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BIM-BASED ONTOLOGICAL FRAMEWORK FOR INDIVIDUALISED SITE ACCESS VERIFICATION

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SUMMARY: *This research proposes a framework and an underpinning ontology (AccVerOnt) for the personalisation of construction safety information, instruction, and training as a means to drive a proposed construction site access verification solution. The framework incorporates established technologies, such as building information modelling and learning management systems, as a means to demonstrate a novel construction safety training solution in this regard. A methontology approach is implemented to develop the ontology. The framework as well as the underpinning ontology and the associated solution (as implemented) is evaluated by sixteen expert participants through expert interviews. A reflexive thematic analysis of the interview data is undertaken, the results of which suggest a propensity by the expert industry participants toward the solution being proposed, but an acknowledgment of the challenges associated with any attempt to implement the proposed solution at a fully personalised level at this time. Instead, having acknowledged the limitations of the delivery environment specifically in respect of hazard identification and ongoing hazard data management, as well as ongoing verification of such data against applicable regulatory frameworks, the expert participant group favoured a lesser baseline personalised version of the solution which appeared to the participants to be more commensurate with the delivery environment of the day. As a result of the findings, this research recommends a coordinated and concerted approach by relevant stakeholders to improve the conditions for the development of a mechanism by which to standardise hazard safety training content development and verification methods at the point of work site access. An end user test with twenty-two prospective end users returned only a marginal improvement in safety perception, consistent with the modest, baseline-level gains achievable in the current delivery environment.*

KEYWORDS: *ontology, individualized training, site access verification, BIM.*

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1. INTRODUCTION

The concept of smart sustainable cities is becoming increasingly important, with the UN (United Nations, 2014) projecting that by 2050, 66% of the global population will be urbanised. Mohanty et al. (2016) assert that by this time 75% of the world's energy consumption will be taking place in so called smart sustainable cities. The built environment shift towards smart and sustainable cities is in part enabled by the implementation of new digital and smart technologies, and their supporting infrastructure. This advancement poses new challenges to the process of operating the built environment and in particular, to the mitigation of emerging hazards associated with the implementation, maintenance, and management of this inherently more complex built environment.

Despite a dearth of studies proposing new ways to cope with an increase in hazards associated with the increased sophistication in the built environment, workforce safety in the construction sector is a well-researched area of study and remains global concern. Indeed, the construction sector has one of the highest rates in fatal injuries in both the developed and the developing world (Kassem et al., 2017). Efforts to improve the safety performance in the construction and engineering industry are plentiful. However, until recently studies have mainly focused on addressing safety issues on the construction site. Facilities management and in particular the operation and maintenance phase of the built asset lifecycle has a much higher rate of injury and illness when compared to all other fields of employment (Wetzel and Thabet, 2018). More effort should be dedicated to address safety risks at this stage. Safety learning and training which is widely considered as a key initiative-taking strategy to improve the safety performance of the construction sector, has received significant attention.

When concerned with hazard mitigation in the construction sector and more specifically in the FM domain, there exist a range of hazard mitigation approaches which are well embedded in professional practice, and which are underpinned by global regulatory compliance arrangements. Such regulatory requirements and associated professional practices in the UK have had a dramatic impact on work related safety outcomes since a step change in practice brought about by the introduction of the Health and Safety at Work Act in 1974. Indeed, according to the UK Health and Safety Executive, fatal injury numbers to employees have fallen by approximately 90% since the introduction of the Act. Since then, fatal injury numbers have been broadly levelled. This levelling out trend is reflected in construction sector specific fatal injury rates with an average of 36 fatalities to construction sector workers, and 5 fatalities to members of the public (occurring as a result of construction activity) each year in the past five years to 2020/21 (HSE 2021). The same levelling trend is observed also in non-fatal work-related injury rates in the construction sector in the UK, with an average of 2870 construction workers per 100000 reporting an injury in the 12-month period 2020/2021, a figure which is broadly in line with the previous period (HSE Labour Force Survey 2021).

