2023 European Conference on Computing in Construction
40th International CIB W78 Conference
Heraklion, Crete, Greece
July 10-12, 2023

TOWARDS A DIGITALLY ENABLED PERSONALISED CONSTRUCTION SAFETY TRAINING FRAMEWORK FOR O&M CONSTRUCTION PROJECTS

James Wakefield[1], Omar Doukari[1], Pablo Martinez Rodriguez[1], and Mohamad Kassem[2]
[1]Northumbria University, Newcastle, UK
[2]Newcastle University, Newcastle, UK

Abstract

As efforts continue at pace to improve the sustainability credentials of the as built environment via refurbishment and retrofit, the safety of those responsible for such is being brought into focus. This paper reviews existing technology enabled construction safety mitigation research and presents an Ontological Conceptualisation Model which proposes four construction safety domain concepts. A personalised safety training framework which explores available technologies as relevant to the domain concepts is put forward. Relationships between those technologies are explored as a means to understand more about the potential for a novel personalised construction safety training solution.

Introduction

Workforce health and safety (H&S) in both new build construction projects and Operation and Maintenance (O&M) of existing built assets remains a significant global concern. Poor H&S outcomes in the construction sector delivered at any stage of the built asset lifecycle having significant human costs, including fatalities, disabilities and increased medical burden (Umer et al., 2017). Regarding fatalities, the construction sector has one of the highest fatal injury rates in both the developed and the developing world (Kassem et al., 2017). In addition to the human cost, poor H&S outcomes are evidenced as leading to project delays and increased economic costs for the sector (Vitharana, De Silva & De Silva, 2015).

The impact of construction work days lost is particularly acute given that a shortage of skilled construction labour is one of the most significant concerns for the sector (Kim, Chang & Castro-Lacouture, 2020). Evidently then there is a need to develop strategies to further drive down construction sector accident, injury, and fatality figures.

Technology has been widely researched a mechanism to improve safety management across the construction sector (Ramani & Arun Kumar 2022). Traditionally, risk identification in construction has been performed manually and is based on drawings and text files (Zhang et al., 2015), but technological advancements in the digital domain have changed how safety in construction is conceived to improve H&S outcomes.

To provide a clear picture that supports improved decision-making in safety measures, knowledge modelling has been historically presented as a paradigm to improve H&S outcomes for the sector by designing out potential hazards. For example, an ontology based risk inferring process was demonstrated by Zhong & Li (2015) as an effective means of predicting risk in the deep pit excavation construction domain. An ontological approach was developed here so that a rule-based risk inferring system could be implemented. Zhang et al. (2015) studied an ontology-based approach to organise, store, and reuse construction safety knowledge, demonstrating the potential of ontologies as an enabler of computer applications that are capable of easily discovering, querying, data linking, and sharing construction safety knowledge. Xing et al. (2019) developed an ontology for formalised safety risk identification in metro construction. This was in response to the suggestion by the authors that safety decision making in the metro construction domain is ill structured and inconsistent. Ding (2016) investigated the potential of ontology and semantic web technology to enable the representation of construction safety hazard data semantically, the study demonstrated the potential of BIM to strengthen outcomes in the sematic modelling for construction safety domain.

Other digital approaches, such as BIM, have shown potential to contribute to improved H&S outcomes in the construction sector. Along with real-time data and semantic models, BIM is lauded as an enabler to improve safety in the construction sector. Tools and workflow enabled by BIM have the potential to support the transfer of hazard mitigation and safety data to operatives involved in assets operation and maintenance (Wetzel and Thabet, 2018). Despite the recognised benefits of BIM in supporting workforce H&S, the current adoption of BIM in the operational phase of the built asset is minimal in comparison to the design and construction phases (Hilal, Maqsood & Abdekhodaee, 2019). However, there are BIM-enabled solutions in this area. Hossain et al. (2018) demonstrated the potential of an intelligent BIM integrated risk review system at the construction design phase which helped designers identify risks related to design along with required design features. The study found that the rule-based risk review system helps to eliminate many risks which would have otherwise been overlooked at the construction design stage. When investigating BIM safety risk libraries for use at the construction design phase, Collinge et al. (2022) found that the BIM safety risk library facilitates tacit and explicit knowledge sharing, which enables the construction industry to benefit from H&S data. The authors note that H&S data structuring of this type opens opportunities for further digital advances including automatic rule checking approaches for H&S data. These findings are a demonstration of the role of BIM and ontology development in construction site safety for new build construction projects, in this case specifically for masonry workers.

While much research has been undertaken into technology enabled construction safety domain, the research is routinely focussed on risk prediction, predominantly though semantic modelling approaches. Research on the relationship of such approaches to construction sector safety training, one of the predominant regulatory and best practice approaches to safety mitigation in the industry, is sparce.

