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CONSTRUCTION SAFETY ONTOLOGY DEVELOPMENT AND ALIGNMENT WITH INDUSTRY FOUNDATION CLASSES (IFC)

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SUMMARY*: A pronounced gap often exists between expected and actual safety performance in the construction industry. The multifaceted causes of this performance gap are resulting from the misalignment between design assumptions and actual construction processes that take place on-site. In general, critical factors are rooted in the lack of interoperability around the building and work-environment information due to its heterogeneous nature. To overcome the interoperability challenge in safety management, this paper represents the development of an ontological model consisting of terms and relationships between these terms, creating a conceptual information model for construction safety management and linking that ontology to IfcOWL. The developed ontology, named Safety and Health Exchange (SHE), comprises eight concepts and their relationships required to identify and manage safety risks in the design and planning stages. The main concepts of the developed ontology are identified based on reviewing accident cases from 165 Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) and 31 Press Releases from the database of the Health and Safety Executive (HSE) in the United Kingdom. Consequently, a semantic mapping between the developed ontology and IfcOWL (the most popular ontology and schema for interoperability in the AEC sector) is proposed. Then several SPARQL queries were developed and implemented to evaluate the semantic consistency of the developed ontology and the cross-mapping. The proposed ontology and cross-mapping gained recognition for its innovation in utilising OpenBIM and won the BuildingSMART professional research award 2020. This work could facilitate developing a knowledge-based system in the BIM environment to assist designers in addressing health and safety issues during the design and planning phases in the construction sector.*

KEYWORDS: *Building Information Modelling, BIM, Ontology, Linked Data, Prevention through Design, Design for safety.*

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1. INTRODUCTION

There were approximately 42,000 work-related injury cases in the Great Britain's construction sector during 2018/2019 based on the annual statistics report by Health and Safety Executive (HSE) (HSE, 2019). These incidents resulted in a significant cost of £524m and lost time of 3.4 million hours for UK construction. It has been claimed that designers can play a significant role in reducing risks involved in construction, operation, and maintenance works (Hare,Kumar and Campbell, 2020). For instance, a survey conducted by Kasirossafar et al. (2012) showed that 75% of respondents believe that most accidents and risks in the construction industry are predictable and, therefore, can be prevented during the design phase if designers utilise appropriate tools and technologies.

In this regard, Design for Safety (DfS) can be highly beneficial as its main aim is to identify hazards during design and before construction to improve working conditions for construction and maintenance personnel. Although understandably, not every risk can be addressed/mitigated in the design phase, risk identification at the design phase would help contractors and facilities managers to prepare for those risks well before commencing their work (Yuan *et al.*, 2019). Such an approach would also help avoid delays that may arise from necessary arrangements in order to prepare for a particular risk during the construction and operation phases (Hossain *et al.*, 2018). Regardless of the designers' level of expertise, it is realised that they need training on safety and digital design tools to assist in addressing safety issues during the design stage (Gibb,Zou and Sunindijo, 2015).

To achieve this, a safety management system (SMS) is acknowledged as crucial for an effective DfS approach. The SMS are designed to (a) prevent a hazardous event by the elimination of risks; (b) visualise and mitigate the effects of a harmful event, thereby reducing the consequences and/or providing a proper mitigation plan; and (c) achieve a combination of (a) and (b) (Vassie,Tomàs and Oliver, 2000). Towards achieving SMS for the UK construction sector, Discovering Safety programme is a multidisciplinary initiative funded by the Lloyds's Resister Foundation started in 2019 in collaboration with HSE. This programme aims to develop new techniques to analyse data and aggregate data from sources worldwide, the key output being new learning to help prevent future accidents from occurring (Collinge *et al.*, 2020b). This paper is a part of that ongoing research (Collinge *et al.*, 2020a) and concentrates on presenting the developed Safety and Health Exchange (SHE) ontology and the proposed mapping to the IfcOWL ontology. The SHE ontology aims are twofold: First, it provides an ontological representation of health and safety in the construction domain based on HSE datasets and potentially other datasets from the industry in the near future. Secondly, it facilitates the practical implementation of the DfS approach through developing an accessible knowledge-based system in a BIM environment.

In terms of structure, this paper begins with a review of the existing literature and related ontologies in section 2. Next, the methodology employed to develop the SHE ontology and map it to IfcOWL is outlined in Section 3. Section 4 illustrates the eight main classes in the developed ontology and the rationale behind them. While section 5 presents the mapping of these classes to IfcOWL classes, and Section 6 presents the evaluation of the mapping between IfcOWL and SHE ontologies. Finally, a summary and future work are presented in Section 7.

2. BACKGROUND

A DfS knowledge-based system should ideally provide the foundational information to enhance the safety design ability of designers. To generate knowledge systems, field experts, facts, and observations should be integrated together to collect, categorise, and analyse available information to generate expressive outcomes (Hare,Kumar and Campbell, 2020). In the construction industry, knowledge bases of health and safety information can be created and managed by individual companies interested in health and safety or governmental bodies responsible for overseeing health and safety activities (e.g., the Health and Safety Executive (HSE) in the UK). Traditionally, DfS relies on tacit knowledge combined with companies' policies and 2D drawings (Choe and Leite, 2017), while other forms of knowledge are not fully utilised, such as domain knowledge from regulations and guidelines, and explicit knowledge from government databases (Farghaly *et al.*, 2021). This lack of integration between various sources of knowledge hinders the mobilisation of effective DfS knowledge base systems. Research works have been conducted to develop a safety knowledge base system for both explicit and domain knowledge to address this gap (Hossain *et al.*, 2018, Jin *et al.*, 2019, Single,Schmidt and Denecke, 2020). The outcome can be classified into three principal areas: knowledge acquisition, knowledge management, and expert systems. For this paper's purpose, the work related to ontology development and matching in these areas is reviewed.

