloading and distributing can cause injury	Bags of cement/concrete blocks on pallets
Strike by something fixed or stationary	Striking against fixed or stationary objects that project into a pedestrian area or route	Formwork or other planks at or lower than head height Concrete ledge Exposed rebar
Exposure to fire Contact with electricity	Damaged electrical equipment such as an exposed wire or frayed cable can cause a spark and fire hazard	Lying bitumen sheets The exposed temporary electricity board Damaged electrical extension board
Trapped by something collapsing/overturning	Workers trapped by a falling structure or tools that cause injuries	Improperly secured slab formwork Improperly supported wall formwork

(3) Risk identification of construction and prototype systems is discussed in terms of existing research and system platforms.

This research aims to formalize a unified construction of H&S knowledge by developing a domain ontology HSM-Onto. This ontology contains domain knowledge managing construction H&S scenarios by providing domain knowledge and reasoning support. As shown in Figure 1, this ontology's context mainly comprises **project and risk contexts**. Project contexts contain construction product information, tasks and activities. They can be aligned with the underlying construction data schema to extract the information, while risk context refers to the knowledge of risk precursors or accidents related to the construction activities and management information. The related information in both project and risk categories is summarized below and was used to create the H&S ontological knowledge base.

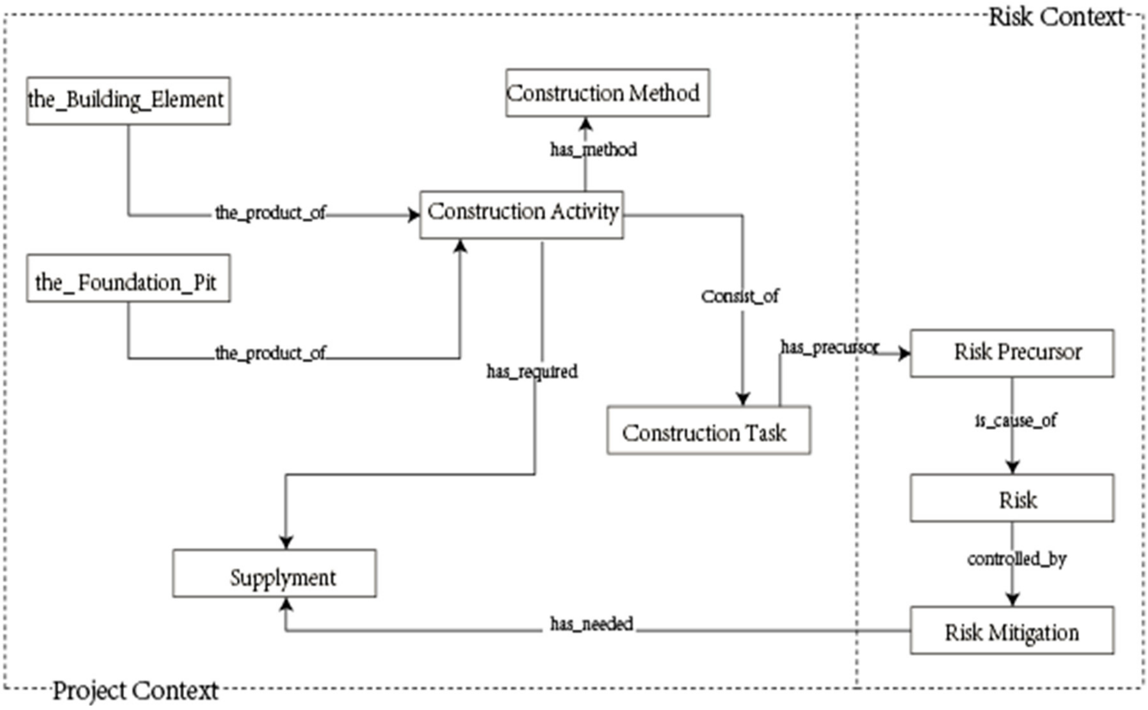

Figure 1. the construction health and safety meta ontology model.

3.2.1. Project Context

Project context mainly contains knowledge from the following two aspects:

- The construction product—encompasses information related to the project, including details about columns, windows, slabs, etc. In this study, these elements follow the BIM-IFC schema structure and consist of two main types: the building element and the foundation pit. The building element contains major functional parts of a building, such as foundations, walls and roofs.
- Construction tasks and activities—can be regarded as the hierarchical breakdown of the construction process. The classes and relations defined in this part leveraged the model proposed by Benevolenshiy et al. [39].

3.2.2. Risk Context

Risk contexts refer to construction health- and safety-related knowledge, such as risk type, risk precursors, risk consequence and mitigations.

- An essential component of risk knowledge is risk precursors. These are conditions, occurrences and progressions before an accident. An accident can happen as the combined result of different precursors, and similar precursors tend to occur as similar accidents [40].
- There are diverse forms of safety risks in construction that may coincide with particular construction activities. The several typical types and classifications of risk and risk scenarios are defined in the Occupational Injury and Illness Classification Manual and accident reports, as seen in Table 2. However, more risks than those listed occur on the construction site during construction, and even a single construction task can be linked to several risks. For example, installing a roof can result in an eye injury, a fall from height, heat and sun exposure, hand–arm vibration, being struck by objects, etc.
- Risk mitigation contains four subclasses: equipment, material, labor and safety measures. It is further explained in Section 3.3.3.

3.3. Define the Class and the Class Hierarchy

In Section 3.2, the related concepts and knowledge sources have already been introduced and developed in our HSM-Onto. Those concepts contain specific sub-concepts based on common logic. Next, a class hierarchy was developed via many techniques, including positives and negatives [41]. In this study, top-down development, which initially defines the most common domain concepts, subsequently filters into particular sub-concepts. In this section, a more detailed hierarchy will be offered in the form of the knowledge taxonomic hierarchy of the proposed HSM-Onto illustrated in Figure 2.