Internet Enabled Construction Site Safety: Instruction and Training

While we observe a broad range of technology enabled safety research and associated solutions, including BIM for H&S, for the construction sector generally, the research tends to focus on construction design for the new build sector rather than for the as built environment. This is despite new buildings only making up 1%-2% of the total building stock in a typical year (Kincaid 2004). Construction safety management however is not purely a construction phase concern and must extend out to the full building lifecycle (Zhang, Cao and Zhao 2017).

When investigating the transfer of relevant safety data for the built asset O&M phase using BIM, Wetzel and Thabet (2018) 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 construct phase to O&M phase. Such challenges exist also where the BIM process is being leveraged to support O&M phase renovation and retrofit of existing buildings.

Naticchia et al. (2018) investigated the use of BIM as a data environment, a cloud-based system for managing information flows, and mixed reality proposing that beyond efficiency and productivity, safety is an obvious next step. Naticchia et al. (2018) conclude 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. Indeed, Wetzel and Thabet (2016) assert 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.

Despite efforts to enhance the construction safety space via the means of technology, technology transfer remains a significant challenge (Welch et al., 2015). Technology transfer refers to the process of conversion of scientific research and technological advances into market ready goods and services for both new build and as built environments. A proposed next step for technology transfer regarding safety mitigation in the construction sector is H&S training. H&S training remains one of the main strategies to reduce H&S risks in construction (Dawood et al., 2014), and is an essential tool for the reduction of construction accidents caused by unsafe human actions (Kazar and Comu, 2021).

Personalised Construction safety Training

Since construction sites are complex scenarios with low management density, safety instructions received by construction workers are usually not timely and precise (Tang, Xu, & Zhu et al., 2019). When concerned with the issue of timely and contextual safety training in the construction domain, Lin et al. (2014) developed a personalized reminder service to help improve daily compliance-based practices and management. More recently, a real time personalised safety instruction management (PSIM) system based on global positioning systems and cloud computing to communicate real time safety instruction to users was demonstrated as reducing construction hazards and creating a safer environment for workers (Tang, Xu, & Zhu, 2019). The system worked by providing individualised instructions to rail sector construction workers via smart phone. The instructions reminded workers of different types of risk and of appropriate actions in different risk scenarios. The study reported that the application of PSIM is an important direction for safety management.

This study looks to build on existing PSIM capability by interfacing a range of existing technologies in a novel way to provide construction workers with more timely and contextual construction safety training. The ability of e-learning, that is training content that can be accessed from a digital device, is recognised as an enabler for timely and contextual safety training delivery. Construction safety training delivered using e-learning resulted in increased safety outcomes when compared to construction safety training delivered in the traditional space (Ho and Dzeng, 2010). The overall performance of computer-aided technologies (including e-learning) to deliver construction site safety training is superior in several technical aspects compared to traditional tools (such as in person classroom-based training), specifically, representing actual workplace situations, providing text-free interfaces, and eliciting better user engagement (Gao, Gonzalez and Yiu, 2019). Other recognizable benefits of computer-aided technologies specifically for construction safety training include the ability of e-learning to support effective health and safety training delivery in a range of languages for personalization in multicultural delivery environments (Williams et al., 2010).

Such understanding also informs efforts to leverage technology to provide short relevant training content at a time when it is most relevant to the task in hand, so called micro credentials (or credentialing). Such a training approach offers the opportunity to disrupt the time-based education and training model (physical space training) and recognises the competence required for tasks that are directly related to employment (Harvey, 2018).

Existing research outlines a great deal of opportunities in the construction sector safety domain to leverage emerging technologies for this purpose. In addition, the existing research cites efforts to enable new construction safety applications through the novel interfacing of both existing and emerging technologies. Much of the research in this regard though is concerned with the new build construction phase and is most often linked to the concept of “designed out” risk, that is the ability to mitigate construction hazards at the pre-construction design phase. This study is concerned with construction projects undertaken during the O&M phase of the built asset lifecycle where it is acknowledged that there is a much higher rate of injury and illness when compared to all other fields of employment (Wetzel and Thabet, 2018). Construction worker safety at the O&M phase of the built asset lifecycle being of particular importance at this current time in the UK and elsewhere owing to the wealth of retrofit and refurbishment works being planned both in the public and the private sector to ensure that the built environment is able to operate in a more environmentally friendly way, and in line with decarbonization targets being enshrined into law by governments around the world.