2.1 Ontology Development

In order to manage the retrieved information, many efforts have been made to bring the ontology concept to the construction safety domain. Ontology identifies the basic terms and relations of a topic's domain knowledge by comprising the vocabulary for defining the terms and the rules for combining the terms and relations (Neches *et al.*, 1991). Information sciences moved ontology from the abstract to the more concrete. Later, the term ontology was adopted by Knowledge Engineering (KE) researchers to create ontologies as computational models that enable automated reasoning. In KE, the most appropriate definition for ontology is "*an explicit specification of a conceptualisation*" (Neches *et al.*, 1991). Based on the conceptualisation definition of ontology, more researchers defined ontology in computer science and added further requirements. Borst (1997) added two requirements to the definition of ontology: *formal*, which means that the ontology is written in a machine language where it is easily processed, and *sharable*, which means that the ontology is developed based on an agreement between experts in the knowledge domain. Both requirements could guarantee the usage of the ontology in different applications.

Linked Data based approach is one of the most common approaches for publishing the ontologies by construction researchers as the machines can easily interpret them (Curry *et al.*, 2013, Farghaly, 2019). Following this approach, different terms required to represent knowledge are modelled as concepts. These concepts are then related to their properties in the form of a statement. Each statement is a directed labelled graph containing three elements: subject, predicate, and object, as shown in **FIG. 1**. In an ontology published using Linked Data, multiple such statements are combined by applying a logical AND operator. The resulting graph is called a Resource Description Framework (RDF) graph, and individual statements are called RDF triple (Pauwels ,Zhang and Lee 2017). An advantage of using this method is that the semantics can be improved using existing RDF vocabularies (W3C, 2014). Furthermore, Web ontology language (OWL) can be used to improve semantic structure. Graphs constructed using OWL can be used as a vocabulary for constructing complex RDF statements. This approach ensures that new information can be inferred during reasoning, thus enabling semantic interoperability (El-Diraby,Lima and Feis, 2005).

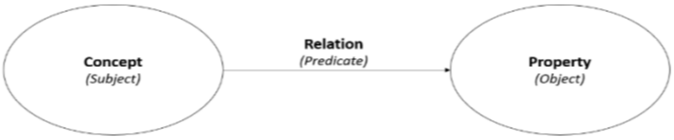


FIG. 1: RDF Statement.

The application of ontologies and Linked Data has enjoyed great popularity in domains, including biology, medical records, cultural heritage, accounting, and social media (Schmachtenberg,Bizer and Paulheim, 2014). These success stories encourage the implementation of ontologies and Linked Data in the Architecture, Engineering, Construction and Operation (AECO) domain (Radulovic *et al.*, 2015). As noted by (Ding *et al.*, 2016), an ontology can offer three main benefits in knowledge modelling and management: 1) improve model flexibility and extendibility; 2) provide a robust semantic representation; and 3) enhance knowledge retrieval by improving the retrieval requests from the concept level. Consequently, several researchers have adopted ontology and Linked Data in various applications for the AECO sector, such as cross-domain information integration for Building Information Modelling (BIM) open standards (Torma, 2015) , cost estimation (Abanda,Kamsu-Foguem and Tah, 2017), manufacturing (An *et al.*, 2019), asset management (Farghaly *et al.*, 2019), energy management (Corry *et al.*, 2015, Tomašević *et al.*, 2015), Look ahead planning (Soman,Molina-Solana and Whyte, 2020) and crowd simulation (Boje, 2019).

Several ontologies have also been proposed in the literature for safety information sharing and job hazards. For instance, an ontology for job hazard analysis for improving construction safety knowledge management in BIM environments was proposed by (Zhang,Boukamp and Teizer, 2015). Other works have been conducted for the same purpose, such as by (Ding *et al.*, 2016) to link risk knowledge with the related building object in a BIM environment using an ontology-based methodology. They modelled risk knowledge into an ontology-based semantic network to produce a risk map from which interdependencies between risks can be inferred semantically. Based on this semantic retrieval mechanism, the applicable knowledge is then dynamically linked to specific objects in the BIM environment.

Similarly, a corresponding representation and reasoning framework were proposed (Wang and Boukamp, 2011), and a domain ontology (SRI-Onto) to retrieve safety risk knowledge in metro construction was developed (Xing *et al.*, 2019). Other work included developing an ontology to represent the construction potential hazard implied in construction images (Zhong *et al.*, 2020). Most of the developed ontologies related to safety management concentrate on the construction phase and only focuses on one or two aspects that eventuates the hazard, such as building element (Ding *et al.*, 2016) and activity (Xing *et al.*, 2019). Little attention has been paid to other aspects such as location and scope of work. The proposed ontology in Section 4 is based on real incidents extracted from the HSE archive, and it considered all the various aspects which can trigger the eventuation of risks.

2.2 Ontology Matching

Ontology matching determines the relationships and correspondences between concepts of different ontologies (Euzenat and Shvaiko, 2007). Ontology matching can be using different techniques. Element level matching can be done to determine the correspondence of entities in isolation - without considering the structure-, whereas structure level matching can be performed to obtain the correspondence by analyzing how entities fit in the ontology structure. Further, the matching could be syntactic, where the interpretation is limited to the instructions in the matching algorithm, or semantic, where interpretation is based on formal semantics (Otero-Cerdeira,Rodríguez-Martínez and Gómez-Rodríguez, 2015). Ontology matching can be divided into three categories: 1) Ontology mapping, 2) Ontology merging and 3) Ontology integration.

Ontology mapping is the process of mapping entities of one ontology to at most one entity of another ontology. The mapping of ontologies is defined in Kalfoglou and Schorlemmer (2002) as "*the task of relating the vocabulary of two ontologies that share the same domain or discourse in such a way that the mathematical structure of ontological signatures [...]* are *respected*." Mapping new ontologies to existing ontologies is a crucial step to gain from the power of the Semantic Web. Schneider (2019) has mapped the BOT ontology to BRICK, IfcOWL, DogOnt, ThinkHome, and SAREF4Bldg ontologies.

Ontology merging is the creation of an ontology from two or more possible overlapping ontologies (Perin and Wouters, 2014). Source ontologies are not altered in this process and this process is analogous to schema integration in databases. In the context of construction project scope management, Cerezo-Narváez et al. (2020) developed an ontology to integrate the datasets of work breakdown structures (WBS) and cost breakdown structure (CBS). This provides an environment to develop WBSs based on CBS, allowing both clients and contractors to develop the schedule based on the construction units level (the units of quantity survey contracts). The work done in ontology merging perform a syntactic and semantic merge by resulting in a single ontology representing the integrated abstract syntaxes of all the considered domains.

