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An ontology-based tool for safety management in building renovation projects

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ABSTRACT

Managing deep renovation projects is challenging due to the interactions with their surroundings, the issues of limited access and space, and the uncertainty around the composition and conditions of existing buildings. The interplay between the building areas, the building elements involved in the deep renovation, and the renovation scenarios and activities present challenging situations for managing safety risks. Research on enhancing safety in building projects using digital approaches such as BIM has mainly focussed on new construction works, yet limited research is available for deep building renovation projects. Using a Design Science Research (DSR) methodology, this paper develops an ontology for representation and identification of hazards in deep building renovations, instantiates the ontology through the development of a digital tool, and demonstrates its usefulness in hazard representation and identification by performing tests with real industry data from deep renovation projects, as part of a Horizon Europe 2020 research project, called RINNO. The testing involved a multi-residence apartment case study and three different renovation scenarios and successfully demonstrated the ability to automatically identify potential hazards relating to a particular renovation strategy. While the proposed ontology can be used to reduce the risk of accidents and injuries in building retrofit projects, its main implication is in laying the foundation for future digitally enabled approaches for managing safety in building renovation projects.

1. Introduction

The building and construction sector's demand on natural resources accelerates climate change as inefficient existing buildings negatively impact both humans and the environment [1]. For instance, in Europe, buildings are responsible for the largest environmental impact, including almost 40 % of European energy consumption, 33 % of waste production, and 50 % of raw material depletion [2,3]. In the UK, according to the National Trust and Historic England, almost a quarter of all the constructed residential buildings (6.2 million properties) are estimated to require retrofitting or renovation and represent about 20 % of all carbon emissions of the country. Although many research efforts have been investigating the processes of constructing new buildings and how to improve their operational performance, the renovation of existing buildings seems to be a neglected area for the architecture, engineering, construction and facilities management (AEC-FM) industry.

Building renovations present real challenges for project participants, policymakers, and occupants. This is because of their operational characteristics, including: (1) high uncertainty [4,5]; (2) short durations to carry out the renovation works [6]; (3) small quan-

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tities-based production; (4) poor understanding of user requirements and the technologies to be used [7]; (5) dearth of tools and approaches to evaluate renovation strategies and scenarios [7]; (6) low degree of anticipation and efficiency in the retrofitting phase [8]; and more importantly (7) high level of interaction and interference with occupants, especially when they remain in the building over the renovation period [9–11]. Renovation challenges usually generate a high increase in the final project costs, schedule overruns, and additional hazards [5,11,12]. Health and safety (H&S) hazards represent one of the main concerns facing the successful planning and delivery of renovation works. For instance, in 2019, the EU reported 756 fatal accidents and more than 365,800 nonfatal accidents that resulted in at least 4 days of work leave within the AEC-FM sector [13], while 30 worker fatalities were reported in the UK during the period April 2018–March 2019 [14,15] (i.e., four times higher than the average rate across all UK industries). Since unidentified renovation hazards represent serious threats to the health and safety of both workers and occupants, they must be systematically identified and assessed as soon as possible in the renovation process so as to be timely mitigated and properly managed. However, up to now, there is no comprehensive framework that automates and facilitates hazard identification and safety risks management for building renovation. The H&S methods and tools proposed in the literature are either not adapted for building retrofit, since developed for new build constructions, or only considering a small number of related concepts and classes [16,17].

Building information modelling (BIM) approaches [18–22] have demonstrated the benefits of visualisation, simulation, and process automation to enable better control and transparency of project execution in the AEC-FM domain. Pre-construction simulation methods are particularly known to be useful tools to identify optimised renovation scenarios in terms of cost and time [23–25]. They also allow project participants to reduce renovation uncertainty, assessing the performance of different renovation approaches and strategies, and assisting decision-making processes [26]. BIM-based simulations particularly enable to share, clarify, and unify the perception of the renovation process by all stakeholders including building occupants. It permits better visualisation, communication, and decision-making through 3D-based simulations of several renovation scenarios and strategies [27–29]. Despite all these advantages and benefits, research works are still lacking on the use of BIM [30] and simulations in renovation [23–25], especially for hazard identification and risk mitigation.

In order to reduce the risk of injuries and accidents on construction sites, this paper develops the foundation for digitally enabled approaches for managing safety in building renovation projects and demonstrates its applicability. On the one hand, it proposes an ontology for hazard knowledge representation and identification that paves the way for the development of BIM-based tools that can automatically process massive amount of hazard data and so contribute to improving safety in building renovation projects. On the other hand, the research validates the applicability of the ontology proposed by developing a knowledge-based system and testing its ability to identify and simulate renovation hazards for different renovation strategies. Automating the hazard identification process will help inform and support hazard mitigation efforts in an efficient way. The remainder of the paper is organised as follows. Section 2 includes a review of related works on health and safety challenges and tools to capture and manage related knowledge in the construction industry. Section 3 describes the research methodology. Section 4 introduces an ontology dedicated to representing hazard knowledge related to renovation projects. Section 5 demonstrates the applicability of the new ontology by developing a knowledge-based system to enable renovation hazard identification. Section 6 tests and experiments the digital tool proposed on a real case study, which is a multi-residence apartment demonstration site. As part of the testing, three different renovation strategies are demonstrated and analysed in terms of the hazards that could be encountered. Finally, Section 7 discusses the results, while Section 8 concludes and outlines future extensions of the proposed solution.

2. Related works

2.1. Health and safety in the AEC-FM industry

This section highlights one of the main challenges facing the successful renovation and retrofit efforts in the built environment. The unforeseen H&S issues that can be caused for both the workforce and occupants, while carrying out a renovation initiative. It also introduces some digital perspectives as revealed by the literature review.

2.1.1. Health and safety challenges

H&S in operation and management (O&M) of existing built assets remains a significant global concern. The UK Health and Safety Executive (HSE) reported 30 worker fatalities in the construction sector during the period April 2018–March 2019 [14], which is around four times as high as the average rate across all industries [15]. The UK Labour Force Survey and Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) for 2016/17–2018/19, and HSE Costs to Britain model estimated that a total of 4.7 million workdays were lost across all UK industry sectors due to nonfatal workplace injuries according to self-reports. The same survey reported that the UK industry average figure for worker injuries was 1710 per 100,000 workers with construction sector worker injuries being statistically significantly higher with a total of 2420 per 100,000 construction sector worker injuries. This figure accounts for 2.4 % of all UK construction sector employees.

Research studies on H&S suggest that construction worker accidents are mainly caused by unsafe behaviours of workers (e.g., failure to fasten the safety hook to an anchor point) and unsafe working conditions (e.g., work at height) [31–33]. Evidently, there is a need to develop strategies to further drive down construction sector accident, injury, and death figures. While legislation has a significant part to play in the advancement of construction sector safety outcomes, legislative approaches cannot fundamentally reduce such figures, because regulation cannot account for the '*intrinsic and unique features*' of the construction delivery environment [34].

2.1.2. Use of digital technologies

Most H&S methods, such as Risk Assessment and Method Statement (RAMS) which is a proactive mechanism for hazard mitigation by which an employer can meet their legal obligations to their employees in respect of job safety [35], rely on manual processes [36]. Emerging digital approaches, such as BIM, have the potential to contribute to improved H&S outcomes in the construction sector. However, the current adoption of BIM in the built asset O&M phase is minimal in comparison to the design and construction phases [37]. Where efforts have been made to explore the benefits of BIM for H&S, these efforts have mainly focussed on new buildings rather than the existing estate. This is despite new buildings only accounting for 1–2 % of the total building stock [38]. In addition, construction safety management is not purely a construction phase concern and must extend to the full building lifecycle [39].