A recent trend of levelling out of injury and fatal injury statistics in the UK construction sector when taken together with the projected compounding increase in complexity of the built environment brought about by a shift to smart and sustainable cities suggests that new more novel approaches to hazard mitigation in the construction and FM sector are required. Such novel approaches have the potential not only to positively affect flat lining construction sector safety statistics, but also to mitigate against the compounding effect of the increased complexities associated with the future smart built environment. The extent of 'personalisation' of learning and training has gained importance in recent time. Personalisation in learning and training aims to provide an 'individualised' or 'personalised' training experience that can be tailored for specific roles, tasks, sites, or clients, and more specifically to the hazards associated with such. This trend is being driven by innovators on the demand side (e.g., forward-looking clients and estate owner/operators aiming to achieve high level of health and safety (H&S) performance to meet ambitious corporate social responsibility objectives) and on the supply side (e.g., specialised learning and training providers and technology developers).

To date, key gaps in this area of study include: 1) a lack of a framework road-mapping the levels of learning and training experiences and recognising the need for personalised experiences; 2) a consensus as to what makes a learning and training experience become a personalised one; and 3) a limited availability of digitally-enabled solutions providing personalised learning and training experiences and evidence of their impact on safety performance. This research aims to address each of these gaps in turn with the overreaching aim being to develop a digitally enabled solution for personalised H&S compliance training and investigate the potential of a range of existing and emerging technologies and processes to be interfaced in order to create a novel H&S training solution which has the potential to contribute to improve H&S outcomes in the construction sector.

2. LITERATURE REVIEW

This section evaluates the existing literature position pertaining to safety in construction classified projects with a focus on projects running at the operation and maintenance (O&M) phase of the built asset lifecycle. It presents a comprehensive literature review in which the theory and reported evidence base pertaining to the potential of new and emerging technology and process to support enhanced O&M phase H&S practices are investigated.

2.1 Safety perception

Workforce H&S in both new build construction projects and 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). High rates of injuries and fatalities continue to be a persistent problem in the construction industry, putting construction companies and sector workers (especially managers) under a great deal of pressure to improve work safety in modern construction projects (Pandithawatta et al., 2023). Improved H&S technologies implementation in the construction sector at O&M phase of the asset lifecycle is needed. When assessing accident and injury rates in the context of the smart technologies roll out as a means to support smart cities implementation, it is important to consider that high accident and fatality rates in the construction sector can be attributed to hazardous environments and to rapidly changing practices (Zhang et al., 2023).

Evidently, there is a need to develop strategies to drive down construction sector accident, injury, and fatality figures, and to deal with increased complexities in processes which may serve as a mechanism to put upward pressure on such figures. H&S outcomes in construction sites have both societal and technological dependencies, specifically around the relationship between employee workplace safety perceptions and H&S outcomes, as well as workplace safety compliance and technical support provided. Zohar (1980) first investigated the concept of 'safety climate' which was defined as the influence that indicates human perception of risk. Since then, this concept has evolved building on the myriads of safety climate definitions, stating that the category (rather than the definition) of safety climate emphasises not only the safety climate itself but in addition its role in the prevention of accidents (Luo, 2020). It is this preventative aspect of safety climate which is relevant to this study. Research to explore workplace safety perception has intensified in recent years, as well as procedure and regulatory arrangements, however construction safety accident and injury rates remain comparatively high when compared with other sectors. To that end, work safety approaches enforced by legislation are not able to drive down construction fatalities, accidents, and injuries fundamentally and sufficiently because those approaches overlook the intrinsic unique features of the construction operational environment (Kim et al., 2021).

The overall responsibility for cultivating a safe worksite culture as well as ensuring that construction workers are safe is the responsibility of the employer (O'Toole 2002). Under UK regulation, these responsibilities also are shared by the principal contractor and, often the estate owner/operator. Cultivation of a safe worksite can be achieved effectively in an "optimistic and positive safety climate" at the job site (Chen, McCabe, & Hyatt, 2018). Many recent studies have contributed to the ability to quantify a safety climate based on safety indicators and evaluations of the effects of those indicators on the greater safety climate. Such studies have put forward recommendations for cultivating a positive safety climate through rigorous training to improve H&S outcomes for construction projects. According to Kim et al. (2021), despite the numerous research efforts and robust regulatory safety frameworks, the construction industry globally continues to suffer poor safety perception and health and safety outcomes (which include high rates of fatalities, accidents, and injuries).

2.2 Personalisation of H&S training

Initially referred to as personalised systems of instruction (PSI), learning personalisation was first investigated by Bloom (1956) where a system of learning was developed to encourage students to take primary responsibility for their own learning. With the emergence of the internet PSI became increasingly popular and the potential of it more far-reaching with a shift towards personalised learning via intelligent tutoring systems (Lin et al, 2014). The capability of technology to enhance personalisation of learning was identified by Johnson & Sherlock (2014) as one of the emerging technologies likely to have a significant impact on teaching and learning. So called technology enhanced learning (TEL) has for some time been anticipated as a being capable of impacting significantly on personalisation of learning capability. TEL enables a higher level of training sophistication in regard to personalisation: name recognition; self-described personalisation; segmented personalisation; cognitive-based personalisation; and whole-person personalisation (Martinez, 2002).