Ontology integration is the inclusion of one ontology inside another ontology. It is usually realised through bridge axioms where bridge axioms are assertions expressing the glue between these ontologies. They are utilised when one singular reference representation can be used to describe a class in different ontologies. McGlinn et al. (2019) proposed utilising BOT ontology as a building reference ontology to connect building and geospatial geometry. This approach was utilised because software applications are commonly built on different geometry kernels, producing inaccuracies when transferring complex, mathematical geometry descriptions from one application to the other. Other work proposed developing several ontologies based on available standards such as Uniclass2 and NRM 1&3 to cross-map the datasets in BIM and asset management platforms (Farghaly *et al.*, 2019). For heat loss calculation, Rasmussen et al. (2019) developed an Ontology for Property Management (OPM) and proposed a semantic bridge with project-specific extensions of the Building Topology Ontology (BOT) and other work developed the integration between integrating BIM and product manufacture data (Niknam,Jalaei and Karshenas, 2019). The work done in ontology integration perform only semantic merge because they only focus on the semantic alignment of the considered domains.

Despite the matching techniques and approaches, the ontology matching is crucial to improve the integration of different datasets and the development cross-domain information environment. Recent implementation of the cross-domain building information using semantic web technologies have shown a great success in the AEC sector (Hu *et al.*, 2021). Accordingly, cross-domain information between the H&S silo datasets and the BIM environment (mainly IfcOWL) can significantly improve the design for safety process. It could provide an accessible knowledgebase in a structured way where interoperability between different platforms and the golden thread of information can be achieved. This knowledgebase also provides an environment for machine learning and predictive analytics.

3. METHODOLOGY

As mentioned in the introduction, the work is a part of the Discovering Safety Programme which aims to develop new techniques to analyse data and aggregate data from sources worldwide, the key output being new learning to help prevent future accidents from occurring. The aim of this research presented in this paper is twofold. First, the development of an ontology, 'Safety and Health Exchange (SHE)' that captures the concepts related to health and safety in construction which can improve the DfS process. Secondly, a proposed mapping between the SHE ontology and IfcOWL. **FIG. 2** illustrates the five steps methodology adapted from (Ehrig and Sure, 2004) to achieve the aim. The first step is the development of the SHE ontology based on the selected ontological datasets. In this research, HSE's archive is the selected datasets source, which includes press releases, investigation reports, and Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR); The second step is to identify the other ontologies which require mapping to the developed ontology. IfcOWL is the identified ontology to be mapped to SHE. The IfcOWL is selected as it is one of the most frequently used ontology in the AECO sector (Pauwels ,Zhang and Lee 2017); The third step comprises mapping all the similarities which are not relying on other similarities such as the label similarity, equal URIs, or the sameAs relation; In the fourth step, all the other similarities are identified and calculated based on the similarity measures introduced by Ehrig and Sure (2004); The last step includes the repetition of steps three and four for multiple rounds till saturation. Once there are no changes per round, the defined mapping can be presented as the final mapping table and evaluate the semantical alignment (Euzenat, 2007).

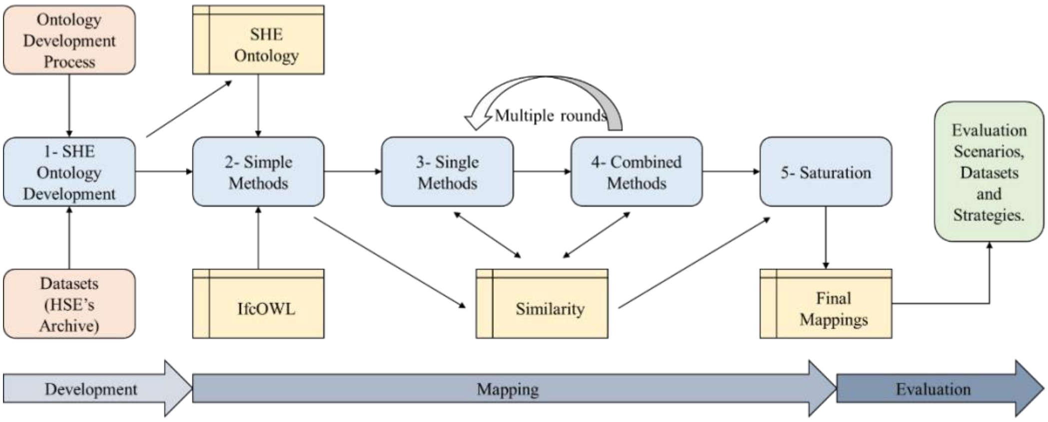


FIG. 2. The process of development and mapping of ontologies.

4. SHE ONTOLOGY DEVELOPMENT

The methodology of ontology development is described similarly in the majority of literature (Farghaly *et al.*, 2019, Soman,Molina-Solana and Whyte, 2020). The SHE ontology has been developed through seven different steps proposed by Noy and McGuinness (2001) and also using Protégé editor as ontology editor, for its open code, free access, and simplicity. Regarding the naming strategy for the entities, the "hashtag" strategy was chosen to avoid redirection issues associated with the "slash" format (World Wide Web Consortium (W3C), 2008). As mentioned before, the ontology classes, attributes, and relationships were developed to achieve specific requirements and to cover the HSE archive datasets.

4.1 Entities/Classes

Entity extraction is the process of identifying terms from related documents in the domain regarding the entities' names and characteristics. During this step of concepts identification, the HSE archive was reviewed, especially the RIDDOR and press releases. The authors' most significant challenge was how the RIDDORs were written and how the description varies from an incident to another. In the end of reviewing the identified datasets, eight concepts were identified: namely, construction scope, activity, building element, location, risk factor, risk, and treatment plan. **TABLE 1** illustrated the list of entities that were agreed upon by the authors and the description of each one. Several sub-concepts are identified for each concept based on available taxonomies and newly developed ones for achieving precise and consistent terminology in the annotation of the datasets (RIDDORs and Press releases). These sub-concepts are presented in the taxonomy section.