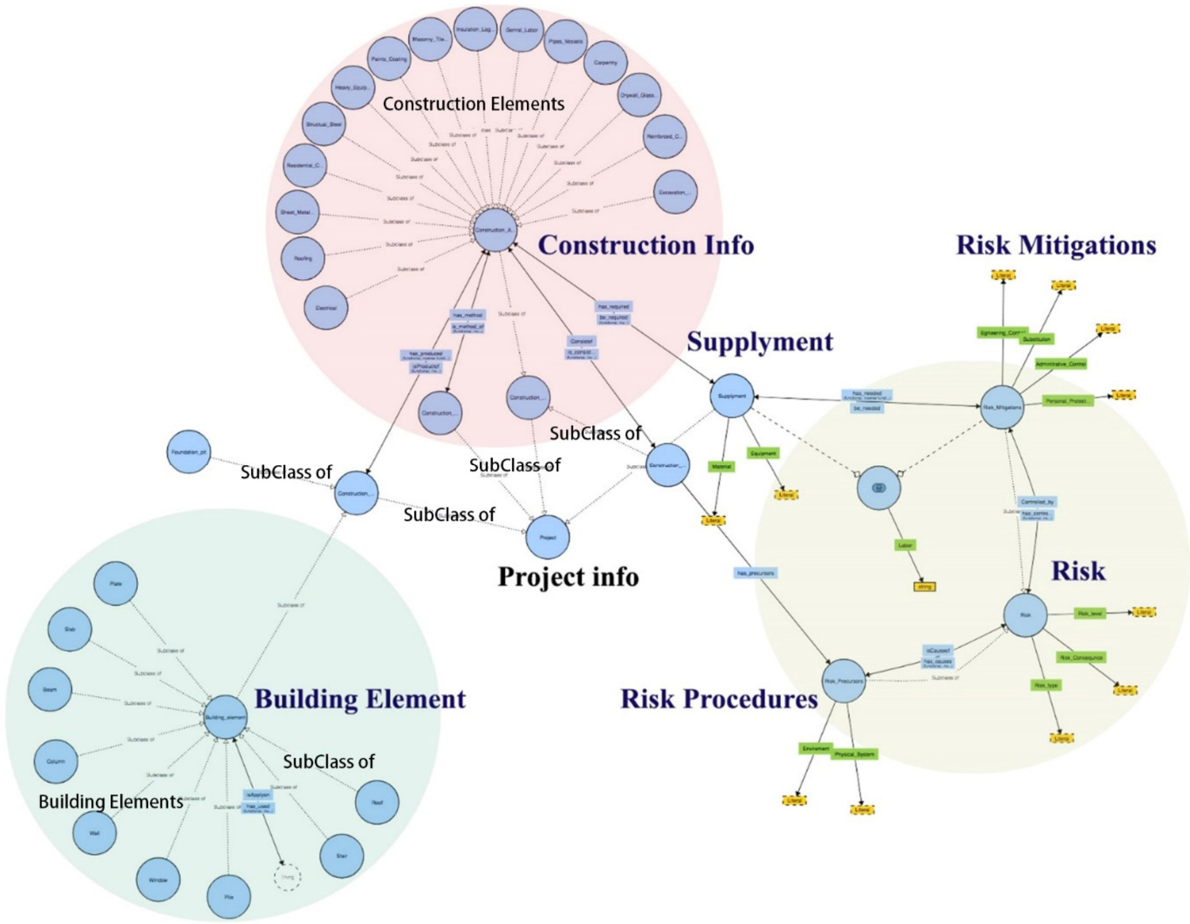

Figure 2. The overall class hierarchy of HSM-Onto.

3.3.1. Construction Activity and Task

Concerning H&S in construction, detailed information about classifying construction activities is available in the construction solution database [42]. According to this database, the typical types of construction activities include: (1) carpentry; (2) drywall, glass and floor covering; (3) electrical; (4) general labor; (5) heavy equipment; (6) insulation and lagging; (7) masonry, tile, cement and plaster; (8) paints and coating; (9) pipes and vessels; (10) reinforced concrete; (11) residential construction; (12) roofing; (13) sheet metal and HVAC; (14) structural steel; (15) excavation and demolition. Every activity discussed in this study can be separated into several individual tasks. For instance, the tasks associated with "pipes and vessels" can be broken down into the following: (i) applying the caulk, cement and plastic solvent sealants; (ii) assembling the pipes, tubing and fittings; (iii) assembling the vessel structures and components; (iv) cutting and drilling holes in the structure; (v) installing the pipe; and so on.

3.3.2. Risk Precursors

Precursors are the core parts of the problem description of risk in construction health and safety. Every type of risk described in HSM-Onto correlates with a risk precursor class. This is because due to similar risk sequences, similar precursors typically carry similar risks. A study by the US National Academy of Sciences concluded that numerous organizations have endeavored to create programs capable of identifying risk precursors. Figure 3 displays a logical way to investigate risk precursors on construction sites (e.g., "environment-related precursors" refers to the natural environmental risks such as typhoons and rainfall and operating environmental risks, such as the working height and weight of loading in the proposed HSM-Onto).

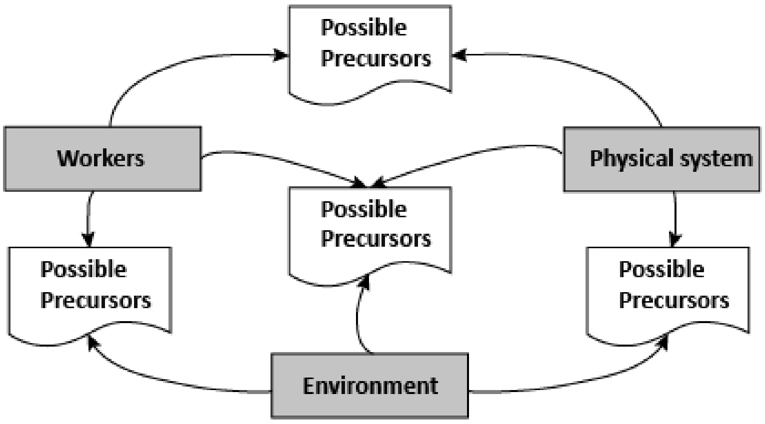

Figure 3. The origination of risk precursors on construction sites.

3.3.3. Risk Mitigations

The risk mitigations class hierarchy of the HSM-Onto is further explained in Figure 4. It comprises the following four mitigation subclasses: (i) equipment, (ii) material, (iii) labor and (iv) risk solutions. The risk solutions class has four subclasses: (a) substitution: for example, workers that move and install drywall or panels may face hazards from stressful hand and wrist activity, then prefabricated drywall pieces can be applied to reduce risks associated with installation; (b) personal protective equipment (PPE), such as fall arrest systems and gloves; (c) engineering control: for example, a glass panel cart can help reduce risks from manual handling of glass panels; (d) administrative control: for example, workers can be trained to conduct the job safely.

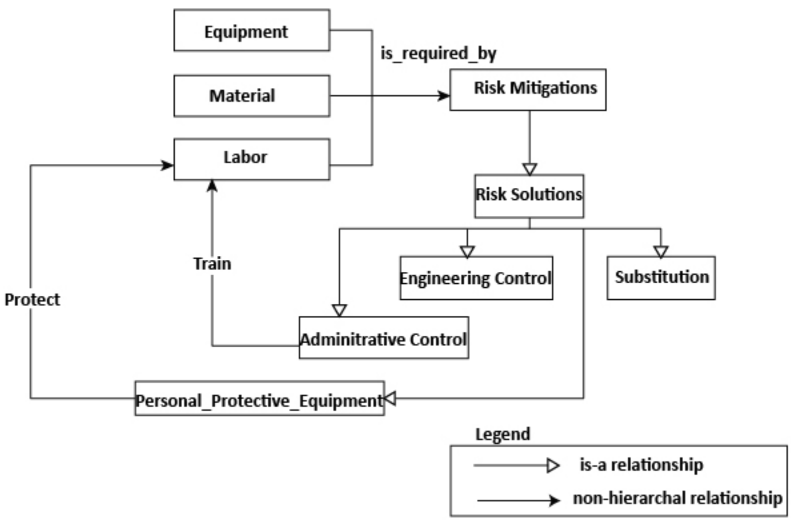

Figure 4. Risk Mitigation Class in the HSM-Onto.

