UNB | Off-site Construction Research Centre
Canadian Society for Civil Engineering

Transforming Construction with Reality Capture Technologies:
The Digital Reality of Tomorrow

August 23-25, 2022, Fredericton, New Brunswick, Canada

ONTOLOGY-BASED HAZARD KNOWLEDGE REPRESENTATION AND IDENTIFICATION FOR DEEP REFURBISHMENT PROJECTS

Doukari, Omar[1,*], Wakefield, James[1], Martinez, Pablo[1], Kassem, Mohamad[2]
[1] Department of Mechanical and Construction Engineering, University of Northumbria, UK
[2] Department of Engineering, Newcastle University, UK
[*] omar.doukari@northumbria.ac.uk

Abstract: The delivery of construction projects in general can be complex and demanding, and presents well-documented challenges to the control of cost, safety, and quality. This situation becomes even more challenging in the case of renovation projects due to the high level of interaction with occupants, especially when they remain in the building over the renovation period. The safety of project participants as well as that of occupants when they are present in the renovation site must be ensured. Although the planning and management of such projects can be greatly enhanced by exploiting some of the advantages of Building Information Modelling (BIM), the process of construction hazard identification and renovation scenarios assessment is still human-based and so requires considerable time and effort. Moreover, there is little research that addresses how hazard identification can best be represented and processed automatically in order to optimise and develop more effective strategies for managing construction projects, particularly those involving the systematic renovation of existing properties for better energy performance. Using BIM along with Artificial Intelligence (AI) tools could help in processing the massive amount of newly-available data and knowledge (e.g., feedback, images captured from smart devices, IoT sensors) that are increasingly obtainable. A prerequisite for doing so is the development of a dedicated ontology that would enable the formalisation of domain knowledge, including associated concepts, relations, and constraints that are specific to renovation project hazard. The authors propose an ontology and demonstrate its application by developing a knowledge-based system for application within the context of deep renovation projects that are part of a large European research project: the RINNO project.

Keywords: hazard identification; artificial intelligence; ontology; knowledge-based system; Protégé platform; BIM; building renovation; scenario-based simulation; RINNO project

1. Introduction

In Europe, buildings are responsible for the largest environmental impacts including almost 40% of global energy consumption, 33 % of waste production, and 50 % of raw material depletion (Passoni et al. 2021). The building and construction sector's demand on natural resources accelerates climate change ('UN Climate Change Conference (COP26) at the SEC – Glasgow 2021' n.d.). Existing and inefficient buildings negatively impact both humans and the environment ('UN Climate Change Conference (COP26) at the SEC – Glasgow 2021' n.d.). Although, many research efforts have been investigating the construction process of new buildings and how to improve their performance, renovation of existing buildings seems to be a neglected area in the architecture, engineering, and construction (AEC) optimisation domain.

Building renovation presents real challenges for project participants, policymakers and occupants. This is because of their characteristics including: (i) high uncertainty (Bozorgi and Jones 2013; Singh et al. 2014); (ii) short durations to carry out renovation works (Manuel 2011); (iii) small quantities-based production; (vi) poor understanding of user requirements and the technologies to be used (Gholami et al. 2013); (v) dearth of tools and approaches to evaluate renovation strategies and scenarios (Gholami et al. 2013); (vi) low degree of anticipation and efficiency in the retrofitting phase (Amorocho and Hartmann 2021), and more importantly (vii) high level of interaction and interference with occupants, especially when they remain in the building over the renovation period (Fawcett and Palmer 2004), (C. O. Egbu 1994; Grath et al. 2013). Renovation challenges usually generate high increase in project costs, hazards and schedule overruns (Singh et al. 2014; Aldanondo et al. 2014; Fawcett and Palmer 2004).

Virtual design and construction (VDC) approaches (Dawood and Sikka 2008; Eastman et al. 2009; Han, Law, and Kunz 2000; Haymaker et al. 2004; Khanzode, Fischer, and Reed 2008) have demonstrated the benefits of visualisation, simulation, and process automation to enable better control and transparency of project execution in the AEC domain. Early-stage simulation methods are particularly known to be useful tools to identify optimised renovation scenarios in terms of cost and time (Kemmer and Koskela 2012; Volk, Stengel, and Schultmann 2014; Chaves et al. 2017). They also allow to reduce renovation uncertainty, assessing the performance of different renovation approaches and strategies and assisting decision-making processes (Sacks, Treckmann, and Rozenfeld 2009). BIM-based simulations particularly enable to share and clarify the perception of the renovation process by all stakeholders including building occupants. It allows better visualisation, communication and decision-making through 3D-based simulations of several renovation scenarios and strategies (Charles O. Egbu 1997; Papamichael 1999; Sheth, Price, and Glass 2010). Despites all these advantages and benefits, research works are still lacking on the use of BIM (Joblot et al. 2019) and simulations in renovation (Kemmer and Koskela 2012; Volk, Stengel, and Schultmann 2014; Chaves et al. 2017), especially for hazard identification and risk mitigation.

This paper shows how using BIM alongside AI tools enables representation, in a machine readable format, and automatic processing of the massive amount of hazard knowledge that are increasingly obtainable through project feedback, human expertise, to name but a few. To do so, Section 2 introduces an ontology dedicated to representing hazard knowledge related to renovation projects. Ontologies are known to be useful AI tools in formalising specific domain knowledge including their concepts, relations, and constraints in a machine-readable format (Hartmann and Trappey 2020). Section 3 demonstrates the applicability of the new ontology by developing a knowledge-based system to enable renovation hazard identification. Before concluding in Section 5, the digital tool proposed is demonstrated on a real case study, which is the RINNO's Greek multi-family dwelling demo site, in Section 4 by analysing and evaluating three different renovation strategies in terms of hazards that could be caused.