TABLE 1: SHE ontology entities and description

Entity	Entity Description
Construction Scope	The entity describes the work required to achieve the scope.
Activity	The entity describes the set of activities took place (High level activities).
Building Element	The entity describes the element produced from the construction scope.
Location	The entity describes the environment surrounding the element from risk perspective.
Risk Factor	The entity describes the situation which triggered the risk eventuation.
Risk	The entity describes the type of risk occurred.
Scenario	The entity describes the overall situation of the risk occurred.
Treatment Plan	The entity describes the solution/plan to handle the risk effectively.

4.2 Taxonomy

Taxonomy sets up the terms hierarchically in a controlled vocabulary without adding any further information. At the crux, the taxonomy provides a structure for the ontology to be easily understandable for humans and simultaneously integrate it with other ontologies. **FIG. 3** presents the taxonomy for the SHE ontology. The terminology utilised to identify the subclasses in the developed ontology, and they have been developed based on existing standards, regulations, and guidelines, as noted below:

- Construction Scope – the sub-classes of this entity are classified based on the guideline CIRIA C755 CDM 2015. The guideline has been structured based on the type of construction work and divided into five main groups which present the five subclasses of this class: Group A – General Planning, Group B – Excavation and Foundations, Group C – Primary Structure, Group D – Building Elements and Services, and Group E – Civil Engineering. Each group consists of several sectors of construction works which categorise the type of related construction work. In total, 40 sectors as individuals/instances for the five subclasses.

- Risk – the diverse types of risks that could occur in the construction sector are classified into two classes: health and safety as in PAS 1192-6 (2018) – Appendix B. In total, there are 29 different risks which are divided between the two subclasses health and safety. These risks are represented as individuals/instances in the SHE ontology such as: fall from open edge, electric shock, material handling, asbestos effect, and noise.

- Element – the elements are classified by the discipline related to easily assigned to the responsible designer. The classification consists of five main groups: structure, architecture, mechanical, electrical, and temporary structures.

- Location –This concept's classification is developed by the authors based on a review of incidents in the HSE archive. It consists of two main groups (till this date, it may increase with time-based on the new reviewed incidents): high-level (such as: openings, edges and spacing between joists) and site logistics (such as: confined area, excavation, and crane area).

- Activity – The class is divided into two sub-classes related to construction activities and in-use activities. The activities' breakdown structure is at a higher level, as the construction means, and methods are not very clear during the design stage.

- Risk Factor – this class seeks to identify the reason behind the risk eventuation, and it is divided into three main groups: physical, material, and task.

- Treatment Plan – this class is not sub-divided; however, it contains two classes that classify the treatment plan based on the type of treatment and the treatment stage.

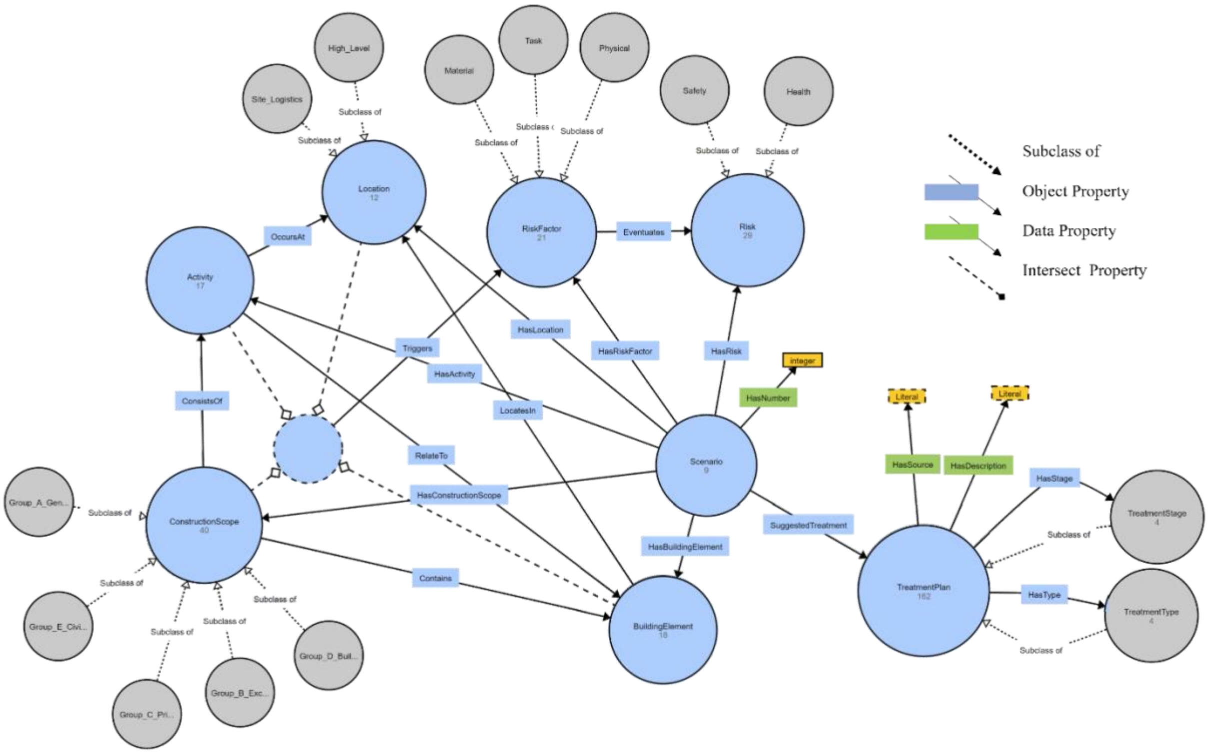


FIG. 3: The SHE ontology classes and relationships.

4.3 Relationships

Relationships show the interaction between the concepts/terms in the domain. Relationships can be categorised into three main groups: namely equivalence, hierarchical and associative. The hierarchical relationships were stated in the previous sub-section, while, as the concepts describe different terms, there are no equivalence relationships. The associative relationships identify relations that are neither equivalent nor hierarchical, and they are defined by the attributes and properties that exemplify the classes of the domain. Two kinds of Protégé properties have been utilised to identify the associative relationships: object properties and datatype properties. Object properties were utilised to relate the main concepts of SHE ontology, while the datatype properties add information to the main concepts. **FIG. 3** and **TABLE 2** represent the different relationships between the different classes of SHE ontology. In **TABLE 2**, the object property *Has** refers to the six different *Has* relationships between the scenario class and other classes. For instance, *HasLocation* refers to that specific scenario that would take place in that specific location.