3.4. Properties

The class hierarchy provided in Section 3.3 does not adequately represent domain knowledge; therefore, addressing the concepts' internal semantic structure is essential. It is possible that the majority of the outstanding terms could be shown to be ontology properties. In this study, the following three properties are employed: (i) object, (ii) datatype and (iii) annotation.

Object property is used to define the relationship between different concepts; for instance, "has_consequence" and "is_cause_of". Object properties establish semantic connections across these classes. A logical statement such as "Risk precursor is_cause_of risk" can be then calculated. Figure 5 illustrates the conversion from UML associations from the ontological knowledge model to object properties in HSM-Ontology.

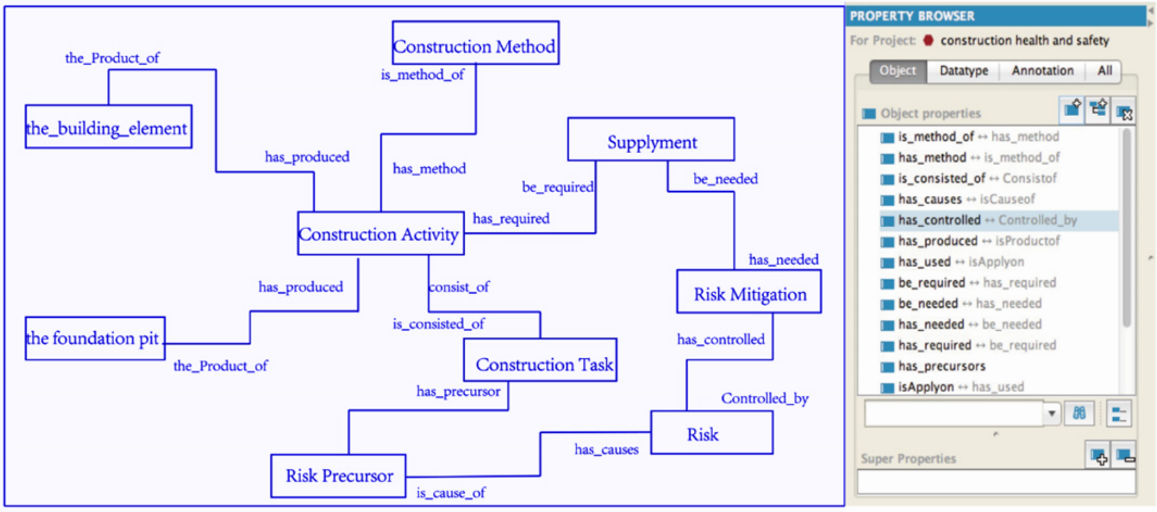

Figure 5. The conversion from UML associations to object properties in HSM-Onto.

If an object property connects person A to person B, the inverse property can connect person B to person A. An example of this is depicted in Figure 6, where an inverse object property in HSM-Onto "Controlled_by" shows the correlation between an instance "Risk_1" in the "Risk" class and "Risk_Mitigation_1" in the "Risk_Mitigation" class. Thus, the inverse property "has_controlled" signifies the inverse link between these two instances in which "Risk_Mitigation_1" "has_controlled" "Risk_1".

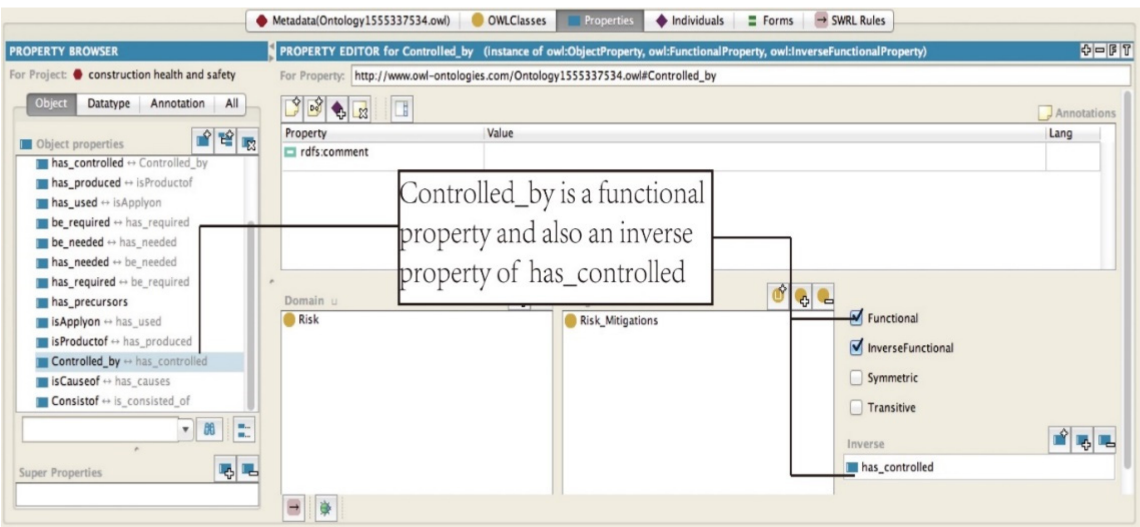

Figure 6. Inverse Property.

Datatype property in ontology defines characteristics of concepts in both quantitative and qualitative ways. Value type includes string and number and can be attached within datatype property. For instance, risk has a risk type labeled "fall from height". HSM-Onto contains a class of "Risk", which has a data type called "risk type" with "fall from height" as the data value. Some essential datatype properties such as "Training" "Labour" and "Personal_Protective_System" can be connected to corresponding entity classes. The conversion from UML attributed to a datatype property in HSM-Onto is demonstrated in Figure 7.