Framework for Digitally Enabled Personalised Construction Safety Training

This paper looks to build on existing research into the technology enabled construction safety domain. The paper proposes a framework for digitally enabled personalised construction safety training which is intended to leverage the existing literature into technology enabled construction safety practices. The framework is made up of a proposed underpinning ontology, an enabling process (BIM) and an enabling technology (learner management system). The specific focus then being on the potential of ontology-based construction safety knowledge to inform personalised safety instruction systems. The framework aims to determine the role of the proposed underpinning ontology, and explore the relationships between the defined enablers, BIM and learner management system (LMS) technology. The paper proposes that the relationships between the enablers as structured and linked by the ontology have the potential to publish individualised hazard data which itself may be leveraged for the purposes of providing individualised construction safety training content directly to the individual construction worker by the means of an LMS. The contribution of the paper is the proposal to leverage existing research to inform the novel interfacing of existing technologies to enable enhancement of existing construction safety practices.

Proposed Solution

In order to understand the relevance of the proposed framework it is necessary to give a basic overview of the proposed solution. The proposed solution seeks to build on existing research in the PSIM system domain. The solution seeks to extend the principles of PSIM, that being the provision of personalised safety instructions considering the features of both the job and the individual worker (Tang et al, 2019). The extension will include features which enable additional contextual H&S information and training to be communicated. In addition, the solution will have the ability to check certain individual credentials, such as a trade specific safety certificates thus digitising hitherto admin intensive processes.

The solution looks to extend PSIM features out to the O&M phase of the built environment by offering an access control facility, essentially checking the individual worker has met the required credentials before assignment of a site access status to the individual worker profile. This is to ensure that construction workers presenting for jobs on O&M phase construction sites are best informed in a timely and contextual fashion as to the specific hazards which may be encountered during the course of that job.

Towards a Domain Ontology: Conceptual Model

Underpinning the proposed framework is the ontological conceptual model. The ontological conceptualisation is adopted to the framework as a means to structure the reality of the domain, and codify the relationships between the domain concepts. The proposed enabling approach (BIM) and the proposed enabling technology (LMS) are then presented in the context of the ontological domain concepts to demonstrate the relationship of the adopted approach and solution to reality of the proposed delivery context. The decision to develop an ontological conceptualisation is based on evidence in the existing literature as to the potential of ontological approaches to support technology enabled construction safety approaches. Ontologies can represent knowledge in specific domains and enable semantic operability through linkage with external sources (Zhang & Diraby, 2012). Moreover, domain ontology can enable knowledge reasoning as well as data querying based on defined classes, properties and relationships (Anumba et al., 2008). The value of an ontological approach specifically for the construction safety knowledge being evidenced for; Risk inference (Zhong & Li 2015), risk identification and knowledge sharing (Xing et al 2019), semantic modelling of construction safety knowledge (Zhang 2015), as well risk knowledge management (Ding et al 2016). Such benefits enabled by ontological approaches seek to normalise knowledge thus creating knowledge sharing opportunities in the construction safety domain. Having determined the case for the development of an ontological approach, an underpinning ontological conceptualisation model is proposed. The model introduces the relevant construction safety domain knowledge concepts and identifies common dependencies (in the form of relationships) within and among the knowledge concept domains. *Figure 1* presents the construction safety ontological