TABLE 2: SHE Ontology relationships and their descriptions

Relationship	Protégé Property	Relationship Description
ConsistsOf	Object Property	Construction Scope *ConsistsOf* Activities
Contains	Object Property	Construction Scope *Contains* Building Element
Eventuates	Object Property	Risk Factor *Eventuates* Risk
LocatesIn	Object Property	Building Element *LocatesIn* Location
OccursAt	Object Property	Activity *OccursAt* Location
RelateTo	Object Property	Activity *RelateTo* Building Element
SuggestedTreatment	Object Property	Scenario SuggestedTreatment Treatment Plan
Triggers	Object Property	Construction Scope, Building Element, Location, Activity *Triggers* Risk Factor
Has*	Object Property	Scenario *Has** Location, Activity, Building Element, Construction Scope, Risk, Risk Factor.

Relationship	Protégé Property	Relationship Description
HasStage	Object Property	Treatment Plan *HasStage* Treatment Stage
HasType	Object Property	Treatment Plan *HasType* Treatment Type
HasCIRIAno.	Data Property	Construction Scope *HasCIRIAno.*
HasDescription	Data Property	Treatment Plan *HasDescription*
HasNumber	Data Property	Scenario *HasNumber*
HasSource	Data Property	Treatment Plan *HasSource*

4.4 Individuals

The individuals to identify risk scenarios were utilised to annotate and categorise 165 RIDDORs and 31 press releases. Based on the annotations, it was noticed that 85% of the reviewed incidents related to falling from open/edge in in-situ concrete, and these could be categorised into nine different scenarios and their associated classes such as construction scope, location, building element, activity, risk, and risk factor. The nine scenarios' treatment actions were identified from a combination of industry workshop events, official industry guidance documents (CIRIA C755; CDM 2015), HSE expert opinion, and the Design for Best Practice Website (www.dbp.org.uk). This process is discussed in detail in the paper submitted and under review (Collinge et al., 2021). The output of this process as individuals were loaded in the ontology as shown in **FIG. 4**, in total 202 treatment plans were added and associated to the relevant from the nine scenarios. Finally, a consistency checking took place using the built-in Hermit reasoner in Protégé.

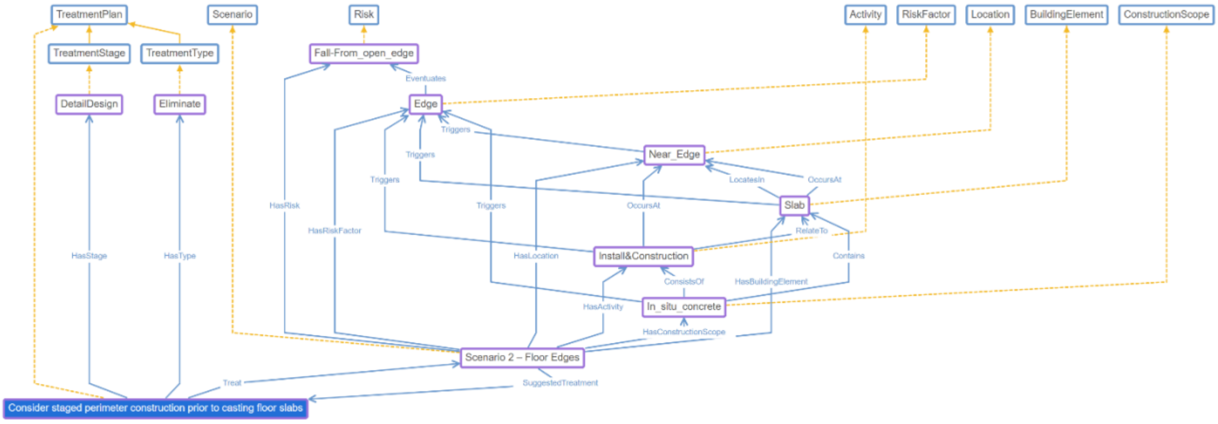


FIG. 4: An example of an induvial for the treatment plan and its associated individuals from other concepts.

5. MAPPING SHE ONTOLOGY TO IFCOWL

As ontologies are dynamic entities that evolve overtime, ontology mapping is not a one-off time process, and it requires updating (Harrow *et al.*, 2019). The developed ontology matching utilised the ontology mapping approach where the initial trial is to map the developed ontology to one of the most frequently used ontologies in the AECO sector – IfcOWL (Pauwels and Terkaj, 2016). The authors carefully considered not replicating any works done before and/or developing more unused ontologies in the AECO domain. Therefore, they worked on mapping the SHE entities to IfcOWL to encourage the designers to utilise it during the developing of their 3D models. On the other hand, the authors mapped the SHE ontology to ifcOWL classes rather than using the ifcOWL classes. The reason behind that is IFC classes to which we have mapped to SHE classes are generic. They do not contain the neither the relationships nor the properties required to represent health and safety ontology. Introducing these relationships in the generic IFC classes would affect other functionalities of IfcOWL.

As mentioned earlier, the developed ontology's primary purpose is to identify, manage and integrate the data related to the eventuation of the risk and the proper way to treat that risk based on best practice during the design stage. Thus, predefining the different individuals of the defined classes could help automatically identify the scenarios where hazard occurs. There were two rounds of matching. First the matching was done using an automated tool and then correspondences were determined manually. To map SHE to IFCOWL, Alignment-Maker, an automated ontology alignment tool was first used (Faria *et al.*, 2013). The match threshold was set to 75% meaning that all the matches with accuracy less than 75% will be eliminated. The results from the tool are presented in **TABLE 3**. Although, Alignment-Maker gave 20 correspondences for matching, most of them were matched using string matching (similarity in names). For example, SHE: HasLocation is matched to IFC4: location_IfcDocumentInformation due to similarity in the string 'location'. However, this is not semantically or syntactically correct. Hence, after the first round of automatic matching, a second round of manual matching was conducted. **TABLE 4** illustrates the mapping between SHE and IfcOWL ontologies and the mapping approach based on the classification proposed by Ehrig and Sure (2004).