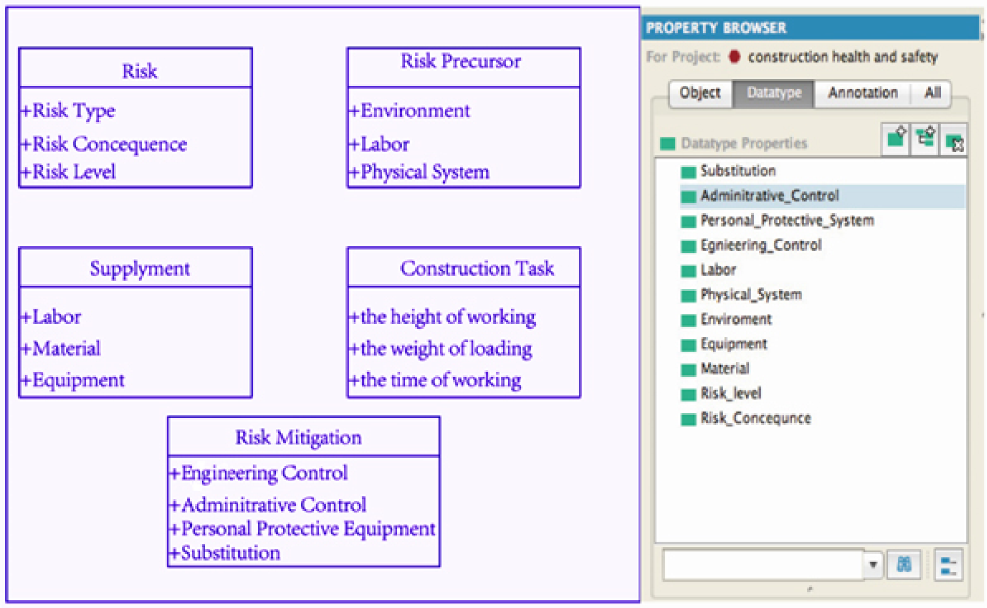

Figure 7. The conversion of UML attributes to datatype properties in HSM-Onto.

The annotation property used in this ontology is for text commentary on some elements. Annotation can help to clarify the data properties.

3.5. Define the Facets

The property value is defined as facets in protégé, the cardinality of the property value and its attached class. The value types are various, including strings, numbers and Boolean types. The "Risk_Level" of "Risk" could be attributed to using the "strings" data type to qualitatively represent three levels of risk: low, average and high. On the other hand, the "size" of "controlled_accessed_zone" can be measured quantitatively using numbers.

3.6. Instances

Instances are significant and inevitable for completion of information sharing and can contribute to the knowledge base's semantic interoperability. Creating an example entails the following three steps: (i) selecting a class, (ii) defining a specific instance of the class chosen and (iii) populating property values. In this part, the instance is created for HSM-Onto's knowledge expression, as displayed in Figure 8, which indicates the ontological relationship of "shoulder tendonitis" and as an instance, in "Risk" class a and Figure 9 shows the "Carpentry_1" instance connected with other instances using object properties.

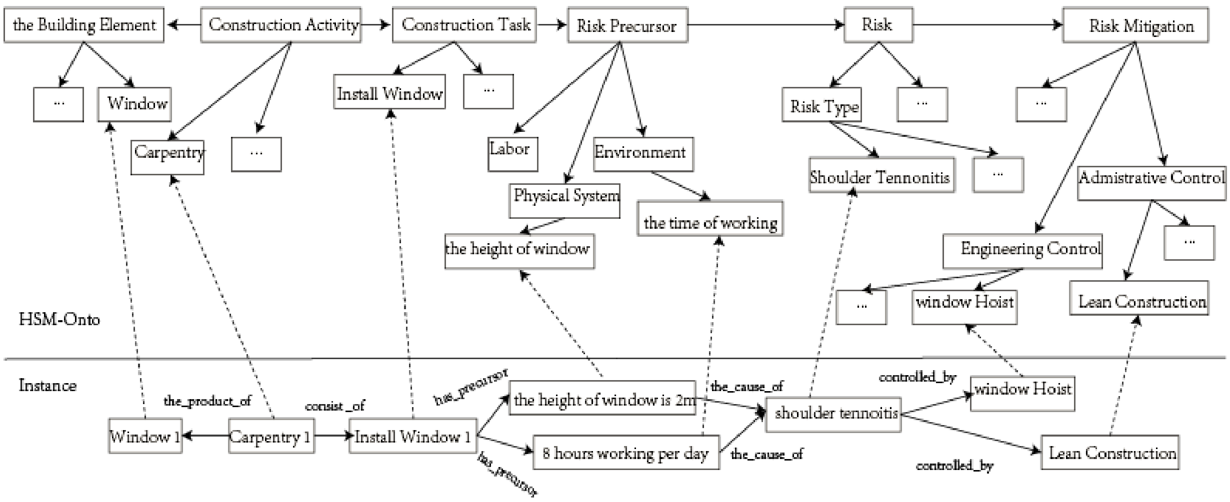

Figure 8. Example of an instance based on the HSM-Onto (shoulder tendonitis risk).

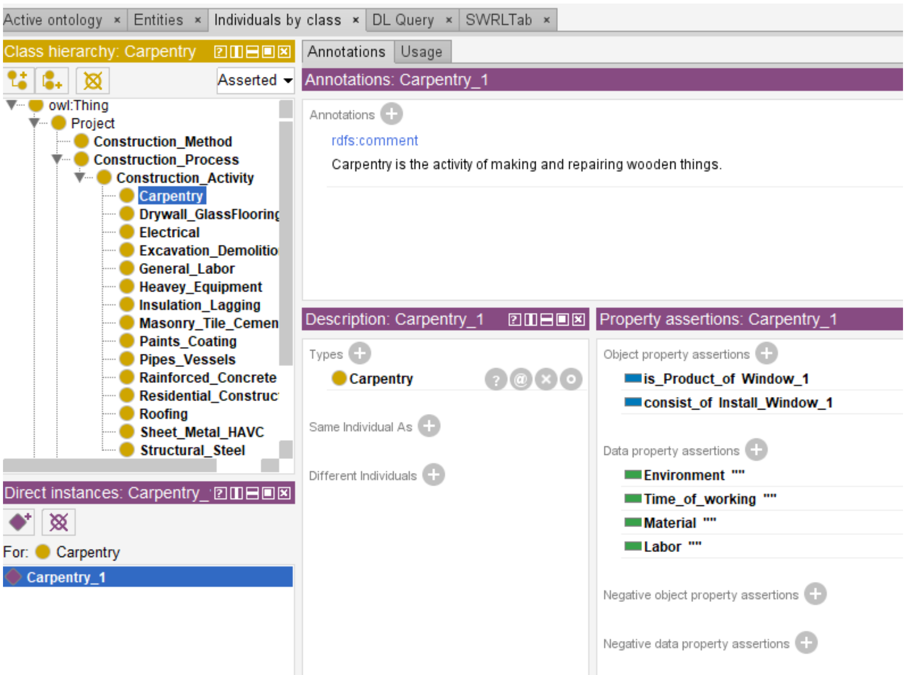

Figure 9. Instances in HSM-Onto.

4. Semantic and Syntactical Validation of HSM-Onto

As an engineering artefact, Ontology must be assessed the same way as any other [43]. Ontology validation determines whether the definitions and their links accurately model the real world. Generally, this activity is roughly classified into form-based (syntax) validation and content-based (semantic) validation.

4.1. Semantic Validation

According to the ontology development approaches, two main methods can be applied to semantic validation. The advising validation methods assist domain experts and examine the semantic definition in the developed ontology from scratch. However, if the developed ontology is aligned to an existing ontology that is often referred to, then the new one can be treated as validated. To assess the HSM-Onto's content and semantic structure, domain specialists were individually interviewed. This is because only some of HSM-Onto's highest-ranking classes are derived from ifcOWL and existing ontologies.