2. An ontology for hazard knowledge representation

The research study reported in this section is part of the RINNO research project (Doukari et al. 2021; Lynn et al. 2021) which aims to develop a holistic multi-disciplinary platform that will ensure accelerating the rate of deep renovation in EU residential buildings. An ontology dedicated to formalising renovation-related hazards is here introduced. First, its knowledge is specified, and then a conceptual model representing its concepts, relations, and constraints is proposed. Ontologies are useful AI tools in formalising specific domain knowledge and enabling process automation and tools development as they provide a machine-readable representation of knowledge.

2.1. Ontology specification

Table 1: Building hazard specification.

Hazard ID	Hazard type	Area Related?	Element Related?	Activity Related?	Area / Element / Activity Examples
1	Asbestos	Yes	Yes	No	Plant room / wall
2	Confined spaces	Yes	No	No	Construction Void
3	Environmental decibel level	Yes	Yes	No	Boiler room / boiler
4	Fragile roof structure	Yes	Yes	No	Roof / roof mounted radio mast
5	HyDeploy	No	Yes	Yes	Smart Gas Meter/ Condensing boiler installation
6	Public Protection	Yes	No	No	Hallway
7	Risk of Shock	Yes	Yes	No	Data centre room / switch board
8	Working at Height	Yes	Yes	Yes	Roof, balcony/ ceiling lights
9	Slips Trips and Falls	No	No	Yes	Site preparation

Table 1 above presents a sample set of common building hazards that could occur while carrying out renovation works. As illustrated in Table 1, three types of hazards exist. Firstly, area-based hazards which are related to the areas where renovation works are taking place, such as ‘confined spaces’ and ‘public protection’ hazards. 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. 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.

Table 2: The RINNO's renovation activities.

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	/

Furthermore, Table 2 presents the renovation activities data base developed within the RINNO project in order to standardise the renovation design process and enable developing and delivering the RINNO design toolbox that includes digital tools for energy, environmental, and LCA/LCC simulations. In this paper, as shown in Table 2, direct causality relationships between these standardised renovation activities and potential building hazards are identified. 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 likely they will be element or area-related hazards. It should be noted that Table 2 identifies

Hazard IDs relevant to Activity name, only where the Hazard identified is part of the sample set as given in Table 1. There are multiple hazards which will be relevant to the respective activities, hazards which are outside of scope for this research and as such not included in the sample set.