TABLE 3: Results from automated ontology alignment tool

IFC class	SHE class	Accuracy
IFC4: relatesTo_IfcMaterial	SHE: RelateTo	0.9101
IFC4: location_IfcPlacement	SHE: HasLocation	0.9
IFC4: location_IfcClassification	SHE: HasLocation	0.9
IFC4: location_IfcDocumentInformation	SHE: HasLocation	0.9
IFC4: location_IfcExternalReference	SHE: HasLocation	0.9
IFC4: location_IfcLibraryInformation	SHE: HasLocation	0.9
IFC4: relates_IfcApproval	SHE: RelateTo	0.8585
IFC4: relates_IfcOrganization	SHE: RelateTo	0.8585
IFC4: IfcBuildingElement	SHE: BuildingElement	0.841
IFC4: containsElements_IfcSpatialElement	SHE: Contains	0.8381
IFC4: internalLocation_IfcPostalAddress	SHE: HasLocation	0.8182
IFC4: placementLocation_IfcGridPlacement	SHE: HasLocation	0.8182
IFC4: locations_IfcStructuralLoadConfiguration	SHE: HasLocation	0.8182
IFC4: relatedBuildingElement_IfcRelFillsElement	SHE: HasBuildingElement	0.804
IFC4: relatedBuildingElement_IfcRelSpaceBoundary	SHE: HasBuildingElement	0.804
IFC4: relatingBuildingElement_IfcRelCoversBldgElements	SHE: HasBuildingElement	0.7931
IFC4: relatingBuildingElement_IfcRelVoidsElement	SHE: HasBuildingElement	0.7931
IFC4: containedIn_IfcPort	SHE: Contains	0.7704
IFC4: hasOpenings_IfcElement	SHE: HasBuildingElement	0.7596
IFC4: hasCoverings_IfcElement	SHE: HasBuildingElement	0.7506

TABLE 4: SHE and IfcOWL mapping

Subject (she:)	Predicate	Mapping Approach	Object (ifc:)
ConstructionScope	owl: equivalentClass	Entities	IfcWorkPlan
Location	owl: equivalentClass	Semantic Nets	IfcSpace
BuildingElement	owl: equivalentClass	Description Logics	IfcBuildingElement
Activity	owl: equivalentClass	Entities	IfcProcess
Scenario	owl: equivalentClass	Entities	IfcEvent
RiskFactor	owl: equivalentClass	Semantic Nets	IfcEventType
Risk	owl: equivalentClass	Semantic Nets	IfcEventTrigger
TreatmentPlan	owl: equivalentClass	Semantic Nets	IfcProcedure

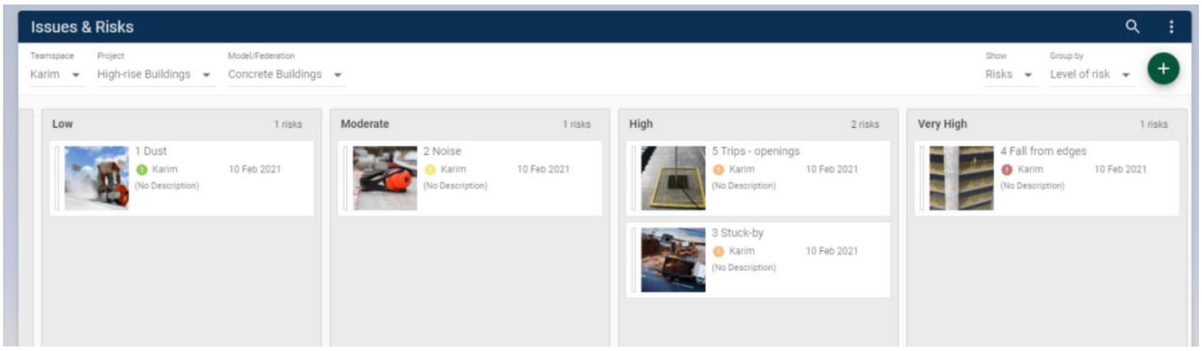
Construction scope class is mapped to the work plan class in IFC. The IfcWorkPlan represents the entity data for work plan in construction or a facilities management project, and that description is aligned with purpose of the construction scope class. It is crucial to mention that, despite that, the 40 identified individuals in construction scope class based on CIRIA C755 can be added to the predefined individuals in IfcWorkPlanTypeEnum class, and it also can work for other classes to host the individuals in the enumeration classes of IFC. The construction scope individuals will be updated in the future work to include the different scope of work proposed by CIRIA C756 CDM 2015 – workplace 'in-use' guidance for designers. Location class is mapped to IfcSpace to categorise the different spaces which are associated with the risk. This mapping could facilitate automatic identification of all the different spaces could cause a risk in a BIM model. Building Element class and its subclasses are mapped to IfcBuildingElement and its subclasses. In IFC schema, IfcProcess entity defined as one individual activity or event, that is ordered in time, that has sequence relationships with other processes, which transforms input in output, and may connect to other processes. IfcProcess has three main subclasses: namely, IfcTask, IfcEvent and IfcProcedure. The scenario is mapped to IfcEvent which have a Risk Factor and Risk which are mapped to IfcEventType and IfcEventTrigger, respectively. Finally, the Treatment Plan is mapped to IfcProcedure.

6. IMPLEMENTATION

As the SHE ontology is developed to identify, manage, and integrate the data related to the eventuation of the risk and treat that risk based on best practice during the design, this section describes SHE ontology's implementation at various stages. 3D Repo is the platform adopted for the implementation. 3D Repo was selected as it is an open-source online platform where designers can build more on it. It also supports IFC schema and is connected through API to one of the most used BIM platforms (Revit – Autodesk). During the implementation, The SHE ontology provides a knowledge base which codifies the safety related knowledge which can be accessed through any online tools which supports IFC schema. This knowledge could be used at any stage of the project such as conceptual stage, detail design stage etc. The developed ontology allows the user to retrieve risks, scenarios, treatment plans during different stages of the project. Listing 1,2,3 and 4 represents four SPARQL queries to retrieve risks, scenarios, treatment plans, and treatment plans by stage, respectively. For implementation, the designers and engineers just require to be familiar with online BIM platforms and understand the different terms of the ontology such as location, risk factor and risk treatments.