When investigating the transfer of relevant safety data for the built asset O&M phase using BIM, Wetzel et al. acknowledge the potential of BIM to improve safety out into the O&M phase but highlight the complexities associated with effective transfer from the design and construction phases to the FM phase [40]. Such challenges exist also where the BIM process is being leveraged to support O&M, renovation and retrofit of existing buildings. Naticchia et al. investigated the use of three technologies: BIM (as a data environment), a cloud-based system for managing information flows, and mixed reality, suggesting that beyond efficiency and productivity targets, hazard mitigation for better safety management is certainly a pertinent perspective [41]. Li et al. pointed out the lack of standardisation of safety concepts and digital tools, and proposed a unifying construction safety framework to enable hazard representation and analysis using spatial artefacts [42]. Naticchia et al. concluded that a dataset related to functional data for buildings is an area for future development regarding BIM enabled safety applications, since functional data can be used to reduce risks in the workplace [41]. Wetzel et al. asserted that safety relevant data when correlated with corresponding hazard mitigation protocols contributes to the effort to identify safety information for mitigation of a range of hazards [40].

2.2. Ontology as a knowledge management tool

An ontology is an explicit conceptualisation of the world, or area of concern, that we want to represent so as to enable knowledge sharing and reusing between human and machine agents and support interoperability [43]. It consists of defining a common vocabulary that includes a set of objects, concepts, constraints, and their relationships. As a knowledge representation and management tool, ontologies have been used to develop successful applications to formalise and facilitate sharing and reusing of AEC-FM related knowledge [17]. These include applications for construction process specification [44], cost estimation [45], operation and maintenance management [46], green construction and sustainability [47], cultural heritage information modelling [48], compliance checking [49], and techno-economic assessment [50].

2.2.1. Health and safety knowledge

To enable specifically managing H&S knowledge automatically, various ontology models have been developed in the literature review. For example, a construction safety ontology has been proposed for automatic generation of job hazard analysis reports [39]. The ontology is built upon three main domain ontology models, namely 'Product', 'Construction Process', and 'Construction Safety' models. Using BIM, ontology, and semantic web technologies, a construction risk knowledge management framework has also been proposed [51]. The latter enables integrating risk knowledge into an ontology-based semantic network in order to generate a visual risk map aiming to capture the interconnections between risks and their paths. Furthermore, to support decision making for safety risk identification in metro construction, a domain ontology, called SRI-Onto, is implemented using Protégé platform [52]. The SRI-Onto structures safety risk knowledge into seven unified entities, including 'Project', 'Construction Activity', 'Risk', 'Risk Factor', 'Risk Grade', 'Risk Consequence', and 'Risk Prevention Measure'. Similarly, to analyse and identify risk factors for tunnel construction projects, an ontology-based information integration model that utilises a hierarchical clustering method has been proposed [53]. Using the Jena inference engine, the ontology developed enables detecting early warning signs of ground subsidence. As another example, an ontology-based text classification is proposed to assist job hazard analysis [54]. To do so, several construction safety documents are collected from which pre-defined activities and hazards are extracted and classified using information retrieval and text classification technologies. Next, based on the construction safety framework introduced in Ref. [55], the SafeConDM ontology is proposed and a prototype implemented to check 'Working at Height' hazard space codes [42]. Moreover, to enable hazard identification from images proactively, an ontology-based semantic modelling approach is introduced [56]. A scoring system to compare and measure similarities between input images and construction hazard specification is developed and used to automatically identify potential existing hazards. Likewise, by combining computer vision algorithms and ontology, a knowledge graph for hazard recognition in construction sites is proposed [57]. The knowledge graph developed is based on three main components, namely a hazard ontological model, a knowledge extraction algorithm, and a hazard inference engine. The framework was illustrated through examples mainly focusing on 'Working at Height' hazard. Also, to enhance the reliability and accuracy of hazard situation recognition from images in construction sites, an ontological inference process is developed by combining deep learning-based image recognition technologies and relation-based reasoning [58]. Finally, for onshore wind farm projects, an ontology for risk identification is developed [16]. It integrates project context information in the risk identification process while classifying risk into three main categories: 'Global External Risk', 'Local External Risk', and 'Internal Risk'. The ontology is implemented using Protégé platform and SPARQL query language and demonstrated with data taken from seven real wind farm Canadian projects.

Most of the existing ontological frameworks previously proposed for H&S knowledge management are developed for new build constructions, thus the hazard related knowledge represented and captured is generic and broad. This makes the inferred hazard instances and profiles potentially not applicable or relevant to renovation projects, especially in situations where the construction site is simultaneously occupied by both building occupants and project teams. Consequently, hazard knowledge management in renovation projects is a neglected research field that is not fully explored, leading to a lack of decision-making tools applicable for hazard identification and simulation in building renovation. Moreover, existing H&S knowledge management frameworks mainly focus on only limited number of factors that cause hazards, such as construction elements and/or activities, but usually neglect other aspects, such as activity spatial location [17]. In addition, these frameworks are limited to specific hazard types, such as 'Working at Height' hazard, and therefore, cannot be used to combine a comprehensive list of all hazard categories potentially present in a renovation project.

2.2.2. Building renovation knowledge

The introduction of new information and communication technologies, such as ontologies, in the AEC-FM industry can contribute to addressing key issues in renovation projects. Up to now, a very little number of studies have contemplated the use of ontologies as a means to represent and manage renovation project knowledge. First, Amorocho et al. proposed the Reno-Inst ontology dedicated to the installation of common renovation products, such as windows and HVAC components [8]. The ontology was developed based on experts' input and renovation engineering documents, implemented using the Protégé platform [52], evaluated and validated with domain experts using a live case study. More recently, Doukari et al. introduced a holistic renovation ontology that captures the general case of renovation projects and includes all types of possible activities, i.e., common renovation products installation as well as general activities, such as 'Site preparation' and 'Façade insulation with cavity insufflation' [50]. This last ontology was implemented using SQL Server and C# programming language so as to enable evaluating and comparing building renovation strategies in terms of project's duration, cost, resources needed and disruptive potential. Therefore, the ontology only represents techno-economic related renovation project knowledge but lacks renovation hazard related knowledge.

Considering the aforementioned renovation ontologies introduced, their suitability and, unfortunately incompleteness, this research proposes to formalise and integrate renovation hazard related knowledge by extending the holistic renovation ontology introduced in Ref. [50] since, so far, it is the most complete in terms of activity, product, and building area definitions.

2.3. Research gaps and contribution

The literature review conducted on H&S tools for building renovation projects, and summarised in the previous sections, clearly shows that there is no comprehensive framework developed to enable health and safety management for building renovation projects. Existing H&S frameworks and tools are either not adapted or principally developed for new build constructions, thus failing to provide a comprehensive framework for building renovation, in which H&S related knowledge can be captured and managed efficiently. To overcome this gap, this paper investigates and demonstrates the potential of BIM and knowledge-based systems using ontologies to inform the hazard mitigation process which is critical to the efforts of the global construction sector. The objective is to enable driving down construction accidents, injuries, and death figures which, in the case of the UK, continue to sit significantly above the national averages. The value of this research lies in the ability to organise and identify hazard data as relevant to a particular construction task, area, and/or component, in an automated way so as to enhance the planning and management of onsite construction safety. In the context of renovation projects, when hazard data is being automatically identified, it becomes possible to leverage this data in order to support and scale hazard mitigation efforts.