The ten professionals who have taken part in the survey have an abundance of practical work experience. These professionals are building safety experts from housing sectors, project management and onsite safety management. The questionnaires are designed based on the previous research [44], and a 5-point Likert scale is used to obtain the experts' feedback (Table 3).

Table 3. Questionnaire made for the ontology semantic validation.

Question	Very Agree (5)	Agree (4)	Neutral (3)	Disagree (2)	Very Disagree (1)	Means/Result
Do you think the domains and ranges of the relations defined in the HSM-Onto are complete?	20%	40%	30%	20%	0	3.9 "Agree"
Do you think the real-world concepts in the HSM-Onto are correct?	30%	50%	20%	0	0	4.1 "Agree"
How easy do you think to understand and navigate through the HSM-Onto	10%	60%	30%	0	0	3.8"Easy"
Are you familiar with the concepts in the HSM-Onto that convey their intended meanings?	40%	50%	10%	0	0	4.3 "Familiar"
Can the HSM-Onto improve the safety management decision-making?	50	50	0	0	0	4.5 "Agree"
Can the HSM-ONTO reduce the risk events on construction sites?	20	50	30	0	0	3.9"Agree"

4.2. Syntax Validation

In this developed ontology, there are 104 sub-entities classes contained in two classes, which are "Project" and "Risk", 30 object properties and 35 data properties. After semantic validation in Section 4.1, it is imperative to validate the syntax to check HSM-Onto's consistency. A Pellet plug-in incorporated in the developer software is used to indicate the syntax errors in the HSM-Onto. Based on the error messages from Pellet, anomalies in the ontology can be eliminated. Figure 10 demonstrated a consistency check for HSM-Onto.

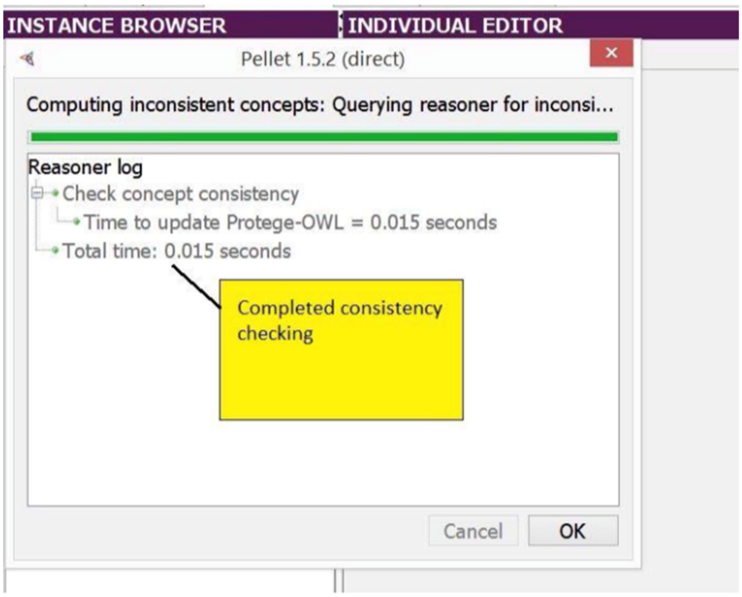

Figure 10. Consistency checking using Pellet reasoner.

5. Case Study

After the syntactic and semantic validation of HSM-Onto in Section 4, the ontology is evaluated for its proposed functionalities. Therefore, a case study is implemented to test whether the HSM-Onto works as intended.

5.1. Rule Development

As presented above, OWL can accurately describe the ontological knowledge of H&S management. However, it cannot be leveraged to express the knowledge rules, e.g., the standards and regulations involved in H&S management. As a standard rule-based semantic language initiated by W3C, SWRL is proposed to represent the domain of health-and-safety-related regulations and standards by successfully integrating domain safety knowledge into the logic rules. In this case study, using HSM-Onto concepts, the removal of formwork in Eurocode 2 (Design of Concrete Structures) was first integrated into SWRL rules. The following examples show (1) the requirement of formwork for slab casting to avoid the risk of "collapse" and (2) minimum formwork stripping time under different temperatures. The objects and attributes in the following SWRL rules are demonstrated in Figure 11.

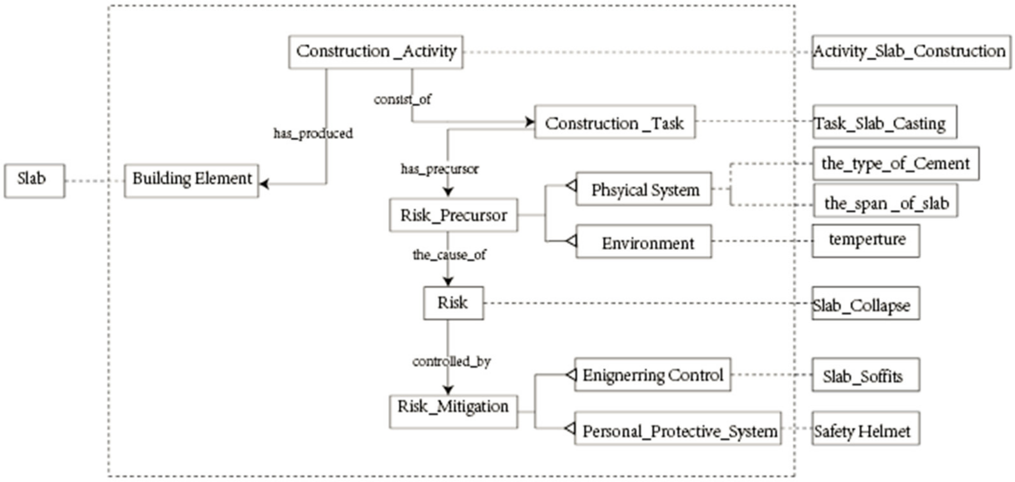

Figure 11. Slab Casting task-related classes and attributes used in SWRL rules 1, 2 and 3.

Eurocode 2: DCS Regulation:

"6.3.2.1 P(1) Formwork and falsework shall be designed and constructed so that they are capable of resisting all actions which may occur during the construction process. They shall remain undisturbed until the concrete has achieved sufficient strength to withstand the stresses to which it will be subjected to stripping or release, with an acceptable margin of safety."

The stripping time for slab soffits is shown in Table 4 when the cement used for slab concrete is O.P.C 33grade (ISI-269), OPC-43grade (ISI-8112) and PPC Cement (ISI-1489) and the span of the slab is under 3.6m (Table 4).

Table 4. Minimum Formwork Stripping Times for Slab Soffits.