6.1 Concept Design Stage

During the concept design stage, engineers who are designing the project would be aware of the construction scope as well as construction activities. Based on this, they can understand the construction risks associated with such activities using SHE ontology. For example, if the construction scope is known to be *Concrete In-Situ* and it contains a construction activity *Install and Construct*, all the reported risks associated from such a combination from previously identified scenarios can be obtained using a query as shown in Listing 1. Listing 1 is a SPARQL query to retrieve risks during concept design stage, given that we know the construction scope and activity. It would give the output as shown in FIG. 5. The knowledge about these risks would help the engineers to choose between combinations with less risk.



Teamspace: Karim
Project: High-rise Buildings
Model/Federation: Concrete Buildings
Show: Risks
Group by: Level of risk

Low — 1 risks
1 Dust — Karim — 10 Feb 2021 — (No Description)

Moderate — 1 risks
2 Noise — Karim — 10 Feb 2021 — (No Description)

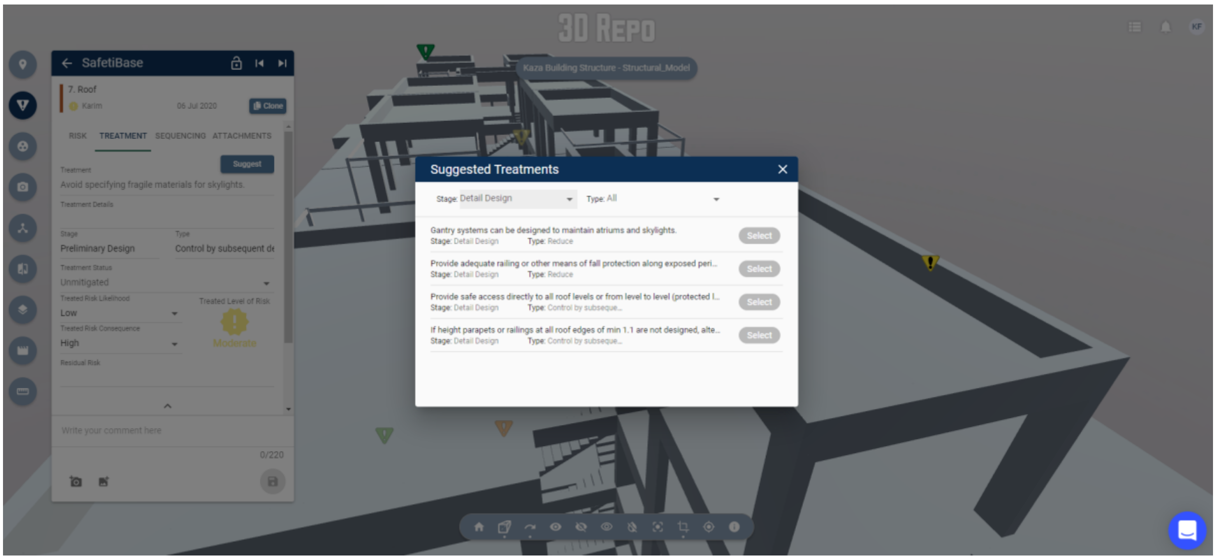
High — 2 risks
5 Trips - openings — Karim — 10 Feb 2021 — (No Description)
3 Stuck-by — Karim — 10 Feb 2021 — (No Description)

Very High — 1 risks
4 Fall from edges — Karim — 10 Feb 2021 — (No Description)

FIG. 5: Screenshot from 3D Repo for the outputs in initial stages before 3D models are developed.

6.2 Detailed Design Stage

Designers would have access to more specifics of the design during the design phase, such as the elements and the location of these elements. With this information, SHE would offer the designers with a list of scenarios of risks for that combination. For example, if the construction scope is known to be *Concrete In-Situ* and it contains a construction activity *Install and Construct* happening at *the edges* to build *Slab*, all the reported scenarios of risks associated from such a combination from the previous combination can be obtained using a query as shown in Listing 2. Listing 2 is a SPARQL query to retrieve risks and scenarios during the detailed design stage. It provides all the scenarios for the given construction scope, activity and location. During the design and planning stage, the designers, planners, and principal designers can select the most appropriate treatment plan for the identified scenarios and can share with other stakeholders for their inputs in a collaborative BIM environment (FIG. 6). SPARQL queries for obtaining the treatment plans are shown in Listing 3 and 4. Also, they would be able to filter the treatment based on phases and types.



7. Roof
Karim 06 Jul 2020

Treatment: Avoid specifying fragile materials for skylights.
Treatment Details:
Stage: Preliminary Design
Type: Control by subsequent de
Treatment Status: Unmitigated
Treated Risk Likelihood: Low
Treated Risk Consequence: High
Treated Level of Risk: Moderate
Residual Risk:
Write your comment here

Suggested Treatments

Stage: Detail Design
Type: All

Gantry systems can be designed to maintain atriums and skylights.
Stage: Detail Design Type: Reduce

Provide adequate railing or other means of fall protection along exposed peri...
Stage: Detail Design Type: Reduce

Provide safe access directly to all roof levels or from level to level (protected l...
Stage: Detail Design Type: Control by subseque...

If height parapets or railings at all roof edges of min 1.1 are not designed, alte...
Stage: Detail Design Type: Control by subseque...

FIG. 6: Screenshot from 3D Repo where treatment plans are filtered by Detail Design Stage.