3. Research methodology

The research methodology of this article falls under Design Science Research (DSR) as the main objective is to enhance and automate hazard related knowledge representation and management in renovation projects by developing a knowledge-based system [59]. DSR is an established research methodology that is known to be suitable for software and information technology development in the field of building engineering [60]. To achieve the research objectives, the methodology was structured as follows.

1. A literature review is performed to understand the available approaches and frameworks relevant to the research objective. As summarised in the previous section, the review is dedicated to related works on H&S in the AEC-FM industry and ontologies for knowledge representation and management. The review methodology consisted of implementing a 4-step process. First, scientific literature databases, such as Scopus and Web of Science, were used to acquire related works and papers through relevant search strings reflecting the main aspects of the study as described in Section 2. Second, to exclude irrelevant studies, bibliographical criteria were defined and applied early in the process. These included year, language and type of publication so as only peer-reviewed conference or journal articles published in English after 2010 are considered. Third, the articles were checked, and their contents rapidly analysed by examining their abstracts in order to only include related works in the review. Finally, the selected papers were analysed, and results summarised as reported in Section 2.
2. To complement the literature findings with industry perspectives, nine fortnightly workshops are conducted, each of which lasted 45–60 min, with the RINNO project experts from key organisations and engineering consultancy companies in Europe that includes, as illustrated in Table 1, eighteen partners: 3 large industrial companies, 6 universities and research institutes, 7 SMEs (Small and Medium-sized Enterprises), 1 social housing company, and 1 non-profit organisation, located in ten different EU countries. The aim is to capture their knowledge in relation to the planning and management of building renovation works and activities, especially with regards to hazard identification and mitigation. First, hazard data is captured, stored, and shared in Excel files in order to allow the workshops' participants to update and manage this data easily. The data includes hazard examples, factors, and types presented in an unstructured way. Second, this data is used to leverage conceptual modelling approaches using UML (Unified Modelling Language) diagrams to explicitly capture and structure hazard related concepts, constraints, and relationships as they exist and occur in real-world projects. The collaborative workshops allow the participants to develop and discuss several ontological models, and finally validate the framework that is proposed in this paper. The findings are reported in Section 4.1.

Table 1
RINNO project participants.

Organisation/Company	Type	Country
A	Large Industrial Company	Italy
B	Research Institute	Greece
C	SME	Spain
D	Research Institute	Spain
E	SME	Denmark
F	Social Housing	Denmark
G	Non-Profit Organisation	Denmark
H	University	UK
I	Large Industrial Company	France
J	Large Industrial Company	Poland
K	Research Institute	Finland
L	SME	Greece
M	SME	Greece
N	SME	Poland
O	SME	Austria
P	SME	Greece
Q	University	Ireland
R	University	UK

3. To enable process automation and provide a machine-readable representation of the captured knowledge, a hazard ontology is proposed, and its concepts, relations and constraints are formalised using UML language, and then implemented through Protégé platform. While UML is a standardised visual language that helps both software developers and non-IT specialists design and validate collaboratively new systems and tools, Protégé platform is an open-source and easy-to-use ontology editor as supported by a large community of users. The ontology is presented in Section 4.2.
4. Ontologies are useful tools for knowledge representation and management that have mainly been used as building block to develop successful applications and software tools to formalise and facilitate sharing and reusing of knowledge. In addition, BIM provides a relevant machine-readable representation of building data, including the building elements and areas, their data, and relations, as well as inherent hazards. Therefore, to demonstrate the usability of the hazard ontology proposed, a BIM-based digital tool is developed for automating renovation hazard identification. The knowledge-based system developed is detailed in Section 5.
5. The developed tool is finally tested on a live case study located in Greece, along with key outcomes analysed (Section 6 and Section 7), and conclusions and future works highlighted (Section 8).

4. Ontology model for hazard knowledge representation

An ontology dedicated to formalising renovation-related hazards is introduced in this section. This effort is part of the EU Horizon 2020 RINNO research project which aims to develop a holistic multi-disciplinary platform to accelerate the rate of deep renovation in EU residential buildings [61,62]. First, its knowledge is specified, and then a conceptual model representing its concepts, relations, and constraints is proposed. The proposed ontology has practical implications especially for technology developers and building renovation stakeholders. While it provides a comprehensive and shared understanding of the complex interrelationships of hazard related concepts and factors for renovation stakeholders, it also introduces the required foundations, through a common and unified vocabulary represented in a machine readable format, that enable construction technologists to easily develop and implement software tools and automated processes for safety management in building renovation projects.

4.1. Ontology specification

Table 2 presents a sample set of common building hazards that could occur while carrying out renovation works. Firstly, area-based hazards which are related to the areas where renovation works are taking place, such as ‘Confined Spaces’ and ‘Working at Height’ hazards. Fig. 1 presents a conventional spatial breakdown of a renovation project into areas and how these areas should be sequenced while conducting renovation works. Secondly, element-based hazards which are hazards that could be caused while manipulating a hazardous building component, such as ‘Asbestos’ and ‘Risk of Shock’ hazards.

The area- and element-based hazards can be represented and integrated into BIM models so as to be stored and queried automatically. Thirdly, and finally, activity-related hazards where the hazard is not related to any specific area or building element, such as ‘Slips, Trips and Falls’ hazard.

Furthermore, a renovation database including twenty renovation activities is developed within the RINNO project [50] in order to standardise the renovation process and enable developing and delivering the RINNO Solution [61]. As illustrated in Table 3, the workshops conducted enabled the identification of direct causality relationships between these renovation activities and potential building hazards.

For instance, when conducting a ‘Site preparation’ activity, the ‘Slips, Trips and Falls’ hazard is more likely to be caused whatever the building element manipulated or the building area occupied, whereas the ‘Façade insulation with cavity insufflation’ activity, as it is performed from inside the building, it should not be the direct cause of any generated hazards, i.e., if any hazards occur, more

Table 2
Building hazard specification.

Hazard ID	Hazard name	Area Related?	Element Related?	Activity Related?	[Area/Element/Activity] Examples
1	Asbestos	✓	✓	✗	[Plant room/Wall/.]
2	Confined spaces	✓	✗	✗	[Construction Void/./.]
3	Environmental decibel levels (i.e., exposure to sounds at or above 85 dBA)	✓	✓	✗	[Boiler room/Boiler/.]
4	Fragile roof structure	✓	✓	✗	[Roof/Roof mounted radio mast/.]
5	HyDeploy (i.e., a blend of hydrogen and other fuels, such as natural gas and petrol)	✗	✓	✓	[./Smart Gas Meter/Condensing boiler installation]
6	Public Protection (i.e., hazards causing risk to the public)	✓	✗	✗	[Hallway/./.]
7	Risk of Shock	✓	✓	✗	[Data centre room/Switch board/.]
8	Working at Height	✓	✓	✓	[Roof, terrace/Ceiling lights/ Photovoltaics on flat roof]
9	Slips Trips and Falls	✗	✗	✓	[././Site preparation]