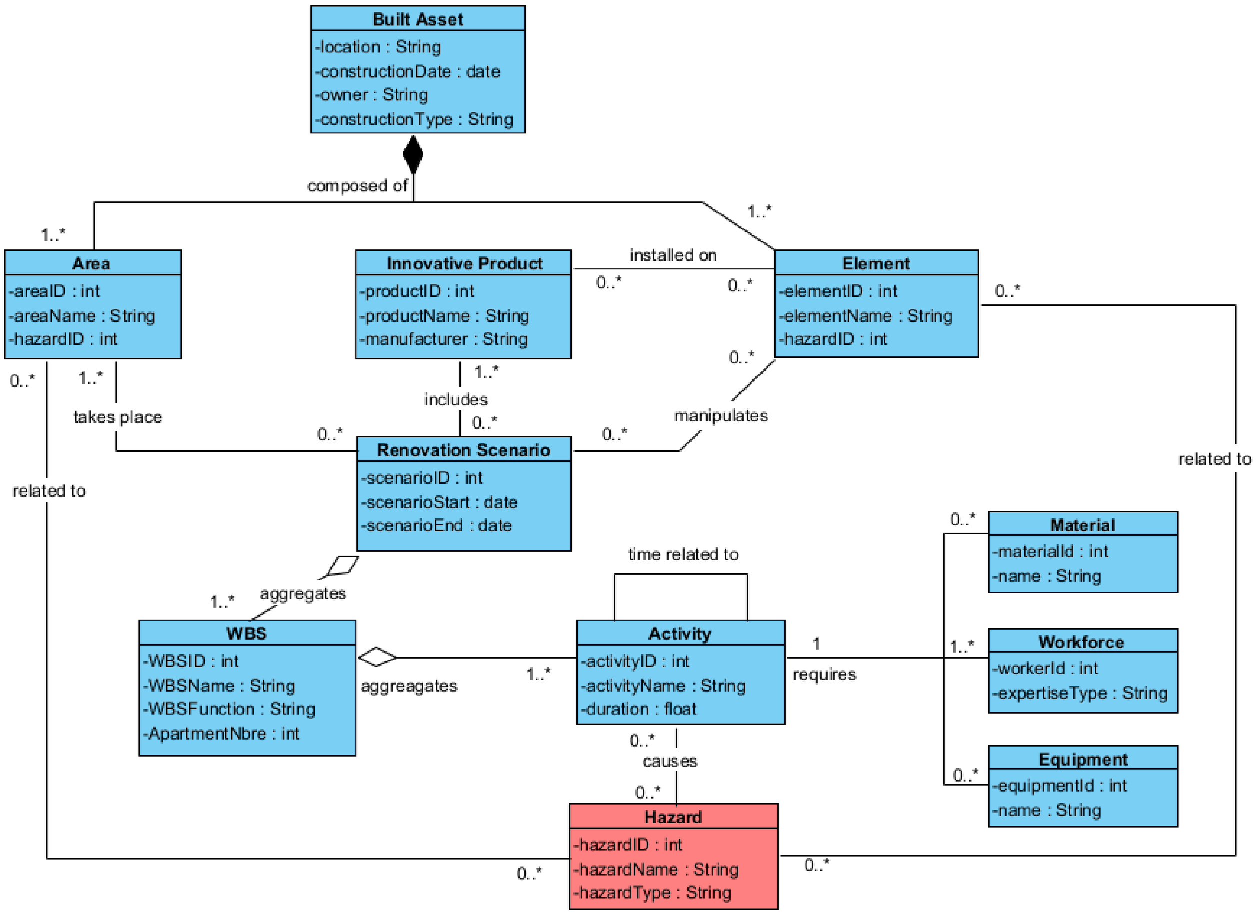

Figure 1: Building renovation hazard ontology.

2.2. Ontology conceptualisation

Figure 1 presents the building renovation hazard ontology via a UML (Unified Modelling Language) 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. As presented in Figure 1, a ‘Built Asset’ is composed of several (at least one) ‘Element’ (e.g. window, wall, HVAC) and many (at least one) ‘Area’ (e.g. room, corridor). An ‘Element’ could be manipulated while achieving a ‘Renovation Scenario’ and could present many ‘Hazards’. A ‘Renovation Scenario’ is an aggregation of ‘WBS’ (Work Breakdown Structure, e.g. floor, external façade), takes place at one or many ‘Area’, manipulates one or many ‘Element’, and could involve the installation of many ‘Innovative Product’. A ‘WBS’ is a combination of renovation activities that could be taken together seen as a work package or macro renovation activity. An ‘Area’ could present many ‘Hazard’, but it could also present none. Each renovation ‘Activity’ is timely constrained by activities that should begin and finish

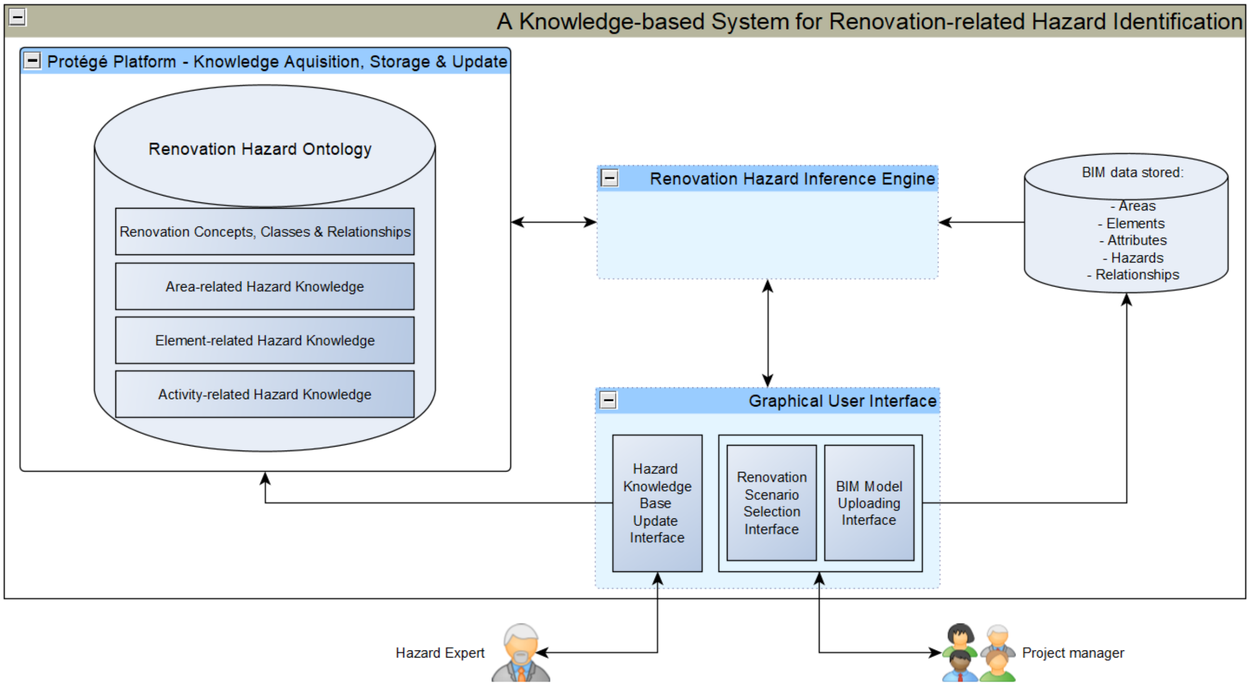

Figure 2: System architecture of the renovation-related hazard identification tool.

before it, whereas some others will be triggered and executed after its completion. It also requires a set of 'Material', 'Workforce' and 'Equipment' so it can be executed and may cause 'Hazard' to the 'Workforce'.

The hazard ontology proposed was implemented using the Protégé platform (Stanford University n.d.) and populated with hazard knowledge described in Section 2.1.

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

This section aims at demonstrating the renovation hazard ontology application by developing a knowledge-based system for application within the context of deep renovation projects that are part of a large European research project named RINNO. 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 (Doukari and Greenwood 2020).