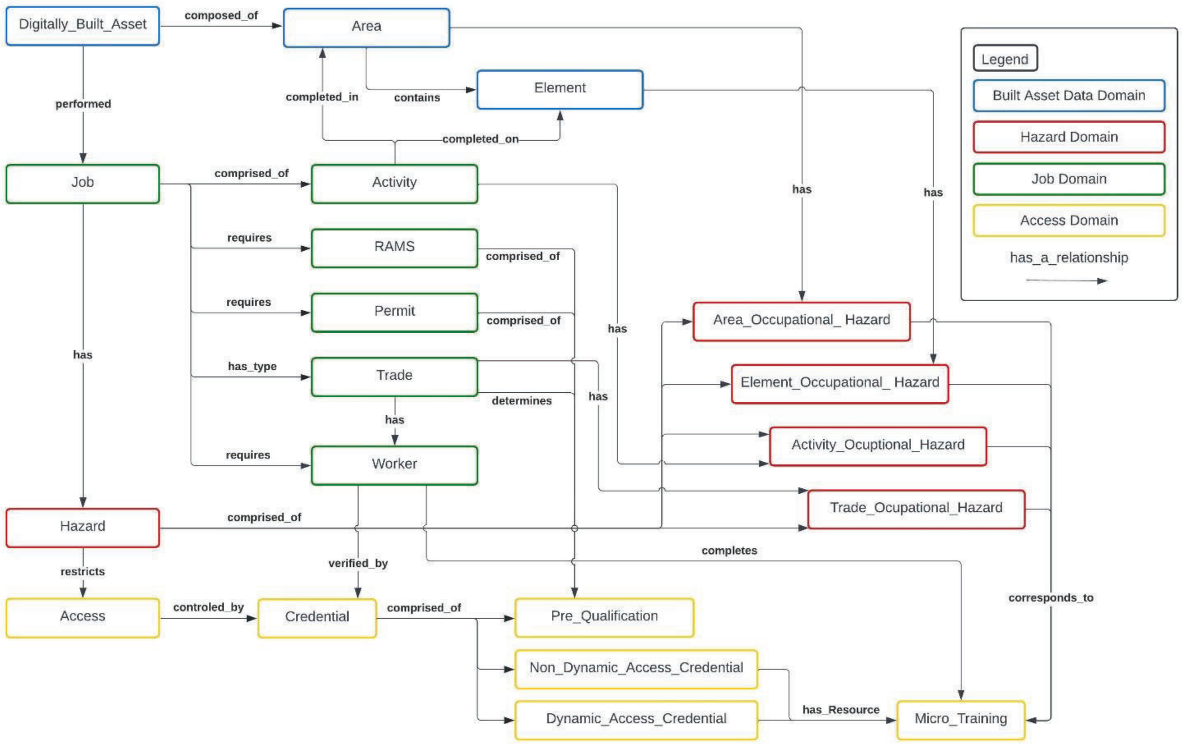

Figure 1: Construction Safety Ontological Conceptual Model

conceptual model, an explanation for each domain of which is given below.

Digitally Built Asset Domain:

The ’Digitally_Built_Asset’ domain is made up of *Area* and *Element* data. Its data classes enable ’Hazard’ domain data to be assigned to specific *Area(s)* and *Element(s)* of a digitally built asset. To this end, within the ’Digitally_Built_Asset’ domain, ’Hazard’ data can be organised according to the relationship of the ’Hazard’ to the building. Structuring the data as a process of ’Hazard data’ assignment (to *Area* and/or *Element*) makes it possible to query the digitally built asset in its entirety and/or down to individual *Area* and/or *Element* level for specific hazard data instances (the parameters of the query being set according to the data contained in the ’Job’ domain). Through the ’Digitally_Built_Asset’ domain it is possible to identify specific *Areas* and *Elements* of a digitally built asset and query for the presence of ’Hazard’ data. Where one or more ’Hazard' instances are returned as the result of such a query, the data are subsequently leveraged in the ’Access’ domain.

Job Domain:

The ‘Job’ domain is made up of data relevant to a specific construction site job instance. The data occurring in this domain is leveraged principally to drive queries of the ’Digitally_Built_Asset’ domain data for the purposes of identifying hazards as relevant to a specific job or jobs. This is enabled via the relationship of the ‘Activity’ class to the *Area* and *Element* subclasses within the ’Digitally_Built_Asset’ domain. Knowing in what *Area(s)* and on what *Element(s)* of the building a construction classified job is to be undertaken enables predefined *Area* and *Element* data to be queried for assigned ‘Hazard’ data. Hazard data returned from such queries is organised as *Area_Occupational_Hazard* and/or *Element_Occupational_Hazard* for use in the *Micro_Training* subclass in the ‘Access’ domain. The ‘Job’ domain also contains classes concerned with regulatory required and best practice construction safety documentation, these are *RAMS* (Risk Assessment and Method Statements) and *Permit*. These classes enable job specific safety documentation to be set as a completion requirement for the individual worker via the relationship between the *RAMS* and *Permit* subclasses, and the *Pre_Qualification* data subclass in the ‘Access’ domain. Also occurring under the ‘Job’ class are the *Activity* and *Trade* classes. The *Activity* class handles data pertaining to the specific activity to be undertaken by the individual worker as part of a specific ‘Job’ instance. The data contained in this class is linked to *Activity_Occupational_Hazard*, itself linked to the *Micro_Training* class in the ‘Access’ domain. Similarly, the *Trade* class stores data linked to the specific job instance for the purposes of managing construction trades certification, the data contained here links to *Trade_Occupational_Hazard*, itself linked to the *Micro_Training* class in the ‘Access’ domain. The *Trade* data subclass is also linked to the *Micro_Training* subclass. Central to the 'Job' domain is the *Worker* class, the data contained here links the individual construction worker (system user) to all relevant safety data via the *Credential* class in the 'Access' domain, where it is possible to set relevant data (such as *Micro_Training* data) such as (site) access credentials for that specific individual construction worker.