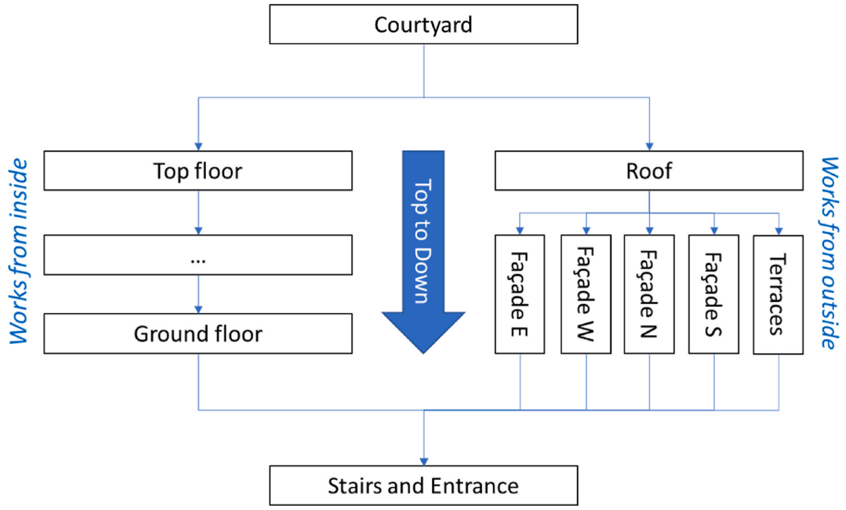

Fig. 1. Spatial breakdown of a building renovation.

Table 3
High level renovation activities and related hazards.

Activity ID	Activity name	Hazard ID
1	Site preparation	9
2	Façade insultation	8
3	Façade insulation with insufflated plug-and-play system	8
4	Façade insulation with PV integrated plug-and-play system	8
5	Façade insulation with cavity insufflation	/
6	Flat roof insulation	8
7	Sloped roof insulation	8
8	Photovoltaics on sloped roof	8
9	Photovoltaics on flat roof	8
10	Windows and doors replacement	/
11	Windows replacement with photovoltaic windows	/
12	Installation of solar collectors on flat roof	8
13	Wall-mounted/integrated heat storage	/
14	Condensing boiler installation	5
15	Mini split installation	/
16	Radiant floor installation	/
17	Non-centralised mechanical ventilation system	/
18	Centralised mechanical ventilation system	/
19	Insulation of existing heating and domestic hot water pipes	5
20	Insulation from the inside	/

likely they will be element- or area-related hazards. It should be noted that Table 3 includes Hazard IDs relevant to Activity name, only where the Hazard identified is part of the sample set as given in Table 2. There are multiple hazards that would be relevant to the respective activities, but which are outside of scope for this research and as such not included in the sample set. Moreover, the activities in Table 3 are high level activities, each of which is being detailed and defined through sub-activities, sequencing rules, and related hazards. For the sake of simplicity, this paper's scope is limited to the high-level renovation activities presented with related hazards in Table 3.

4.2. Ontology conceptualisation

Fig. 2 presents the building renovation hazard ontology via a UML class diagram illustrating the ontology concepts, their relations, and constraints as well as the attributes or properties that define each concept (here class or entity) to facilitate its implementation as a renovation knowledge base. The reuse of existing ontologies has been one of the main advantages of their development, and this is regardless the applications and data they are supposed to serve and populate [63]. Therefore, the renovation hazard ontology developed in this article is built through extending the ontology proposed by Doukari et al. as part of the techno-economic assessment framework that is developed to evaluate and simulate the concept of disruption (greyed in Fig. 2) for renovation projects [50].

As presented in Fig. 2, a 'Built Asset' is composed of many 'Elements' (e.g., window, wall) and many 'Areas' (e.g., room, corridor). An 'Element' can be manipulated while achieving a 'Renovation Scenario' and can present many 'Hazards'. A 'Renovation Scenario' is an aggregation of 'WBS' (Work Breakdown Structure), takes place at one or many 'Areas' (e.g.: floor, external façade), manipulates one or many 'Elements', and can involve the installation of various 'Innovative Products'. A 'WBS' is a combination of related renovation activities that can be taken together as a work package or macro renovation activity. An 'Area' represent a spatial location in the 'Built Asset' and could enclose many 'Hazards'. Each renovation 'Activity' is timely constrained by activities that should begin and finish before it, whereas some others will be triggered and executed after its completion. It also requires a set of 'Material', 'Workforce' and 'Equipment' so that it can be executed and may cause 'Hazard' to the 'Stakeholder' (i.e., 'Workforce' and 'Occupant').

The hazard ontology proposed is implemented using the Protégé platform [52] and populated with hazard knowledge described in Section 4.1. Unlike the Reno-Inst ontology [8], the hazard ontology proposed in this paper considers the general case of renovation projects that include products installation as well as more general activities, such as façade insulation. Further research is still however needed to complete, refine, and validate the hazard knowledge captured with safety experts, project managers and end users through workshops and interviews.

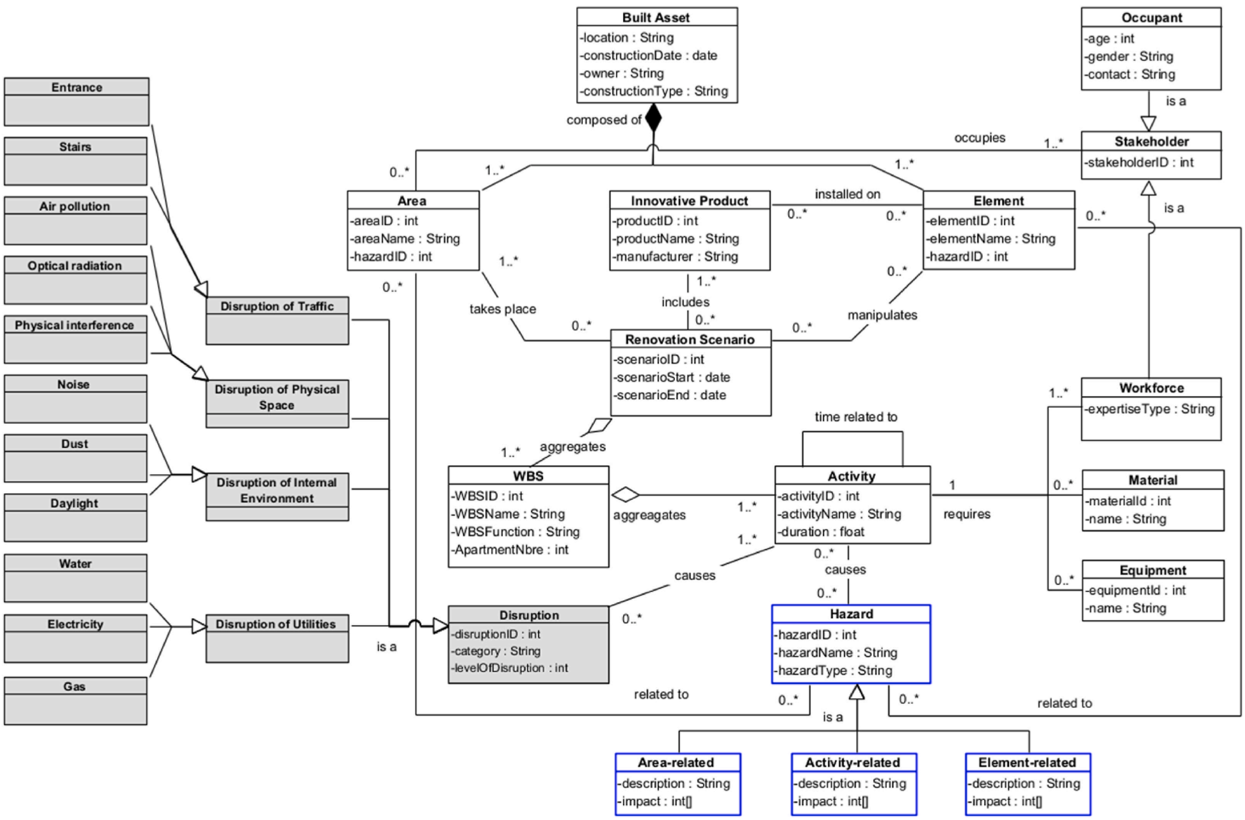

Fig. 2. Building renovation hazard ontology.