Formed Surface	Hot Conditions >20 °C	Average Conditions ≤2 °C >1 °C	Cold Conditions ≤12 °C
Slab soffits	11days	17days	23days

The Logic Rule Here is:

Rule 1. *If the temperature is T > 20 °C, then the stripping time of slab soffits should be at least 11 days.*

The SWRL rules of the above can be written like this:

Construction_Activity(Formwork_Slab_Soffits)^Consist_of(Formwork_Slab_Soffits,?SC)^Slab_Casting(?SC)^has_produced(?SC,?S)^Slab(?S)^has_precursor(?SC,?RP)^Risk_Precursor(?RP)^temperature(?RP,?T)^swrlb:greaterThan(?T,20)->has_risk(?R,collapse)^has_mitigation(?R,formwork)^has_period(?R,11)

Rule 2. *If the temperature is 12 °C < T < 20 °C, the stripping time of slab soffits should be at least 17 days.*

The SWRL rules of the above can be written as:

Construction_Activity(Formwork_Slab_Soffits)^Consist_of(Formwork_Slab_Soffits,?SC)^Slab_Casting(?SC)^has_produced(?SC,?S)^Slab(?S)^has_precursor(?SC,?RP)^Risk_Precursor(?RP)^temperature(?RP,?T)^swrlb:greaterThan(?T,12)^swrlb:lessThan(?T,20)->has_risk(?R,collapse)^has_mitigation(?R,formwork) ^has_period(?R,17)

Rule 3. *If the temperature is 20 °C < T, then the stripping time of slab soffits should be at least 23 days.*

With the SWRL rules:

Construction_Activity(Formwork_Slab_Soffits)^Consist_of(Formwork_Slab_Soffits,?SC)^Slab_Casting(?SC)^has_produced(?SC,?S)^Slab(?S)^has_precursor(?SC,?RP)^Risk_Precursor(?RP)^temperature(?RP,?T)^swrlb:lessThan(?T,12)->has_risk(?R,collapse)^has_mitigation(?R,formwork)^has_period(?R,23).

5.2. Individual Generation

The individual generation presents the process to create HSM-Onto instances based on related data from BIM and other information sources. Figure 12 has illustrated the entire process for this case study. For example, “Slab_269” is generated as an individual of “Slab”, a subclass of Building_Element. The slab geometry information (the span of a slab, the length of a slab), material property (the type of cement) and construction activity schedule information (the start time and the end time of slab construction) can be obtained from BIM, while a weather forecasting application can provide the temperature information.

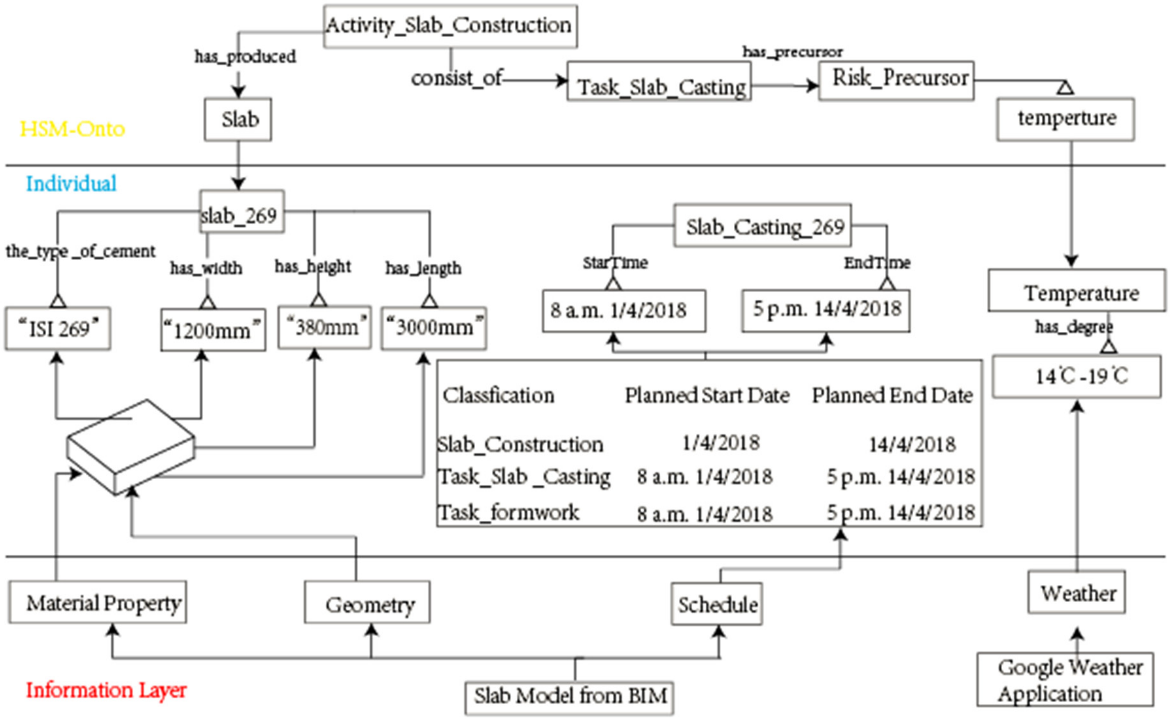

Figure 12. Ontology-based individual generations.

5.3. The Execution of SWRL Rules and Result Reporting

Jess engine is a scripting and rule environment for the Java platform. OWL HSM-Onto model and SWRL constraint rules can be translated into Jess facts by the Jess engine. In this case, study, SWRL rules and the OWL-based knowledge base created in Protégé can be automatically converted to Jess knowledge using the SWRLJessTab plug-in.

The geometry information "the span of the slab" of the individual "slab_269" can be extracted from the BIM model, which is 1200 mm. The cement type can also be obtained as "ISI_269", monitored by a weather-forecasting application, and it is between 15 °C and 19 °C. According to the input information, SWRL Rule 1–3 are chosen to run, and the engine deduces and automatically fills in the "has_precursor" "risk_type" and "controlled_By" property of the individual "Slab_Casting". Therefore, the risk is determined as "collapse" and the solution is confirmed as "remove the formwork after 17days" and "use the personal protective system-safety helmet" (Figure 13). In this way, the user can easily rerun the SWRL rules and quickly get updated on safety-related decision-making results if the schedule of the project changes.

The individual of slab construction can show the decision-making process for H&S management in construction, as the traditional way may require safety experts with rich experience and may even go through massive regulations on construction sites, which is time consuming and inefficient. The output of the risk and risk mitigation can warn the safety personnel and workers in real time and guide them in avoiding the potential risk. It can provide H&S management in a time-efficient manner and become a useful training tool to improve workers' safety awareness. As the development of ontology is an iterative process, the knowledge base can be extended all the time. It indicates that all H&S provisions can be progressed and preserved in the HSM-Onto knowledge base by defining OWL classes and SWRL rules.

In practice, health and safety management in construction is a knowledge-intensive, complex process. However, the current safety information is fragmented, which leads to obstacles in knowledge sharing and reuse among different stakeholders and communities. Further, the link between information models and safety management is still missing, thereby increasing difficulties in H&S management.