Hazard Domain:

The 'Hazard' domain is made up of 'Hazard' related data and is the principal supplier of data to the 'Access' domain, itself concerned with credential setting for the individual *Worker*. 'Hazard' data is a central component of the ontology, as the data occurring within the domain is a critical enabler of the proposed solution. In order to add value to the individual construction worker it is necessary that the solution is able to rationalise the relevance of 'Hazard' data to the individual *Worker*. Without such, all 'Hazards' would be relevant to all individuals which of course is clearly not representative of the reality of the O&M phase construction H&S domain. The *Area_Occupational_Hazard* and *Element_Occupational_Hazard* data classes are related to the *Area* and *Element* classes in the 'Digitally_Built_Asset' domain. The respective relationships here enable queries to be made of the 'Digitally_Built_Asset' for the purposes of identifying relevant 'Hazards' as determined according to the specific 'Job' data, at a building *Area* and/or *Element* level. Also existing within the 'Hazard' domain are the *Activity_Occupational_Hazard* and *Trade_Occupational_Hazard*. These classes enable 'Hazard' data, as linked to specific activities and trades to be organized and leveraged through respective relationships to the *Micro_Training* subclass existing under the 'Access' domain.

Access Domain:

The 'Access 'domain is made up of data classes ultimately concerned with control of access by the individual *Worker* to the O&M construction site. Central to the 'Access' domain is the *Micro_Training* class. The data contained in this class facilitates the assignment of *Micro_Training* content in the form of eLearning content out to the individual *Worker*. In that respect the *Micro_Training* subclass is unique in that it directly informs that which the end user of the proposed system (the individual construction *Worker*) will see and experience. The *Micro_Training* class has relationships within the 'Access' domain, and externally to the 'Job' and 'Hazard' domains. The relationships of the *Micro_Training* class to the respective hazard classes facilitates matching of construction safety data (in the form of eLearning content) to 'Hazard' data (as determined to be relevant). The corresponding construction safety data is then set as a *Credential* (as relevant to the *Worker*) via the *Dynamic_Access_Control* class. *Non_Dynamic_Access_Credential* data has the same relationships only this class is concerned with static (pre-defined) construction safety data such as data linked to the *Worker Trade* or the *Permit* required for a specific 'Job', i.e., data not determined by querying the 'Digitally_Built_Asset' classes, *Area* and *Element*. Critically, the *Micro_Training* class also has a relationship with the *Worker* class to facilitate the assignment of and access to *Micro_Training* data back to the individual *Worker*, thus enabling the individual user profile to be maintained and assessed for required access credentials.

Introducing a Framework for Personalised Construction Safety Training

The framework presented in *Figure 2* builds out from the ontological conceptual model. The framework proposes enabling technologies and approaches as relevant to each of the four domain concepts. Each of the technologies and approaches is introduced with a focus is given to the principle enabling process (BIM) and technology (LMS) as relevant to the concept domains.

The value of BIM to the framework is recognised principally in the ability of BIM to enable construction safety data to be structured and interpretable by the proposed solution. In this regard BIM is put forward as a key structural enabler of the framework, acting as the Digitally Built Asset domain to link with the Hazard and Job domains. BIM has the capacity to both support the operation of the tool as an external hazard data storage location and provide a contextualizing environment by which structured hazard data may be queried by the tool. To fulfil this objective the information model must be maintained according to an agreed hazard processing methodology.

The capacity of BIM to store and structure 'Hazard' data such that hazard data may be queried according to both *Area* (where the individual construction worker is operating) and *Element* (the component or components of the building) upon which the individual will be working is especially important regards qualifying BIM as an appropriate process to support for the proposed solution. Of the research that has been done into PSIM, Tang et al. (2019) leveraged a hazard database for the purpose of structuring hazard data. Such a solution however is proprietary and so limited in capacity to support wider safety information processing. The use of BIM in this regard ensures reliable safety information storage, fast computation and robust information processing capability (requirements as adapted from (Tang et al., 2019).

The framework proposes that such safety knowledge sharing opportunities enabled by a domain ontology linked to a BIM enabled approach offer much in the way of capability to the construction safety space. This is particularly the case for the proposed solution, the central value in the proposed solution being to provide personalised safety training to construction workers.