7. CONCLUSION AND FUTURE WORK

Modern technologies and innovations, including Ontologies and Linked Data, help address the interoperability challenges in the AEC sector. That is by offering the potential to leverage available heterogeneous data in a manner that can enable to make better decisions related to safety, planning and cost in construction. The current research project establishes the foundation of a decision-making tool, based on ontology and BIM, to integrate the H&S concepts along with the physical models, location, and construction and operation activities. The developed SHE ontology could allow the classification of all the aspects related to H&S, such as location, element, activity, risk factor, treatment plans, treatment plans, and the relationships among them. On the other hand, each class in the developed ontology is cross mapped with the IFC schema. There were two rounds of matching. The matching was first done using an automated tool and then correspondences were determined manually. Finally, the developed mapping is implemented through the developed SPARQL queries.

The developed mapping can be the foundation for developing a Model View Definition for safety management exchange and developing a rule checking system for design models against specific regulations based on the incidents in the past years in the construction sector. Professionals can utilise this work for enhancing their design for safety procedures, also the scholars in this domain can utilise the SHE ontology for understanding the root causes of the incidents in various sources and adapt the process of matching with IfcOWL for other aspects such as time, cost, and sustainability. Also, the process adapted to develop the ontology and mapping with ifcOWL can be replicated for other purposes such as sustainability. This work has won recognition on the industrial and academic stage as it is the winner of the BuildingSMART professional research award 2020. Future work includes the enhancement of the developed ontology and evaluation in real case studies. As the output of this research has now moved into an industry piloting phase, designers' active usage will improve the tool's` utility and functionality, enabling the risks/treatments held in a growing safety in design knowledge base.

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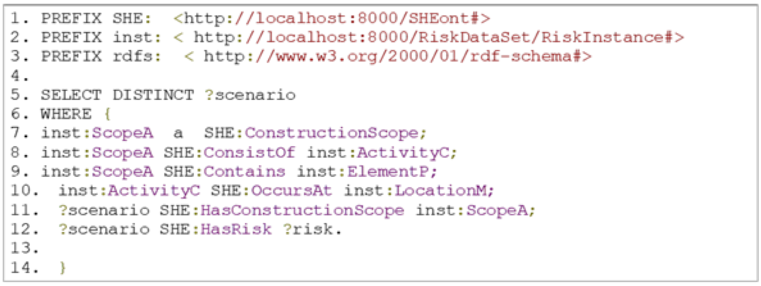
APPENDIX

```
SHE:  <http://localhost:8000/SHEont#>
PREFIX inst: < http://localhost:8000/RiskDataSet/RiskInstance#>
PREFIX rdfs:  < http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?risk
WHERE {
inst:ScopeA  a  SHE:ConstructionScope;
inst:ScopeA SHE:ConsistOf Inst:ActivityC;
?scenario SHE:HasConstructionScope inst:ScopeA;
 ?scenario SHE:HasRisk ?risk.
 }
```

Listing 1: SPARQL query to retrieve risks during concept design stage.



```
PREFIX SHE:  <http://localhost:8000/SHEont#>
PREFIX inst: < http://localhost:8000/RiskDataSet/RiskInstance#>
PREFIX rdfs:  < http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?scenario
WHERE {
inst:ScopeA  a  SHE:ConstructionScope;
inst:ScopeA SHE:ConsistOf inst:ActivityC;
inst:ScopeA SHE:Contains inst:ElementP;
 inst:ActivityC SHE:OccursAt inst:LocationM;
 ?scenario SHE:HasConstructionScope inst:ScopeA;
 ?scenario SHE:HasRisk ?risk.

 }
```

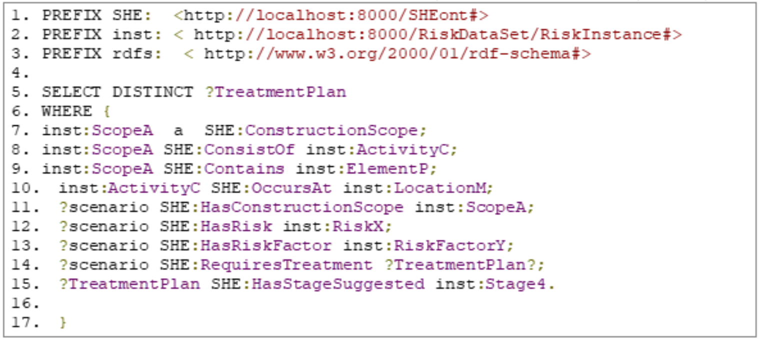
Listing 2: SPARQL query to retrieve risks and scenarios during the detailed design stage.

```
PREFIX SHE:  <http://localhost:8000/SHEont#>
PREFIX inst: < http://localhost:8000/RiskDataSet/RiskInstance#>
PREFIX rdfs:  < http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?TreatmentPlan
WHERE {
inst:ScopeA  a  SHE:ConstructionScope;
inst:ScopeA SHE:ConsistOf inst:ActivityC;
inst:ScopeA SHE:Contains inst:ElementP;
 inst:ActivityC SHE:OccursAt inst:LocationM;
 ?scenario SHE:HasConstructionScope inst:ScopeA;
 ?scenario SHE:HasRisk inst:RiskX;
 ?scenario SHE:HasRiskFactor inst:RiskFactorY;
 ?scenario SHE:RequiresTreatment ?TreatmentPlan.

 }
```

Listing 3: SPARQL query to retrieve treatment plans during the detailed design stage.



```
PREFIX SHE:  <http://localhost:8000/SHEont#>
PREFIX inst: < http://localhost:8000/RiskDataSet/RiskInstance#>
PREFIX rdfs:  < http://www.w3.org/2000/01/rdf-schema#>

SELECT DISTINCT ?TreatmentPlan
WHERE {
inst:ScopeA  a  SHE:ConstructionScope;
inst:ScopeA SHE:ConsistOf inst:ActivityC;
inst:ScopeA SHE:Contains inst:ElementP;
 inst:ActivityC SHE:OccursAt inst:LocationM;
 ?scenario SHE:HasConstructionScope inst:ScopeA;
 ?scenario SHE:HasRisk inst:RiskX;
 ?scenario SHE:HasRiskFactor inst:RiskFactorY;
 ?scenario SHE:RequiresTreatment ?TreatmentPlan?;
 ?TreatmentPlan SHE:HasStageSuggested inst:Stage4.

 }
```

Listing 4: SPARQL query to retrieve treatment plans for specific stage during the detailed design stage

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