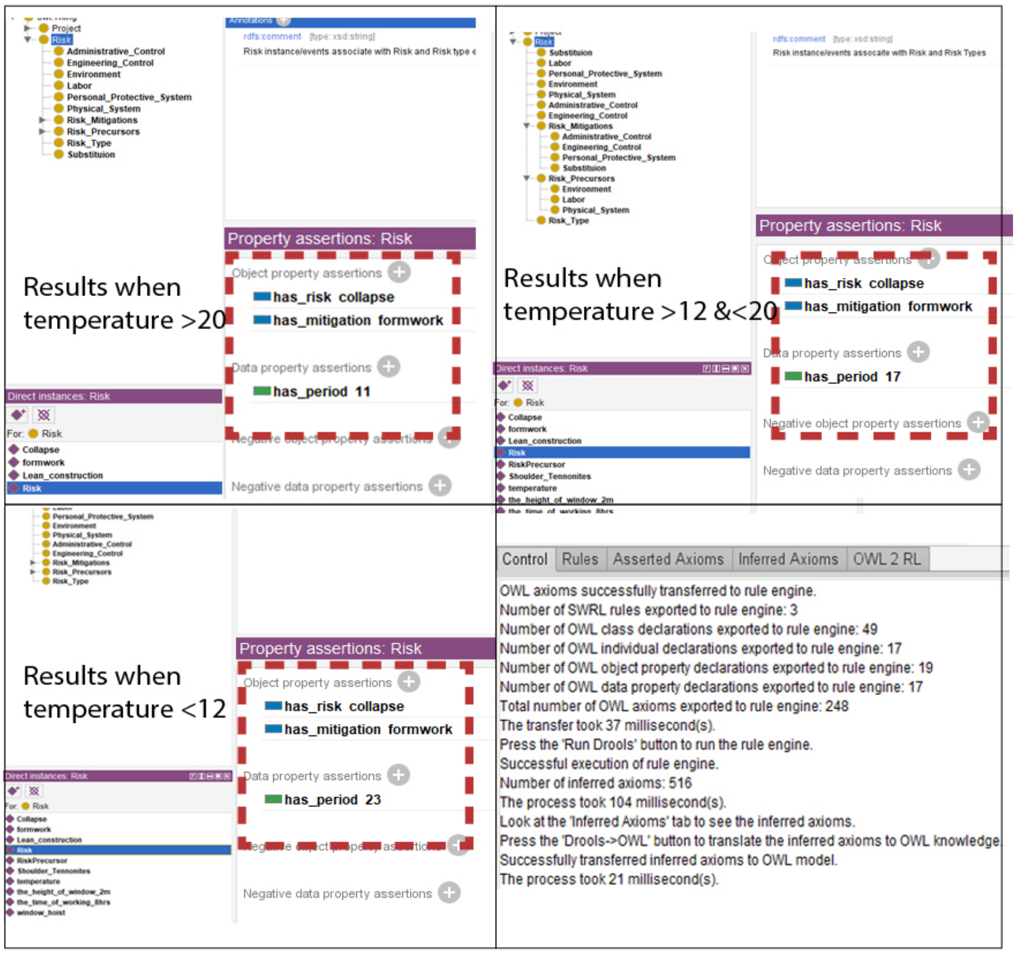

Figure 13. Protégé screenshot of execution and results of SWRL rules for decision making.

6. Conclusions

This study created an H&S ontology and introduced how to present related safety information in an ontological environment. Examples were also conducted in ontology software to indicate the reasoning process for decision making, which has its advantages compared to existing experienced-based safety management. It can input real-time information in the developed HSM-Onto by extracting information from BIM and other platforms or data sources. The main contributions of the HSM-Onto knowledge base are manifold. Firstly, the ontology provides structured and formalized domain safety knowledge by reorganizing related safety regulations, accident reports and databases to fill the knowledge gap. Thus, knowledge sharing and reuse can be enhanced without semantic ambiguity among various parties and between humans and computers. The developed ontology can also be used to create decision-making systems that connect to project information models. The potential risk of a specific construction task and accurate risk mitigation can be obtained effectively by a safety engineer or manager at the front end of a project, which releases field staff from deciding with limited time and limited safety knowledge. Moreover, the HSM-Onto can provide a dynamic solution rather than a static one by linking to other information models. Therefore, it is assumed that human-behavior monitoring can also serve as a dimension of the decision-making system. Future research will go a step further to enrich the developed ontological structure in the construction H&S domain, define the most efficient way to combine project data with the knowledge base and summarize the existing linked-data approaches and usability in a common data environment.

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References

1. Moghadami, M.; Mortazavi, A. Development of a Risk-based Methodology for Rock Slope Analysis. *Int. J. Civ. Eng.* **2018**, *16*, 1317–1328.
2. Jin, R.; Zou, P.X.; Piroozfar, P.; Wood, H.; Yang, Y.; Yan, L.; Han, Y. A science mapping approach based review of construction safety research. *Saf. Sci.* **2018**, *113*, 285–297.
3. Ding, L.; Zhou, C. Development of web-based system for safety risk early warning in urban metro construction. *Autom. Constr.* **2013**, *34*, 45–55.
4. Xing, X.; Zhong, B.; Luo, H.; Li, H.; Wu, H. Ontology for safety risk identification in metro construction. *Comput. Ind.* **2019**, *109*, 14–30.
5. Han, S.H.; Kim, D.Y.; Kim, H.; Jang, W.-S. A web-based integrated system for international project risk management. *Autom. Constr.* **2008**, *17*, 342–356.
6. Gruber, T.R. Toward principles for the design of ontologies used for knowledge sharing? *Int. J. Hum-Comput. Stud.* **1995**, *43*, 907–928.
7. Chandrasekaran, B.; Josephson, J.R.; Benjamins, V.R. What are Ontologies, and Why do We need them? *IEEE Intell. Syst. Appl.* **1999**, *14*, 20–26.
8. Dibley, M.; Li, H.; Rezgui, Y.; Miles, J. An ontology framework for intelligent sensor-based building monitoring. *Autom. Constr.* **2012**, *28*, 1–14.
9. Tah, J.H.M.; Carr, V. Knowledge-Based Approach to Construction Project Risk Management. *J. Comput. Civ. Eng.* **2001**, *15*, 170–177.
10. Tserng, H.P.; Yin, S.Y.L.; Dzeng, R.-J.; Wou, B.; Tsai, M.D.; Chen, W.Y. A study of ontology-based risk management framework of construction projects through project life cycle. *Autom. Constr.* **2009**, *18*, 994–1008.
11. Lin, Y.-C.; Wang, L.-C.; Tserng, H.P. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. *Autom. Constr.* **2006**, *15*, 693–705.
12. Carrillo, P.; Chinowsky, P. Exploiting Knowledge Management: The Engineering and Construction Perspective. *J. Manag. Eng.* **2006**, *22*, 2–10.
13. Hillson, D. Using a Risk Breakdown Structure in project management. *J. Facil. Manag.* **2003**, *2*, 85–97.
14. Wang, W.C.; Liu, J.J.; Chou, S.C. Simulation-based safety evaluation model integrated with network schedule. *Autom. Constr.* **2006**, *15*, 341–354.
15. Seo, J.W.; Choi, H.H. Risk-Based Safety Impact Assessment Methodology for Underground Construction Projects in Korea. *J. Constr. Eng. Manag.* **2008**, *134*, 72–81.
16. Alanen, J.; Linnosmaa, J.; Malm, T.; Papakonstantinou, N.; Ahonen, T.; Heikkilä, E.; Tiusanen, R. Hybrid ontology for safety, security, and dependability risk assessments and security threat analysis (STA) method for Industrial Control Systems. *Reliab. Eng. Syst. Saf.* **2022**, *220*, 108270.
17. Collinge, W.H.; Farghaly, K.; Mosleh, M.H.; Manu, P.; Cheung, C.M.; Osorio-sandoval, C.A. Automation in Construction BIM-based construction safety risk library. *Autom. Constr.* **2022**, *141*, 104391.
18. El-Diraby, T.; Osman, H. A domain ontology for construction concepts in urban infrastructure products. *Autom. Constr.* **2011**, *20*, 1120–1132.
19. Pandit, A.; Zhu, Y. An ontology-based approach to support decision-making for the design of ETO (Engineer-To-Order) products. *Autom. Constr.* **2007**, *16*, 759–770.
20. Rezgui, Y. Ontology-Centered Knowledge Management Using Information Retrieval Techniques. *J. Comput. Civ. Eng.* **2006**, *20*, 261–270.
21. Lin, K.-Y.; Soibelman, L. Promoting transactions for A/E/C product information. *Autom. Constr.* **2006**, *15*, 746–757.
22. El-Diraby, T.; Zhang, J. A semantic framework to support corporate memory management in building construction. *Autom. Constr.* **2005**, *15*, 504–521.
23. Lee, Y.-C.; Eastman, C.M.; Solihin, W. An ontology-based approach for developing data exchange requirements and model views of building information modeling. *Adv. Eng. Inform.* **2016**, *30*, 354–367.