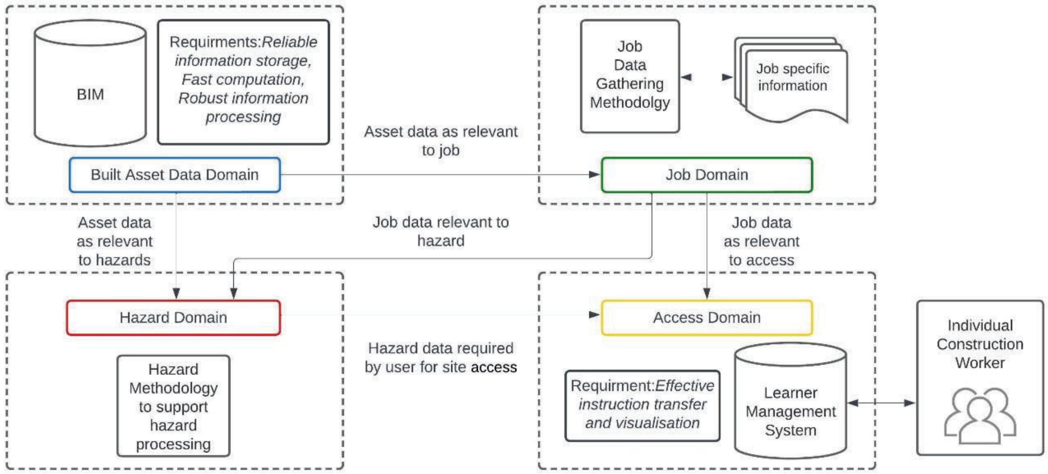

Figure 2: Framework for Digitally Enabled Personalised Construction Safety Training

While the benefits of E-learning as a general safety training mode are well understood, the application of E-learning technologies (systems and content perspective) to personalised construction safety training domain are not well researched. When researching PSIM, Tang et al. (2019) leverage a proprietary app for the purposes of individual safety information access. Such an approach evidently adds value but would likely be costly at scale and would be significantly constrained in terms of readily available functionality.

The proposed technology by which effective instruction transfer and visualisation is achieved here is the LMS and while the role of LMS in this regard is not meaningfully explored in the construction safety literature, LMS technologies are proposed by the authors as the most appropriate of the available solutions. In the LMS development space there is much in the way of existing proprietary code as well as publicly available open-source code. The existing code base has the potential to be leveraged in order that LMS technologies can provide the functionality as required for the proposed solution and according to the 'Access' ontological domain. The key role of the LMS in this respect is assign individualised 'hazard data to relevant individual users (construction workers). Individualised hazard data is that which is deemed relevant to the individual worker according to the specific job attributes. In order that such data can be leveraged as part of a personalised safety training solution, it is necessary to link individualised hazard data to corresponding construction safety content. So, where a fall from height hazard is detected for example, the corresponding content would be some form of fall from height content. With the 'Job', 'Hazard' and 'Digitally_Built_Asset' domains having demonstrated the potential to generate personalised hazard data, LMS technology is deemed to be the most appropriate of the available solutions for the alignment of that data to corresponding hazard content. In this regard the LMS is capable of publishing personalised safety training out to the individual worker, as well as monitoring completion and expiry or such content. This functionality is critical to driving the Access component of the solution, whereby it is possible to check individual user safety training completion and other credentials as a means to determine the access status of an individual worker to specific O&M phase work sites. for enabling individual user access to, as well as system reporting of individualised safety training content completion.

Framework in Action

In order to demonstrate the framework in action, hazard data was allocated at both the area and element level to a sample information model hosted in Revit using the Uniclass classification system. The information model created using Autodesk Revit enabled the representation and integration of 'Working at Height' hazard data into elements such as 'balcony' and areas such as 'roof' located at least 6 feet high from the ground, as well as 'Risk of Shock' hazard data into elements such as 'Mechanical ventilation'.

The model was leveraged as a hazard database and was queried according to the job data for a sample scenario at which point hazard data was outputted in a basic report format. The job data included information about the areas, elements and activities targeted by the sample work scenario, and so enabled querying to identify only the relevant hazard data. The reported hazard data was classified into *Area* hazards, *Element* hazards, and *Activity* hazards, and then sent to the LMS in JSON (JavaScript Object Notation) format which is, despite its name, language agnostic, human and machines readable, in addition to being one of the most widely used file formats in web technologies. Subsequently, the reported hazard data was leveraged in the LMS to enable inference and assignment of corresponding hazard safety training data to the individual user account. Technically, the LMS content is structured as '*if Hazard_X, then Safety_Training_Y*' rules-based knowledge, thus whatever hazard data is identified, respective safety training content will be inferred and assigned. In doing so