3.1. System architecture

Figure 2 presents the system architecture of the digital tool proposed which aims to substitute for human experts and provide support to project managers that are learners, beginners or lacking hazard-related knowledge. In addition, this tool is equipped with learning capabilities via a dedicated 'Hazard Knowledge Base Update' user interface so that human 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 the BIM model uploaded, through the 'BIM Model Uploading' user interface, and the hazard knowledge represented within the 'Renovation Hazard Ontology'.

3.2. System behaviour

Figure 3 describes the automated hazard identification process implemented based on the renovation ontology introduced in Section 2.2. The automated process, represented here 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) (Figure 4 – (A) & (B)), 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 WBS 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 identification results and enabling an automatic documentation of them (Figure 6).

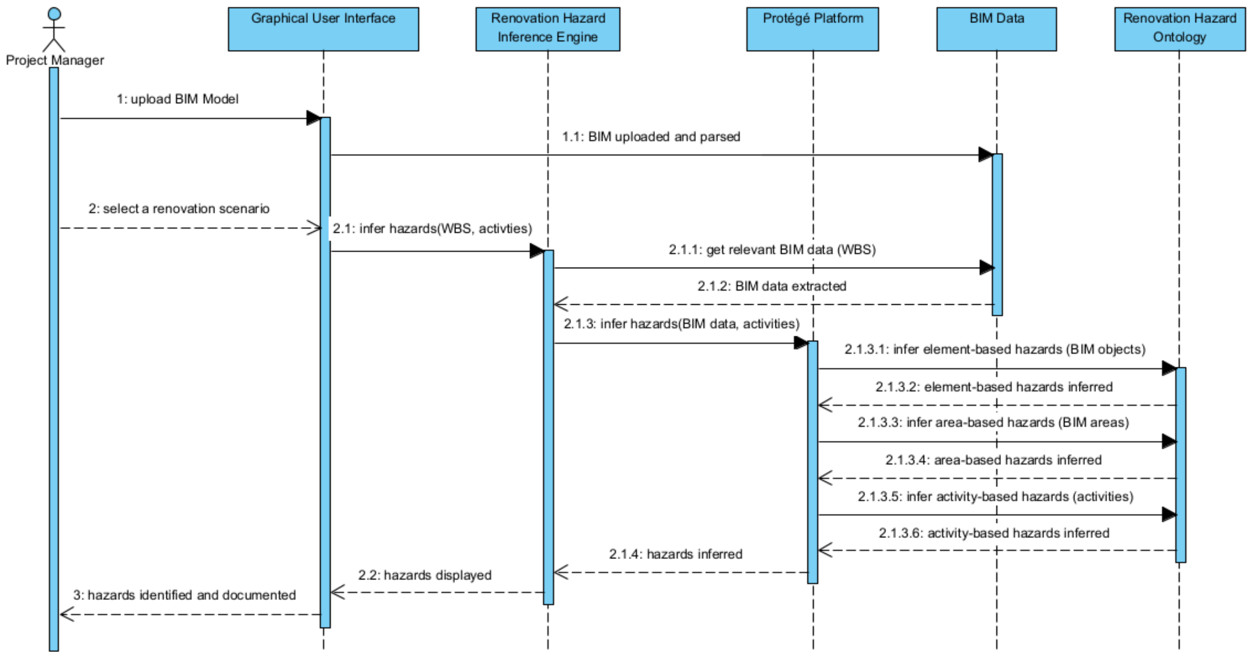

Figure 3: Automated renovation hazard identification process - UML Scenario

3.4. Graphical user interfaces

To streamline renovation hazard identification, facilitate interaction with the Hazard identification tool, and assist project managers for renovation scenario definition and selection, a friendly user interface was developed. Figure 4 illustrates the corresponding GUI and shows both the WBS selection tab (Figure 4 – (A)) and the Activity selection tab (Figure 4 – (B)).

4. Case Study of the RINNO's Greek demo site

The Hazard identification tool and its ontology were demonstrated using a real case study; one of the four RINNO project's demo sites which is the Greek multi-family dwelling illustrated in Figure 5 – (A). the first step consisted in creating the Greek demo site's BIM model (Figure 5 – (B)), representing and integrating the hazard data into it (Figure 5 – (C)), and then uploading it into the Hazard identification tool to be used as a BIM-based hazard database. Then, basic renovation project information, such as start date, owner, address, description and project name are inputted as well as a renovation scenario is selected including a combination of different WBS and a set of renovation activities that will be performed in each relevant WBS.

To demonstrate their accuracy towards both hazard identification and renovation strategy assessment in terms of hazards that could be caused during renovation works, three (03) renovation scenarios were selected and processed using the digital tool and the ontology developed (Figure 6). The three scenarios consisted of conducting the same set of renovation activities but related to different WBS, such that Scenario 1 was to renovate the building's 'Basement', Scenario 2 for the 'Ground Floor', and Scenario 3 was dedicated to the '1st Floor' renovation.

Although the three scenarios were defined through the same renovation activities, different hazard identification results were concluded. As illustrated in Figure 5, Scenario 1 has caused {'Slips, Trips and Falls'}, Scenario 2: {'Asbestos', 'Slips, Trips and Falls'}, and finally Scenario 3: {'Working at Height', 'Slips, Trips and Falls'} hazards.