5. A BIM-based digital tool to enable renovation-related hazard identification

This section aims at demonstrating the renovation hazard ontology usability by developing a knowledge-based system for application within the context of deep renovation projects. The digital tool developed enables renovation project managers in the Planning and Design phase, as well as the Retrofitting phase, to automatically identify hazard data as relevant to a specific renovation initiative and so allow them to efficiently assess and compare different renovation scenarios and strategies in order to enhance the planning and management of onsite retrofitting safety, and maximise the workforce and occupants' wellbeing. Knowledge-based systems are known to be ‘intelligent’ due to their inherent ability to mimic the human decision process while reasoning and using domain specific knowledge [64].

5.1. System architecture

Fig. 3 presents the system architecture of the digital tool proposed to support project participants that are learners, beginners, or lacking hazard-related knowledge when assessing hazard in building deep renovation projects. In addition, this tool is equipped with learning capabilities via a dedicated ‘Hazard Knowledge Base Update’ user interface so that experts can continuously update and extend the knowledge represented within the ‘Renovation Hazard Ontology’ component. The ‘Renovation Hazard Inference Engine’ enables hazard identification for a renovation scenario selected, through the ‘Renovation Scenario Selection’ user interface, by using: (i) project data extracted from the BIM model uploaded, through the ‘BIM Model Uploading’ user interface; and (ii) the hazard knowledge represented within the ‘Renovation Hazard Ontology’, extracted through Protégé API [52].

5.2. System behaviour

Fig. 4 describes the main use case implemented which is the hazard identification process based on the hazard ontology introduced in Section 4.2. The automated process, represented in Fig. 4 as a UML scenario diagram, enables project managers to leverage the BIM data and automatically identify and list the renovation hazards related to the renovation scenario selected at the beginning of the process. After uploading the BIM model and selecting a renovation scenario via two main GUI (Graphical User Interface), the ‘Renovation Hazard Inference Engine’ enables the hazard identification process by: (i) parsing and storing the BIM data; (ii) extracting BIM data relevant to the scenario selected and particularly to the areas identified; (iii) inferring renovation hazards relevant to the BIM data extracted and the scenario selected by identifying element-, area- and activity-based hazards; and finally (iv) displaying the results and enabling an automatic documentation in the form of hazard reports.

5.3. Graphical user interface

To streamline hazard identification in renovation projects, facilitate interaction with the Hazard identification tool, and assist project managers for renovation scenario definition and selection, a user-friendly interface was developed. Fig. 5 illustrates the corresponding GUI and shows both the Area selection tab (Fig. 5 – (A)) and the Activity selection tab (Fig. 5 – (B)).

6. Case study of the RINNO's Greek demonstration site

6.1. Data preparation

The hazard identification tool and its ontology are demonstrated using a live case study. It is one of the four RINNO project's demonstration sites: a multi-residence apartment building illustrated in Fig. 6 – (A) located in Greece. The first step created the site's BIM model (Fig. 6 – (B)), representing and integrating some of element- and area-based hazard data (Fig. 6 – (C)), where ‘Working at height’ hazard data is added to areas such as ‘Roof’ and ‘Terrace’ located at least 6 feet high from the ground [65], and ‘Asbestos’ hazard data is integrated into ‘Wall’ elements in accordance with inspection results of the building. The BIM model is then uploaded

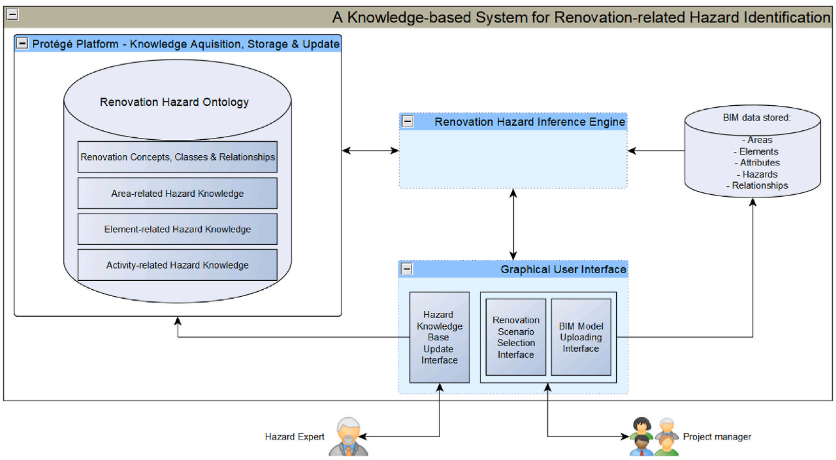

Fig. 3. System architecture of the renovation-related hazard identification tool.

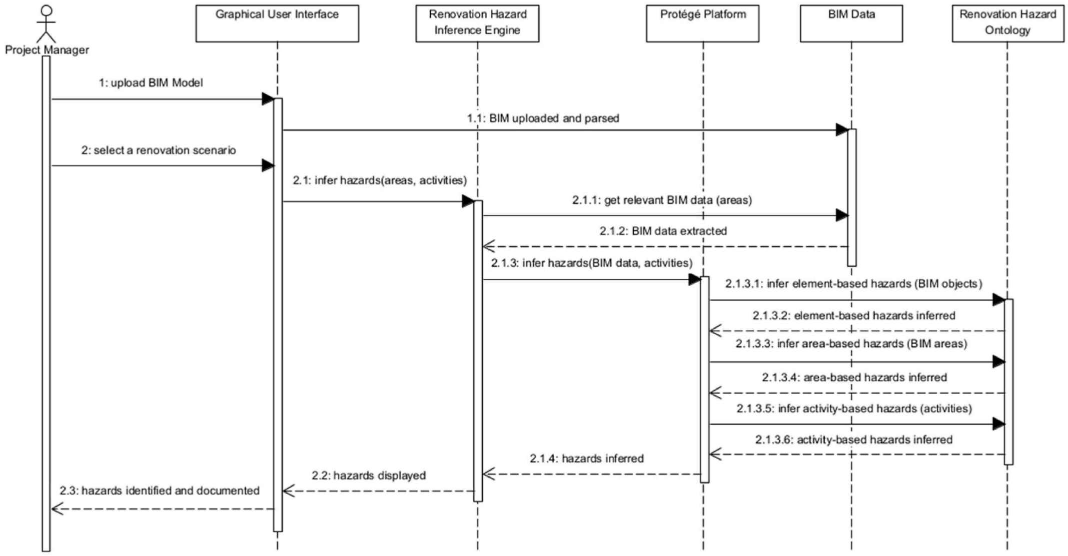

Fig. 4. Automated renovation hazard identification process - UML Scenario.