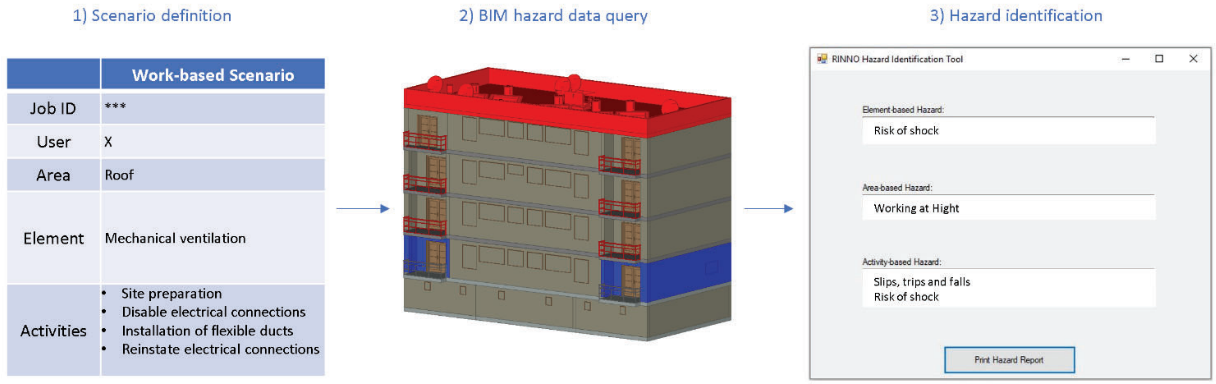

Figure 3: BIM Enabled Hazard Data Identification and Reporting

the LMS set the corresponding safety training content as completion credentials for the individual user.

Figure 3 shows the process by which the above was achieved according to a work-based scenario whereby a user was assigned to a Job located on the roof (*Area*) of the building depicted. The job scenario required work to be done on a roof mounted component of a mechanical ventilation system (*Element*). The activities to be undertaken included site preparation, disable (pre-install), and reinstate (post-install) the electrical connection, as well as install upgraded flexible ducts.

The information model contains working at height hazard data for the roof area (indicated in red on the model), as such *Working at Height* hazard is reported. The information model also contains *Risk of Shock* hazard data as assigned to the mechanical ventilation (*Element*), also reported. In addition, *Slips, Trips and Falls*, and *Risk of Shock* hazard data are reported as linked to the *Activity* class under the 'Job' domain. The identified hazard data are now reported out to the LMS.

Conclusions and Future Research

As the need for retrofit projects in the existing built environment grows in the coming decades so too will the volume of construction classified projects being undertaken at the O&M phase of the built asset lifecycle. Construction safety remains a global concern, especially so at the O&M phase of the built asset lifecycle. Technology enabled construction safety solutions are therefore of critical importance if construction accidents, injuries, and death figures are to be driven down. This research demonstrates the potential of BIM and LMS technology to enable personalised safety instruction for construction sector workers, while also demonstrating the potential to leverage LMS technology as a means to manage individual worker access to construction sites. To this end, ensuring that those individual construction workers presenting for construction site access have the necessary credentials to permit access to the site and inform individual worker safety while working on site. The research leverages an ontological conceptual model to underpin the proposed framework, ensuring that which is proposed is put forward in the context of the construction site safety domain as it exists in reality.

In order to progress this research, it is first necessary to validate the domain ontology as a mechanism to underpin the solution design architecture, this could be achieved through a formal research process with O&M phase domain industry experts and academics. In addition, it is necessary to formalise the domain ontology, this could be achieved in the first instance by implementation of the ontology into a reasoner. In order to progress to a functional framework capable of informing a solution architecture for a functional application it is necessary to understand more about the framework approaches not covered in detail here. That is the respective hazard identification and job data methodologies, a clear methodology for each would need to be developed. The aim of both this research and the proposed next steps is to inform the design architecture for the proposed solution, such that a fully functional version of the solution could be developed for testing in a live real-world environment.

References

Anumba, Issa, R. R. A., Pan, J., & Mutis, I. (2008). Ontology-based information and knowledge management in construction. Construction Innovation, 8(3), 218–239. https://doi.org/10.1108/14714170810888976

Collinge, Farghaly, K., Mosleh, M. H., Manu, P., Cheung, C. M., & Osorio-Sandoval, C. A. (2022). BIM-based construction safety risk library. Automation in Construction, 141, 104391. https://doi.org/10.1016/j.autcon.2022.104391

Dawood, Kassem, M., Patacas, J., & Miller, G. (2014). Combining Serious Games and 4D Modelling for Construction Health and Safety Training. Computing in Civil and Building Engineering (2014) (pp. 2087–2094). https://doi.org/10.1061/9780784413616.259

Ding, L. Y., Zhong, B. T., Wu, S., & Luo, H. B. (2016). Construction risk knowledge management in BIM using ontology and semantic web technology. Safety

Science, 87, 202–213. https://doi.org/10.1016/j.ssci.2016.04.008

Gao, Gonzalez, V. A., & Yiu, T. W. (2019). The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review. Computers and Education, 138, 101–115. https://doi.org/10.1016/j.compedu.2019.05.003

Harvey, D. (2018). MAKE WAY FOR MICRO-CREDENTIALS. Canadian HR Reporter, 31(3), 19.