(A)

(B)

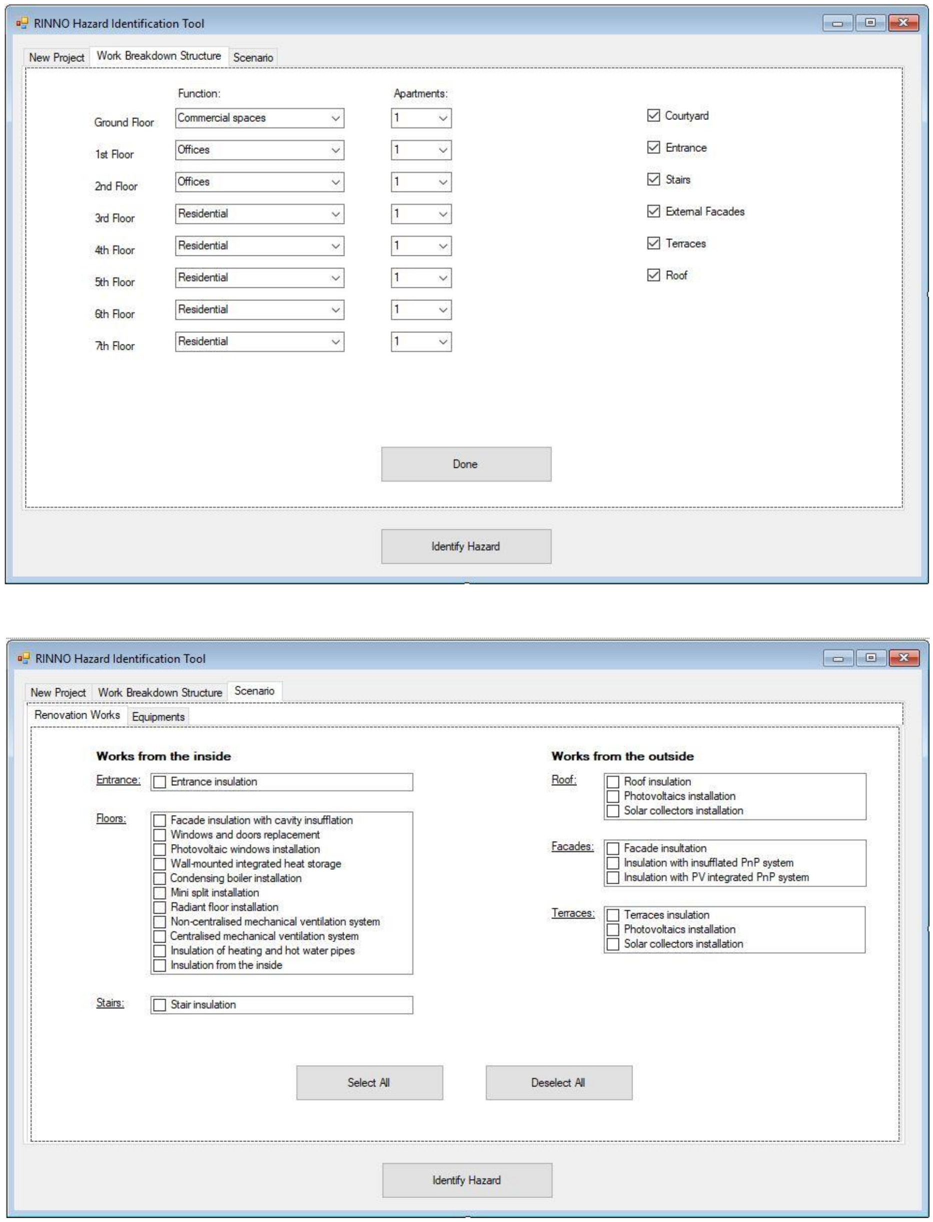

Figure 4: Renovation scenario selection GUI. (A) WBS selection GUI.
(B) Activity selection GUI.