24. Ren, G.; Li, H.; Liu, S.; Goonetillake, J.; Khudhair, A.; Arthur, S. Aligning BIM and ontology for information retrieve and reasoning in value for money assessment. *Autom. Constr.* **2021**, *124*, 103565.
25. Jiang, S.; Wang, N.; Wu, J. Combining BIM and Ontology to Facilitate Intelligent Green Building Evaluation. *J. Comput. Civ. Eng.* **2018**, *32*, 4018039.
26. Palombi, O.; Jouanot, F.; Nziengam, N.; Omidvar-Tehrani, B.; Rousset, M.-C.; Sanchez, A. OntoSIDES: Ontology-based student progress monitoring on the national evaluation system of French Medical Schools. *Artif. Intell. Med.* **2019**, *96*, 59–67.
27. Chuprina, S.; Alexandrov, V.; Alexandrov, N. Using Ontology Engineering Methods to Improve Computer Science and Data Science Skills. *Procedia Comput. Sci.* **2016**, *80*, 1780–1790.
28. Bernasconi, A.; Masseroli, M. Biological and Medical Ontologies: Systems Biology Ontology (SBO). *Encycl. Bioinform. Comput. Biol.* **2019**, 858–866.
29. Zhong, B.; Wu, H.; Li, H.; Sepasgozar, S.; Luo, H.; He, L. A scientometric analysis and critical review of construction related ontology research. *Autom. Constr.* **2019**, *101*, 17–31.
30. Pauwels, P.; Zhang, S.; Lee, Y.-C. Semantic web technologies in AEC industry: A literature overview. *Autom. Constr.* **2017**, *73*, 145–165.
31. Wang, H.-H.; Boukamp, F. Ontology-Based Representation and Reasoning Framework for Supporting Job Hazard Analysis. *J. Comput. Civ. Eng.* **2011**, *25*, 442–456.
32. Chi, N.-W.; Lin, K.-Y.; Hsieh, S.-H. Using ontology-based text classification to assist Job Hazard Analysis. *Adv. Eng. Inform.* **2014**, *28*, 381–394.
33. Zhang, S.; Boukamp, F.; Teizer, J. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Autom. Constr.* **2015**, *52*, 29–41.
34. Fang, W.; Ma, L.; Love, P.E.; Luo, H.; Ding, L.; Zhou, A. Knowledge graph for identifying hazards on construction sites: Integrating computer vision with ontology. *Autom. Constr.* **2020**, *119*, 103310.
35. Li, B.; Schultz, C.; Teizer, J.; Golovina, O.; Melzner, J. Advanced EngineeringInformatics Towards a unifying domain model of construction safety, health and well-being : SafeConDM. *Adv. Eng. Inform.* **2022**, *51*, 101487.
36. McDermott, D. Building large knowledge-based systems: Representation and Inference in the Cyc Project. In *Artificial Intelligence*; Lenat, D.B., Guha, R.V. Eds.; Elsevier: Amsterdam, The Netherlands, 1993, Volume 61, pp. 53–63.
37. Fernández-López, M.; Gómez-Pérez, A.; Juristo, N. METHONTOLOGY: From Ontological Art Towards Ontological Engineering. In Proceedings of the Ontological Engineering AAAI-97 Spring Symposium Series, Stanford University, EEUU, Stanford, CA, USA, 24–26 March 1997.
38. El-Gohary, N.M.; El-Diraby, T.E. Domain Ontology for Processes in Infrastructure and Construction. *J. Constr. Eng. Manag.* **2010**, *136*, 730–744.
39. Benevolenskiy, A.; Roos, K.; Katranuschkov, P.; Scherer, R. Construction processes configuration using process patterns. *Adv. Eng. Informatics* **2012**, *26*, 727–736.
40. Lu, Y.; Li, Q.; Xiao, W. Case-based reasoning for automated safety risk analysis on subway operation: Case representation and retrieval. *Saf. Sci.* **2013**, *57*, 75–81.
41. Uschold, M.; Gruninger, M. Ontologies: Principles, methods and applications. *Knowl. Eng. Rev.* **1996**, *11*, 93–136.
42. CPWR|Construction FACE Database. Available online: https://www.cpwr.com/research/data-center/construction-face-database/ (accessed on 20 August 2022).
43. Vrandečić, D. Ontology Evaluation. In *Handbook on Ontologies*; Staab, S., Studer, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2009.
44. Ding, L.Y.; Zhong, B.T.; Wu, S.; Luo, H.B. Construction risk knowledge management in BIM using ontology and semantic web technology. *Saf. Sci.* **2016**, *87*, 202–213. https://doi.org/10.1016/j.ssci.2016.04.008.