Hilal, Maqsood, T., & Abdekhodaee, A. (2019). A hybrid conceptual model for BIM in FM. Construction Innovation, 19(4), 531–549. https://doi.org/10.1108/CI-05-2018-0043

Ho, & Dzeng, R.-J. (2010). Construction safety training via e-Learning: Learning effectiveness and user satisfaction. Computers and Education, 55(2), 858–867. https://doi.org/10.1016/j.compedu.2010.03.017

Hossain, M. A., Abbott, E. L. S., Chua, D. K. H., Nguyen, T. Q., & Goh, Y. M. (2018). Design-for-Safety knowledge library for BIM-integrated safety risk reviews. Automation in Construction, 94, 290–302. https://doi.org/10.1016/j.autcon.2018.07.010

Kazar, G., & Comu, S. (2021). Effectiveness of Serious Games for Safety Training: A Mixed Method Study. Journal of Construction Engineering and Management, 147(8). https://doi.org/10.1061/(asce)co.1943-7862.0002119

Kassem M., Benomran L., Teizer J. Virtual environments for safety learning in construction and engineering: seeking evidence and identifying gaps for future research, Visualization in Engineering, Springer, 5:16, 2017, http://doi.org/10.1186/s40327-017-0054-1

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic Modeling for Analyzing Impacts of Skilled Labor Shortage on Construction Project Management. Journal of Management in Engineering, 36(1). https://doi.org/10.1061/(asce)me.1943-5479.0000720

Lin, K. Y., Tsai, M. H., Gatti, U. C., Je-Chian Lin, J., Lee, C. H., & Kang, S. C. (2014). A user-centered information and communication technology (ICT) tool to improve safety inspections. Automation in Construction, 48, 53–63. https://doi.org/10.1016/j.autcon.2014.08.012

Ramani, P. V., & Arun Kumar, T. R. (2022). Developing a schedule integrated automated safety planning tool for residential construction projects. International Journal of Occupational Safety and Ergonomics. https://doi.org/10.1080/10803548.2022.2079825

Tang, N., Hu, H., Xu, F., & Zhu, F. (2019). Personalized safety instruction system for construction site based on internet technology. Safety Science, 116, 161–169. https://doi.org/10.1016/j.ssci.2019.03.001

Umer, Antwi-Afari, M. F., Li, H., Szeto, G. P. Y., & Wong, A. Y. L. (2018). The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis. International Archives of Occupational and Environmental Health, 91(2), 125–144. https://doi.org/10.1007/s00420-017-1273-4

Vitharana H., De Silva S., De Silva S. Health hazards, risk and safety practices in construction sites – a review study, Engineer - Journal of the Institution of Engineers, Sri Lanka 48(3):35 2015 DOI: 10.4038/engineer.v48i3.6840

Welch, L. S., Russell, D., Weinstock, D., & Betit, E. (2015). Best practices for health and safety technology transfer in construction. American Journal of Industrial Medicine, 58(8), 849–857. https://doi.org/10.1002/ajim.22456

Wetzel, & Thabet, W. Y. (2016). Utilizing Six Sigma to develop standard attributes for a Safety for Facilities Management (SFFM) framework. Safety Science, 89, 355–368. https://doi.org/10.1016/j.ssci.2016.07.010

Wetzel, E. M., Thabet, W. Y., & Jamerson, W. E. (2018). A CASE STUDY TOWARDS TRANSFERRING RELEVANT SAFETY INFORMATION FOR FACILITIES MAINTENANCE USING BIM (Vol. 23). Wetzel & Thabet. http://www.itcon.org/2018/3

Williams, Ochsner, M., Marshall, E., Kimmel, L., & Martino, C. (2010). The impact of a peer-led participatory health and safety training program for Latino day laborers in construction. Journal of Safety Research, 41(3), 253–261

Xing, X., Zhong, B., Luo, H., Li, H., & Wu, H. (2019). Ontology for safety risk identification in metro construction. Computers in Industry, 109, 14–30. https://doi.org/10.1016/j.compind.2019.04.001

Zhang, S., Boukamp, F., & Teizer, J. (2015). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). Automation in Construction, 52, 29–41

Zhang, Cao, T., & Zhao, X. (2017). Applying Sensor-Based Technology to Improve Construction Safety Management. Sensors (Basel, Switzerland), 17(8), 1841. https://doi.org/10.3390/s17081841

Zhang, & El-Diraby, T. E. (2012). Social Semantic Approach to Support Communication in AEC. Journal of Computing in Civil Engineering, 26(1), 90–104. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000130

Zhong, B., & Li, Y. (2015). An Ontological and Semantic Approach for the Construction Risk Inferring and Application. Journal of Intelligent and Robotic Systems: Theory and Applications, 79(3–4), 449–463