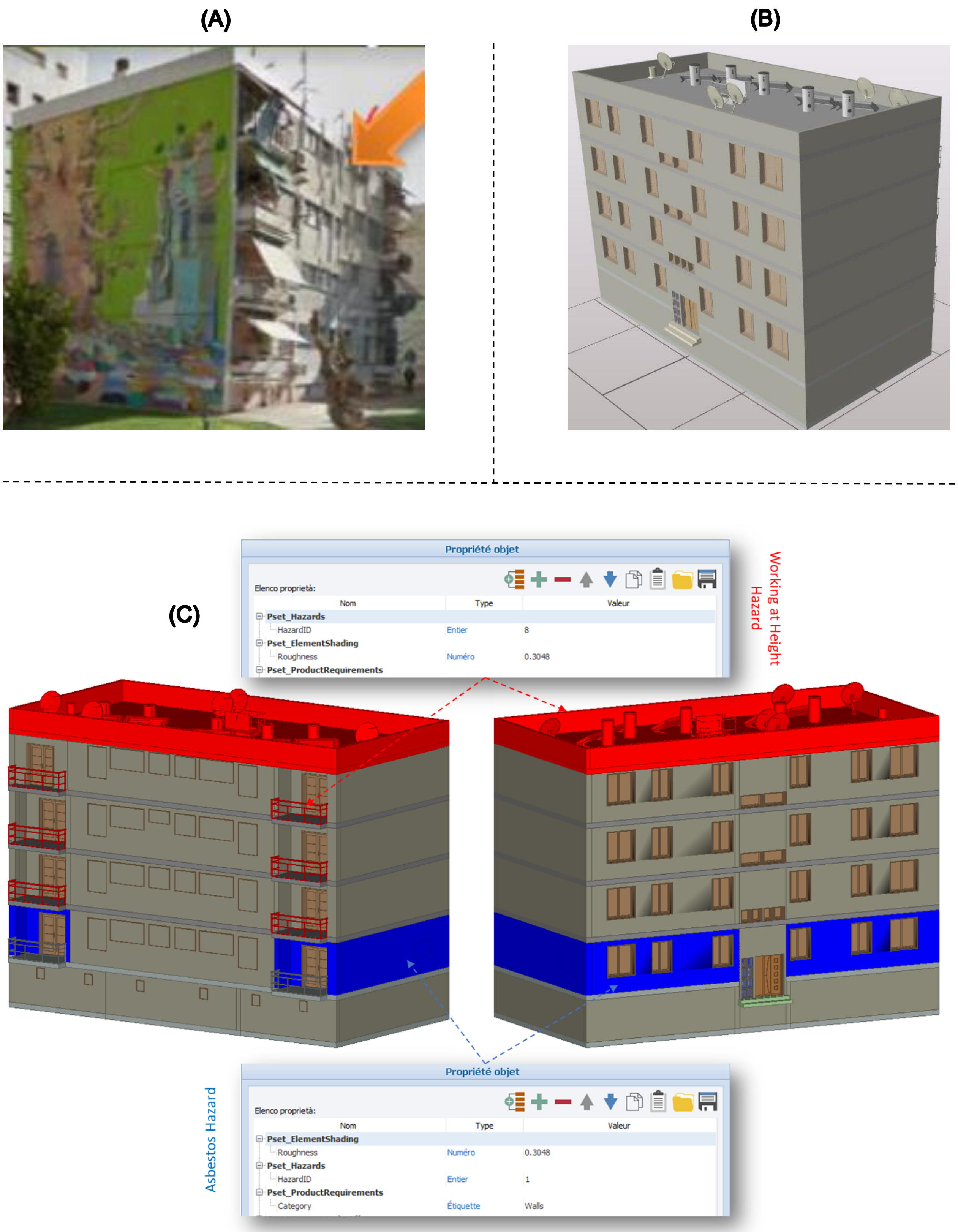

Figure 5: The RINNO's Greek multi-family dwelling demo site. (A) The real building. (B) IFC BIM model of the Greek building. (C) Hazard data represented and integrated in the BIM model.

	Scenario 1	Scenario 2	Scenario 3
WBS	Basement	Ground Floor	1st Floor
Activities	- Site preparation - Façade insulation with cavity insufflated - Windows and doors replacement - Radiant floor installation - Terraces insulation	- Site preparation - Façade insulation with cavity insufflated - Windows and doors replacement - Radiant floor installation - Terraces insulation	- Site preparation - Façade insulation with cavity insufflated - Windows and doors replacement - Radiant floor installation - Terraces insulation