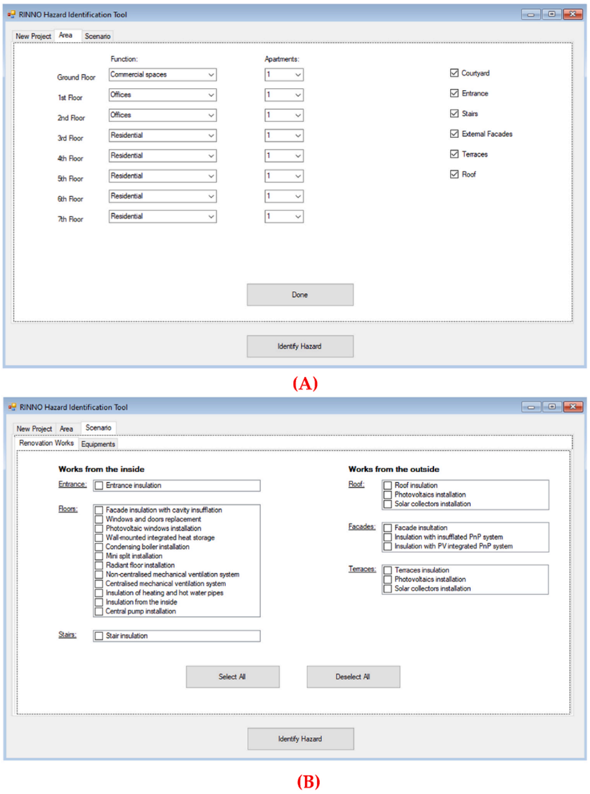

Fig. 5. Renovation scenario selection: (A) Area GUI. (B) Activity GUI.

into the hazard identification tool to be used as a hazard database. Basic project information, such as start date and project name, was inputted as well as renovation scenarios were selected, each of which included a combination of different area and renovation activities.

To demonstrate the accuracy of hazard identification and enable renovation strategy safety analysis, three renovation scenarios are selected and processed using the digital tool and the ontology developed. The three scenarios consisted of conducting the same set of renovation activities but related to different areas. They included: Scenario 1 which is to renovate the building's ‘Basement’, Sce-

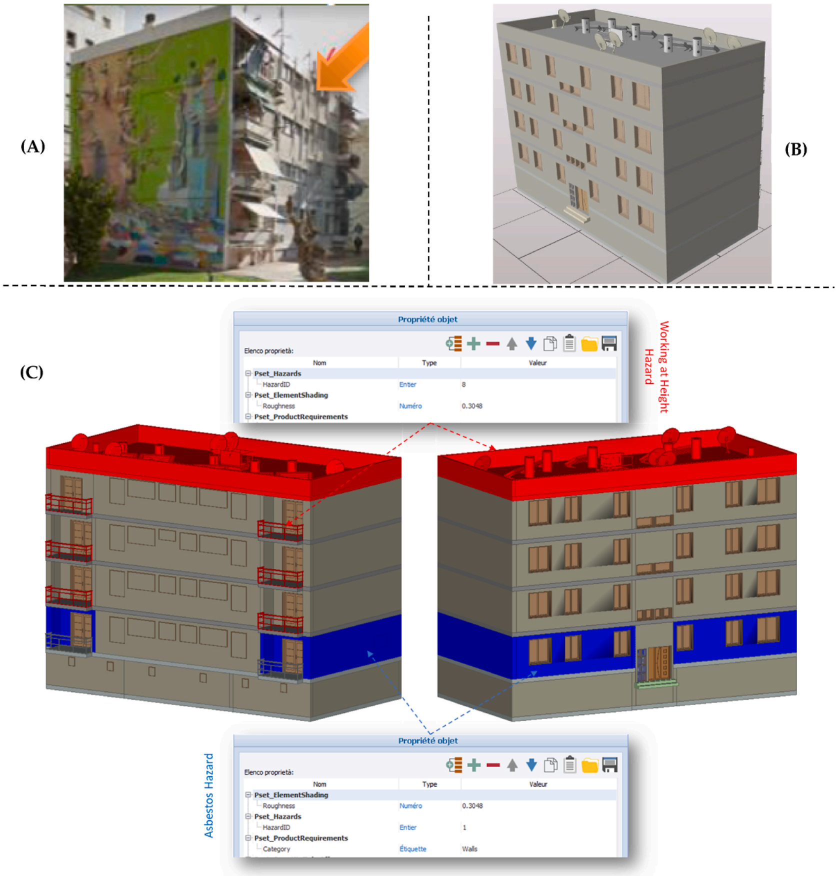

Fig. 6. The RINNO's Greek multi-residence apartment demonstration site: (A) The real building, (B) IFC BIM model of the Greek building, and (C) Hazard data represented and integrated into the BIM model.

nario 2 for the 'Ground Floor', and Scenario 3 for the '1st Floor'. As for the renovation activities considered, they are all the identical and comprise the following activities and tasks.

(i) '*Site preparation*': which consists of the construction of fencing and access to the site as well as setting up the warehouses, material storage areas and fixed facilities.
(ii) '*Façade insulation with cavity insufflation*': which is a type of insulation carried out from inside the building and contains two main steps: 'drilling holes in walls from the inside' and then 'blown-in cellulose insulation'.
(iii) '*Windows and doors replacement*': which includes elements removal, and fixed frames and new sashes installation; and
(iv) '*Terraces insulation*': which consists in insulating the building terraces from the outside, including sub-activities such as 'scaffolding installation', 'plaster removal', 'application of insulation panels', 'plastering, smoothing, and painting of external surfaces', 'pluvial and ventilation ducts installation', and 'scaffolding disassembly'.

6.2. Results

As illustrated in Fig. 7, Scenario 1 includes {'Slips, Trips and Falls'}, Scenario 2: {'Asbestos', 'Slips, Trips and Falls'}, and finally Scenario 3: {'Working at Height', 'Slips, Trips and Falls'} hazards. These results demonstrate that the prototype developed is correct and sound in terms of hazard related knowledge representation and identification and behaves exactly as designed. It enables the exploitation of BIM data in order to query the hazard ontology developed and infer relevant hazards that are related to a specific renovation strategy consisting of a set of WBS and activities along with a combination of building areas and elements to be renovated.

7. Discussion

Although the three scenarios are defined through the same renovation activities, different hazard identification results are obtained due to the different locations and areas considered (Fig. 7). As such, the findings confirm the importance of the activity location factor while representing and processing hazard related knowledge, which is unfortunately still missing in most of existing frameworks, as well as its impact in causing different types of hazards [17].

The 'Slips Trips and Falls' hazard is a common hazard in renovation projects. Although the 'Site preparation' activity is mainly carried out to avoid this type of hazards, the process itself is often responsible of causing most 'Slips Trips and Falls' related accidents.