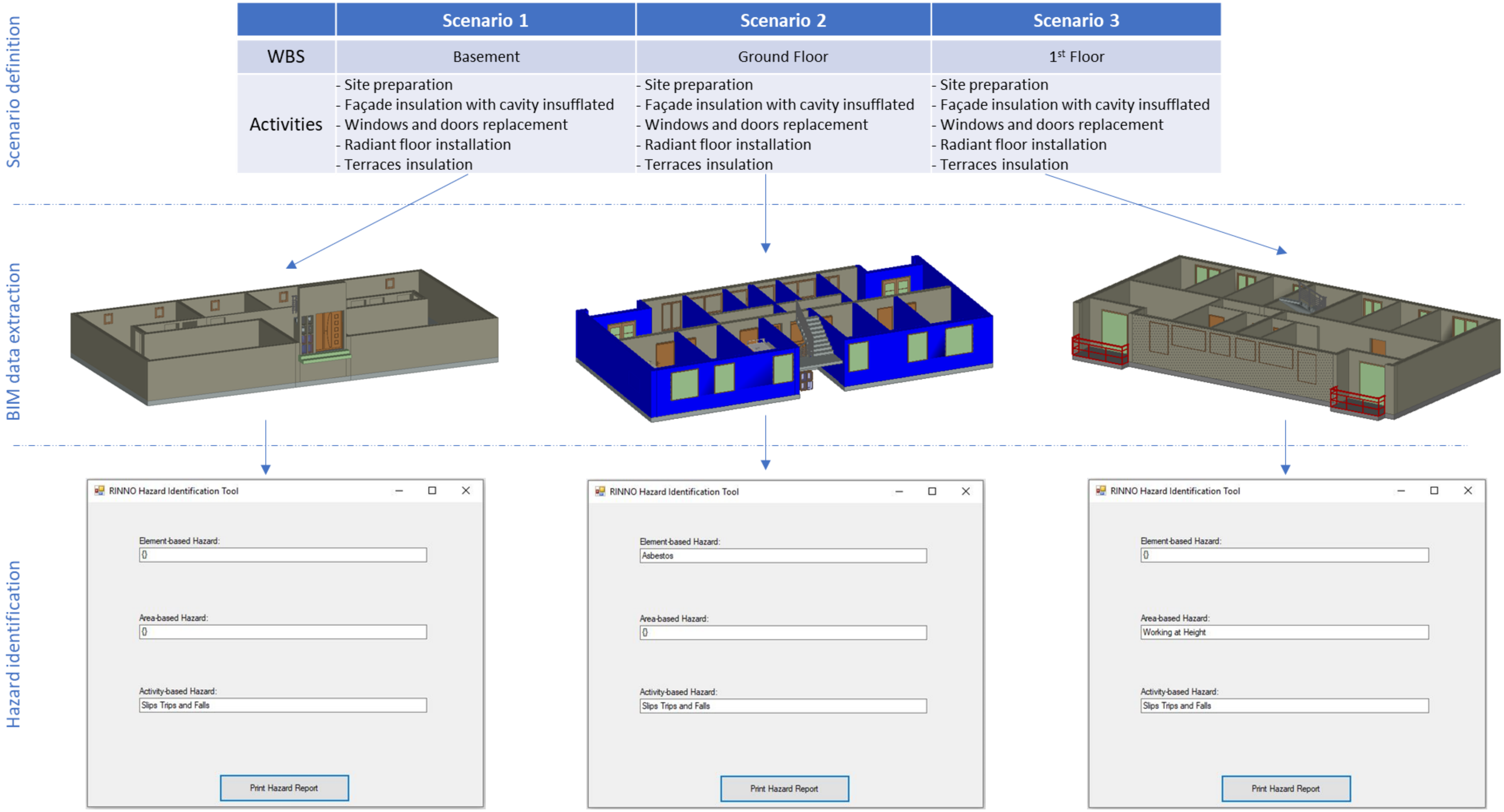

Figure 6: Automatic hazard identification for three 03 different renovation strategies.

5. Conclusion & perspectives

Compared to new constructions, renovation projects are more challenging because of the high level of interaction with occupants that usually stay in the building while renovation works are performed. The safety of project participants as well as that of occupants is the main priority when managing a construction project. To optimise hazard mitigation processes and ensure project participants safety, this paper proposed an ontology to capture and represent renovation-related hazard knowledge and demonstrated its application by developing a digital tool enabling automatic hazard identification and renovation strategy assessment. These tools were then tested and demonstrated on a real case study taken from a large European research project which is the RINNO project. Three (03) different renovation strategies have been selected for the Greek multi-family dwelling, 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 combination. This could rationally be explained by the heterogenous distribution of hazard through different areas, elements and components of the same building.

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., WBS and activities are the same) assessment and comparison, the time dimension should be integrated. One such application is ‘4D BIM’ 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 duration. For example, ‘Working at Heigh’ hazard evaluation will be different for two workers where one only spent one day working on the roof and another two days. Consequently, to reduce hazard durations (and so to be less exposed to it) and optimise the renovation process, project managers would begin by scheduling first, in one go, the activities related to elements and areas that are more likely to cause hazards.

Acknowledgements

This work was funded by (i) the European Union’s Horizon 2020 Research and Innovation Programme through the RINNO project (https://RINNO-h2020.eu/) under Grant Agreement Number 892071, and (ii) the SEND programme (ref. 32R16P00706) which is part-funded through the European Regional Development Fund (ERDF), and the UK Department for Business, Energy and Industrial Strategy (BEIS) (https://www.keele.ac.uk/business/businesssupport/smartenergy/).

References

Aldanondo, M., A. Barco-Santa, E. Vareilles, M. Falcon, P. Gaborit, and L. Zhang. 2014. ‘Towards a BIM Approach for a High Performance Renovation of Apartment Buildings’. In *Product Lifecycle Management for a Global Market*, edited by Shuichi Fukuda, Alain Bernard, Balan Gurumoorthy, and Abdelaziz Bouras, 21–30. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-662-45937-9_3.

Amorocho, Jerson Alexis Pinzon, and Timo Hartmann. 2021. ‘Reno-Inst: An Ontology to Support Renovation Projects Planning and Renovation Products Installation’. *Advanced Engineering Informatics* 50 (October): 101415. https://doi.org/10.1016/j.aei.2021.101415.

Bozorgi, A., and James R. Jones. 2013. ‘Improving Energy Retrofit Decisions by Including Uncertainty in the Energy Modelling Process’. In . https://doi.org/10.17831/REP:ARCC%Y196.

Chaves, Fernanda Justin, Patricia Tzortzopoulos, Carlos Torres Formoso, and Clarissa Notariano Biotto. 2017. 'Building Information Modelling to Cut Disruption in Housing Retrofit'. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 170 (6): 322–33. https://doi.org/10.1680/jensu.16.00063.

Dawood, Nashwan, and Sushant Sikka. 2008. 'Measuring the Effectiveness of 4D Planning as a Valuable Communication Tool'. *Journal of Information Technology in Construction (ITcon)* 13 (39): 620–36.

Doukari, Omar, and David Greenwood. 2020. 'Automatic Generation of Building Information Models from Digitized Plans'. *Automation in Construction* 113 (May): 103129. https://doi.org/10.1016/j.autcon.2020.103129.

Doukari, Omar, Theo Lynn, Pierangelo Rosati, Antonia Egli, Stelios Krinidis, Komninos Angelakoglou, Vasileios Sougkakis, Dimitrios Tzovaras, Mohamad Kassem, and David Greenwood. 2021. 'RINNO: Transforming Deep Renovation through an Open Renovation Platform'. In . Nice, France.

Eastman, C., Jae-min Lee, Yeon-suk Jeong, and Jin-kook Lee. 2009. 'Automatic Rule-Based Checking of Building Designs'. *Automation in Construction* 18 (8): 1011–33. https://doi.org/10.1016/j.autcon.2009.07.002.

Egbu, C. O. 1994. 'Management Education and Training for Refurbishment Work within the Construction Industry'. Phd, University of Salford. http://usir.salford.ac.uk/id/eprint/14743/.

Egbu, Charles O. 1997. 'Refurbishment Management: Challenges and Opportunities'. *Building Research & Information* 25 (6): 338–47. https://doi.org/10.1080/096132197370156.

Fawcett, W., and J. Palmer. 2004. *Good Practice Guidance for Refurbishing Occupied Buildings*. CIRIA C 621. London: Construction Industry Research and Information Association.

Gholami, Elaheh, Steve Sharples, Abrishami Sepehr, and Tuba Kocaturk. 2013. 'Exploiting BIM in Energy Efficient Refurbishment: A Paradigm of Future Opportunities'. In *PLEA2013 29th Conference, Sustainable Architecture for a Renewable Future*. Munich, Germany.

Grath, Teresa Mc, Sreejith Nanukuttan, Kieran Owens, Muhammed Basheer, and Peter Keig. 2013. 'Retrofit versus New-Build House Using Life-Cycle Assessment'. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 166 (3): 122–37. https://doi.org/10.1680/ensu.11.00026.

Han, Charles, Kincho Law, and John Kunz. 2000. 'Computer Models and Methods for a Disabled Access Analysis Design Environment'. 123. Stanford University, Stanford. CIFE.

Hartmann, Timo, and Amy Trappey. 2020. 'Advanced Engineering Informatics - Philosophical and Methodological Foundations with Examples from Civil and Construction Engineering'. *Developments in the Built Environment* 4 (November): 100020. https://doi.org/10.1016/j.dibe.2020.100020.

Haymaker, John, John Kunz, Ben Suter, and Martin Fischer. 2004. 'Perspectors: Composable, Reusable Reasoning Modules to Construct an Engineering View from Other Engineering Views'. *Advanced Engineering Informatics* 18 (1): 49–67. https://doi.org/10.1016/j.aei.2004.10.002.

Joblot, L., T. Paviot, D. Deneux, and S. Lamouri. 2019. 'Building Information Maturity Model Specific to the Renovation Sector'. *Automation in Construction* 101 (May): 140–59. https://doi.org/10.1016/j.autcon.2019.01.019.

Kemmer, S., and L. Koskela. 2012. 'Developing a Lean Model for Production Management of Refurbishment Projects'. In *20th Annual Conference of the International Group for Lean Construction*. San Diego, CA, USA. https://www.semanticscholar.org/paper/Developing-a-Lean-Model-for-Production-Management-Kemmer-Koskela/b6edfd87b9447309e66703563e1152c8f952e33d.

Khanzode, Atul, Dr Martin Fischer, and Dean Reed. 2008. 'Benefits and Lessons Learned of Implementing Building Virtual Design and Construction (VDC) Technologies for Coordination of Mechanical, Electrical, and Plumbing (MEP) Systems on a Large Healthcare Project'. *Journal of Information Technology in Construction (ITcon)* 13 (22): 324–42.

Lynn, Theo, Pierangelo Rosati, Antonia Egli, Stelios Krinidis, Komninos Angelakoglou, Vasileios Sougkakis, Dimitrios Tzovaras, Mohamad Kassem, David Greenwood, and Omar Doukari. 2021. 'RINNO: Towards an Open Renovation Platform for Integrated Design and Delivery of Deep Renovation Projects'. *Sustainability* 13 (11): 6018. https://doi.org/10.3390/su13116018.

Manuel, John. 2011. 'Avoiding Health Pitfalls of Home Energy-Efficiency Retrofits'. *Environmental Health Perspectives* 119 (2). https://doi.org/10.1289/ehp.119-a76.

Papamichael, Konstantinos. 1999. ‘Application of Information Technologies in Building Design Decisions’. *Building Research & Information* 27 (1): 20–34. https://doi.org/10.1080/096132199369624.
Passoni, Chiara, Alessandra Marini, Andrea Belleri, and Costantino Menna. 2021. ‘Redefining the Concept of Sustainable Renovation of Buildings: State of the Art and an LCT-Based Design Framework’. *Sustainable Cities and Society* 64 (January): 102519. https://doi.org/10.1016/j.scs.2020.102519.
Sacks, R., M. Treckmann, and O. Rozenfeld. 2009. ‘Visualization of Work Flow to Support Lean Construction’. *Journal of Construction Engineering and Management* 135 (12): 1307–15. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000102.
Sheth, Amey, A. Price, and Jacqueline Glass. 2010. ‘BIM and Refurbishment of Existing Healthcare Facilities’. *Association of Researchers in Construction Management, ARCOM 2010 - Proceedings of the 26th Annual Conference*, January.
Singh, Yash, Tariq Abdelhamid, Tim Mrozowski, and Mohamed A. El-Gafy. 2014. ‘Investigation of Contemporary Performance Measurement Systems for Production Management of Renovation Projects’. *Journal of Construction Engineering* 2014 (July): 1–9. https://doi.org/10.1155/2014/417853.
Stanford University. n.d. ‘Protégé’. Accessed 28 April 2022. https://protege.stanford.edu/.
‘UN Climate Change Conference (COP26) at the SEC – Glasgow 2021’. n.d. UN Climate Change Conference (COP26) at the SEC – Glasgow 2021. Accessed 21 February 2022. https://ukcop26.org/.
Volk, Rebekka, Julian Stengel, and Frank Schultmann. 2014. ‘Building Information Modeling (BIM) for Existing Buildings — Literature Review and Future Needs’. *Automation in Construction* 38 (March): 109–27. https://doi.org/10.1016/j.autcon.2013.10.023.