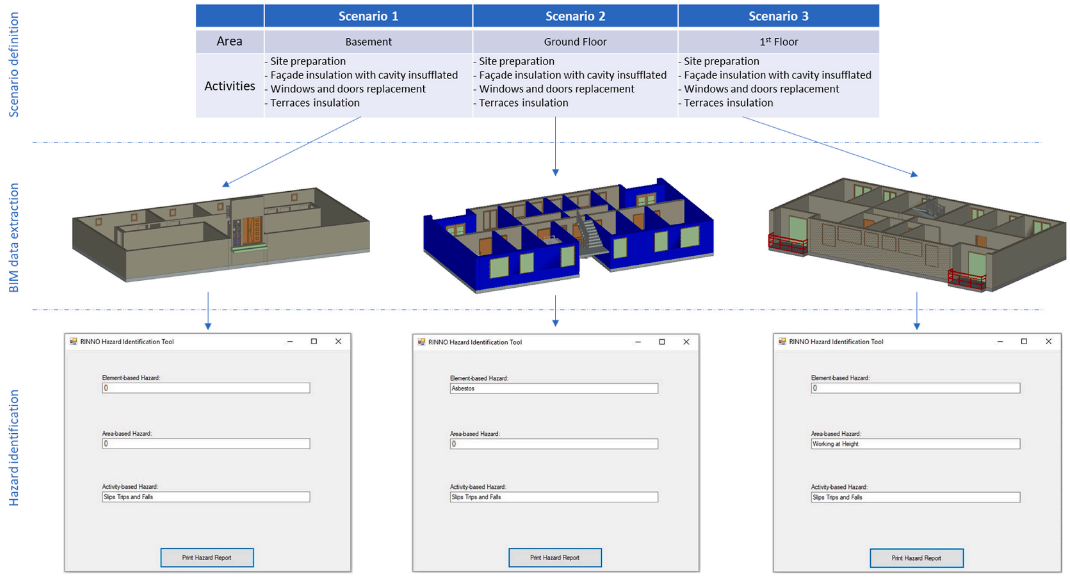

Fig. 7. Automatic hazard identification for three different renovation scenarios.

This is due to the renovation site still being wet that includes trailing objects and is not yet tidied up. For the three renovation scenarios, the project manager must ensure an effective and constant cleaning of the renovation site by providing the right information, instruction, equipment, and training to allow delivering renovation works safely.

On the other hand, the risks and impacts of 'Asbestos' on the health and safety of the workforce and occupants are significant as it causes thousands of fatalities each year and various dangerous diseases as a result of direct exposure [66].

The results in Fig. 7 show that both scenarios 1 and 3 do not include 'Asbestos' hazard as there are no asbestos-containing materials that can be manipulated or disturbed in these two renovation initiatives. Therefore, 'as-usual' renovation process can be carried out in terms of managing and working with asbestos-containing materials. However, scenario 2 includes elements containing asbestos which leads to cause 'Asbestos' hazard, hence detected and identified by the digital tool developed. As stipulated by the Control of Asbestos Regulations 2012 [67], effective adaptation actions, in this case, should be implemented so as to arrange a better management of the risks engendered. Thus, the project manager must adapt the renovation process in order to minimise the risks of exposure to these materials and protect both the workforce and occupants. For instance, renovation strategies, such as Fawcett's [68], that consist in relocating occupants and vacating the premisses before intervening in these areas will be prioritised. Additionally, this will minimise the workforce exposure to the dangerous materials as these strategies usually contributes to the optimisation of the renovation project duration as well as disruption that can be caused to occupants [50].

Similarly, 'Working at Height' hazard is one of the main causes of H&S fatalities and serious injuries, which often result in permanent disabilities, in the AEC-FM industry. Building's fragile areas, such as roofs and terraces, are common causes to falls from height and so workers injuries [69]. To plan works safely in scenario 3, the project manager must take all required precautions before starting retrofitting works. Roofs, terraces, and balconies that are located beyond 6 feet high from the ground should be assessed thoroughly by a specialist. The renovation schedule must be created accordingly, as well as the right type of equipment and training must be timely provided to the workforce. To enable safe interventions, the renovation schedule should be adapted to include extra time as needed to conduct the retrofitting works as well as to plan and supervise properly the duration and frequency of work at height. In particular, the 'Site preparation' activity, in this context, is usually longer than 5 days which is the conventional time required to prepare a renovation initiative [50]. As for scenarios 1 and 2, no specific adaptations are required regarding the management of 'Working at Height' hazard.

While it is important to address the gap in ontologies and digital tools for hazards modelling and identification in deep renovation projects, the interrelations of such developments with reality of adoption and foresight in managerial decisions is equally critical, in particular in domains such as health and safety due to the regulatory compliance requirements and potential criminal liabilities involved. In relating the proposed development to these aspects, a number of key considerations emerged, both challenging and supporting the proposed development. One particular notion that simultaneously challenges and supports the proposed development is that firms need health and safety 'learning culture' [70]. This correctly broadens the notion of health and safety to cover a more extensive than just the utilization of tools and ontologies but also highlight the importance of enabling continuous learning and adaptation within the adopting organisation. Since reusing and maintaining ontologies is crucial to provide and maintain a shared vocabulary and knowledge that is accessible for both humans and machines, the proposed ontology, built using an existing ontology extended with hazard knowledge and their associated concepts, relations, and constraints, can play a key part in continuous learning within organisations. As the ontology is typically the foundation of a knowledge domain (health and safety hazards in this case) and is technology-agnostic, there is a real opportunity for organisations to improve their capability of hazard identification and the broader health and safety management process if it is socially adopted within the organisations whereby employees report near misses, incidents and failures in a 'no-blame' context [70]. Supporting the proposed development are also the findings that the adoption of safety management systems are driven by key attributes such as 'safer working conditions' and 'reduced harm to workers' [71] and the 'reliability' and 'effectiveness' of the technology involved [72], which are attributes exhibited by the proposed ontology and tools.

The importance of ontologies as digital tools for hazard modelling and identification cannot be overstated in the fast-evolving Artificial Intelligence (AI) era. Although ontologies require a continuous maintenance and update effort (especially as new regulation or hazards appear), they provide consistent and interoperable data structures across domain fields and facilitate data-centric approaches, including the development of AI-based tools. It also makes data more transparent, circular, and accessible to relevant stakeholders as digital tools can be used to extract information relevant to stakeholders more systematically. Continuously employing an ontology tailored to digitise and recognise safety hazards is key to establish a standardised framework for AI systems and give the ability to accurately identify safety concerns before they occur [73]. The current use of AI in renovation projects, including deep renovation ones, is quite limited in literature and the proposed ontology should support further development in this area as data is collected in a structured manner [74].

Finally, to better comprehend the proposal contributions, it is important to highlight the research limitations. First, the prototype tested in this paper is only based on the 'high level' twenty renovation activities and related hazard knowledge introduced in Table 3, and so needs to be extended to more detailed activities and procedures so that more practical and operational renovation schedules can be considered and assessed. Second, the automated process proposed exhibits a strong reliance on the quality and completeness of building data, especially H&S related data, represented in BIM models. Although several studies show that geometric information of BIM models can be generated automatically through, for example, laser scanned point clouds and Machine Learning techniques [87,88], semantic BIM data generation, including H&S related data, is still a laborious manual process based on site inspection. In the case study presented in Section 6.1, only 'Asbestos' and 'Working at height' hazards are incorporated into the Greek BIM model, and because of lack of data, the other types of hazards are not integrated. Thus, the hazard knowledge and data used in the Greek case study are incomplete which can explain the intuitive hazard identification results of the three renovation scenarios.

8. Conclusion

Compared to new constructions, renovation projects are more challenging because of the high level of interaction with their surroundings, the potential issues with limited access and space for both executing the renovation activities and storing materials, and the uncertainty around the composition and condition of existing buildings. The safety of project participants as well as that of occupants is the main priority when managing a renovation project. The identification of H&S risks must be conducted as early as possible in the retrofitting process so as to enable mitigation and adaptation actions. Existing risk identification approaches both conventional and automatic are not suitable for use in the context of building renovation. Conventional methods are manual processes based solely on project managers expertise, previous projects feedback, and H&S documents review [36]. Therefore, they are usually subjective, incomplete, and inconsistent, since based on human-reasoning and judgment [75], in addition to being time-consuming and labour-intensive processes. On the other hand, a few automatic risk identification approaches have been developed for new build constructions using either case-based reasoning [76], natural language processing [77], rule-based system [78], or ontology-based framework [52]. The latter method has outperformed all other identification techniques and has shown good performance, especially in considering and mapping project data to risk information [16]. However, none of the existing methods propose a comprehensive risk identification framework in which all risk factors, including job location, and risk types are considered. Furthermore, they are not suitable for managing the O&M phase in general, and renovation works in particular, since they are developed for new build projects and mainly focusing on the construction phase. To overcome these gaps and enable preventing health and safety risks in building renovation, the contribution of this research is twofold. First, a comprehensive ontology that captures all risk factors (i.e., building elements, areas, and renovation activities) for hazard knowledge representation and management is developed so as to lay the foundations enabling the development of BIM-based frameworks and tools for automatic safety management in building renovation projects. Second, a knowledge-based system using the ontology proposed is developed and its capabilities to automatically identify and simulate renovation hazards for different renovation strategies is demonstrated through a real-world case study.

The main benefit of creating ontologies is knowledge sharing and reuse. However, research in knowledge engineering shows that ontology reuse, even within the same application domain, is still limited and not fully exploited [79,80]. Researchers seem to prefer creating their own ontological models instead of extending and building upon existing ones, which leads to the existence of many conceptual models representing the same reality, but most of the time, using different vocabulary and being inconsistent when taken together. This usually generates serious problems to knowledge sharing and data analysis, and real obstacles to interoperability between software tools. Defining a unified and shared vocabulary for solving construction management problems is essential not only for human understanding and communication but also for algorithms and automated processes interoperability [81]. Also, the development of ontologies from scratch is a long and complex process that necessitates the collaboration of multidisciplinary teams, including knowledge managers and engineers, and domain experts. To overcome this problem, and make the most of the ontology reuse principal, the renovation hazard ontology developed in this article is built through extending an existing renovation ontology which was proposed in Ref. [50] as part of the techno-economic assessment framework aiming to evaluate and simulate renovation strategies. To enable risk avoidance and mitigation processes and ensure the safety of project teams and occupants, the ontology proposed captures renovation-related hazard knowledge, including the Hazard concept and subsequent constraints, sub-classes, and relations.

Furthermore, the applicability of the hazard ontology was demonstrated by developing a digital tool enabling automatic hazard identification and renovation strategy assessment. The development of these tools was informed by 9 collaborative workshops conducted with renovation project experts from key EU construction companies. They were tested and demonstrated on a real case study taken from the RINNO project. Three different renovation strategies have been selected for the Greek multi-residence apartment building, assessed, and then compared in terms of the hazards they could generate. Different hazard identification results were concluded even if the three scenarios considered were defined based on the same renovation activities. This could rationally be explained by the heterogenous distribution of hazard through different areas, elements, and components of the same building. Clearly, such a framework paves the way for the development of fully individualised health and safety training systems [82] to improve the performance of the AEC-FM sector. However, further research works are needed to ensure the proposed framework meets the practitioners' needs and prove its added value and benefits for the AEC-FM sector before deployment. For this, the RINNO project provides a relevant and real-world application context with three additional demonstration sites located in France, Denmark, and Poland, arranging a total of 3386 m^2 of floor area. The hazard ontology along with the digital tool developed will be practically implemented and experimented by end users on the three additional demonstration sites that include both single-residence and multi-residence apartment buildings and integrate different construction systems and building amenities. This will enable extending the knowledge represented within the hazard ontology through the learning capabilities of the system to provide more complete, precise, and accurate hazard identification.

8.1. Perspectives

To standardise the framework introduced in this paper and its related concepts, such as building elements and activities, it is crucial to implement and use a classification system. Based on a set of consistent and hierarchically organised tables, Uniclass 2015 allows the classification of all types of elements that could be considered in the context of a construction project. This system also enables the classification of physical objects using the 'Entities', 'Elements', 'Systems' and 'Products' tables, as well as construction processes and activities through the 'Activities' table.

The automated process introduced in this paper clearly enables hazard identification for different renovation scenarios. However, in order to better optimise this process and enable 'equivalent' renovation strategies (i.e., areas and activities are the same) assessment and comparison, the time dimension must be integrated. One such application is '4D BIM' [83] which involves linking the tasks in a project's construction schedule to its element-orientated 3D-model to improve the logistical decision-making and delivery of the project. In our case, the time dimension must be linked to the hazard concept so that it will not be an absolute value, but a measure/KPI that can be increased depending on its frequency and duration. For example, 'Working at height' hazard evaluation will be different for two workers where one only spends one day working on the roof while the other spends two days. Consequently, to reduce exposure to hazard and decrease the overall safety risk level of the renovation process, project managers would prioritise the planning and execution of renovation activities that are more likely to cause hazards as early as possible in the renovation process.

This automated hazard identification process presents a powerful range of opportunities in the field of hazard mitigation for renovation and retrofit projects. Hazard identification through automation in this domain has the potential to inform and enhance existing hazard identification and elimination processes to complement the widely adopted processes such as RAMS. The solution being put forward has also the potential to benefit multiple stages of the renovation lifecycle. Management representatives may be able to leverage the system at the planning phase as a means to inform (compliment rather than replace) the RAMS writing process. To this end, the system has the potential to add to the robustness of the RAMS process as a means to mitigate risk in the execution phase. In addition, given that RAMS are invariably written up front (late planning stage) and most often not by the construction site operative(s) responsible for the execution of the process, the solution has the potential to improve accessibility by construction site operative(s) to relevant (job specific) RAMS documentation. This could be achieved via the means of digital communication to construction site operative(s) assigned to specific jobs, ensuring that RAMS documentation is readily available to those most in need of it. This process may be able to be extended to include reporting mechanisms (back to management level operatives) which for example could document that a construction site operative "accepts" and "has read and understood" RAMS documentation as associated with a given job. In both use cases (management and operative scenario) the solution can be recognised as having the potential to enhance existing RAMS process through alignment with existing processes. The proposed solution can support future research in dynamic operator health and safety training scheduler, also called individualised safety training solutions [84], while the ontology can be further extended to be implemented in the context of the LCA methodology [85,86].

BIM models quality, which refers to the completeness and correctness of BIM data, is crucial for the automation and improvement of the AEC-FM sector's processes. This data includes 3D geometric information of the building and its elements as well as semantic data that describes each of these elements and the relationships between them. While geometric BIM data could be generated automatically through laser scanned point clouds and Machine Learning approaches [87,88], semantic BIM data has to be created manually over site inspection, leading to a waste of time and money, and usually to errors when entering the data. To overcome this issue, future works will consider extending the proposed framework by developing a second interconnected knowledge-based system enabling semantic BIM enrichment in order to automate semantic BIM data generation, such as Asbestos related data. This system will use information, such as location of the building, and year and type of construction, etc., and help generating the semantic data and automatically enrich the BIM model [64] that will be submitted to the digital tool developed for hazard identification.

CRediT authorship contribution statement

Omar Doukari: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **James Wakefield:** Writing – review & editing, Validation, Methodology, Investigation, Data curation,

Conceptualization. **Pablo Martinez:** Writing – review & editing, Validation, Methodology, Conceptualization. **Mohamad Kassem:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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