Following existing personalisation frameworks, individual characteristics, demographics, and other personal information is used to deliver an individualized TEL approach (FitzGerald et al., 2018). The availability of data to determine the optimal teaching approach and delivery is key to appropriate learning outcomes. This research focuses on the 'how' of the training personalisation, looking at its technical aspects, and creating the appropriate links to the construction information environment. While the authors recognize the importance of learning in a social context, this research takes content focus, considering the external factors, rather than the individual social needs, as a driver of personalisation of learning content. Social aspects of training have been extensively researched across the field, with numerous methods available to improve learning outcomes through these means (Mikic et al., 2022).

Considering H&S training, contextual information is key to impactful delivery, however teaching practice follows a one-size-fits-all approach to learning, be that either the individual or the work environment. Single set instructions and regulations determine the knowledge to acquire for specific site activities and situations. The learning process is completely detached from the individual learning capabilities, aptitudes and interests, as well as the construction site or built environment in which the hazardous activities may be found. This was identified as a key challenge for future H&S training as built environments become more hazardous due to their increased complexity (Mote et al., 2016).

Incorporating safety data within BIM methodologies supports the integration of occupational hazards into BIM and following safety regulations at the design stage showed a decrease in occupational accidents (Cortes-Perez et al., 2020). Researchers have shown recently the importance of including safety knowledge as early as possible in construction projects to improve H&S outcomes. Collinge et al. (2022) found that the development of a BIM safety risk library facilitated 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. Nonetheless, digital BIM approaches on their own are not able to leverage safety knowledge and regulations in an integrated way that impacts H&S outcomes and the safety perception of workers onsite. Personalised approaches require easy and timely access to safety data of construction environments that determines the correct approach to each training delivery based on external factors.

Studies have proposed personalized feedback through virtual reality training (Wolf et al. 2022), optimization-based VR training scene synthesis (Li et al., 2022) and training content recommendation based on workers' personal characteristics and learning needs (Duan et al., 2024). Undoubtedly, significant advances have been made to address the shortcomings of conventional pedagogic approaches in construction safety training. Immersive approaches, and virtual reality in particular, are the most prominent in this literature, and reviews report them to be at least as effective as, and often more engaging than, conventional handout- and classroom-based methods (Kassem et al., 2017; Man et al., 2024). They are not, however, the only route, and most safety delivery frameworks are agnostic to the delivery medium. The provision of suitable training materials is crucial in preparing construction workers for the safety risks inherent in their work environments. Ding et al. (2016) investigated the potential of ontology and semantic web technologies to enable the representation of construction safety hazard data semantically and demonstrated the potential of BIM to strengthen outcomes in the sematic modelling of the construction safety domain. The focus of the study was on the strength of an ontology-based methodology as a means to establish a mechanism by which to facilitate safety knowledge reuse in the construction domain, which will be explored in the following subsections.

2.3 BIM in construction safety

BIM provides a structured, object-oriented digital representation of a built asset across its lifecycle, in which geometry, component data, and associated metadata are federated in a single model (Volk et al., 2014). This makes BIM a natural repository for safety- and hazard-relevant information: data can be attached to, and later queried against, the specific elements, systems, and spaces to which it applies, and exchanged between platforms through industry-standard schemas such as IFC and COBie (Pauwels et al., 2017). It is this element-level association of data that allows safety information to be filtered and delivered in a targeted way rather than as undifferentiated documentation. The approach has been used to link safety risks to treatments under a Prevention-through-Design logic (Collinge et al., 2022) and to manage occupational hazards across the construction and maintenance phases (Cortés-Pérez et al., 2020).

BIM alone, however, is limited as a reasoning substrate. The IFC schema is oriented towards the representation and exchange of geometry, object types, and property sets, and expressing safety knowledge, e.g, which hazards arise from which tasks under which conditions, and which controls mitigate them, quickly exceeds what BIM supports. This has motivated the translation of IFC into web-ontology form (ifcOWL) and, more broadly, the use of semantic approaches alongside BIM so that model data can participate in inference, rule-based checking, and semantic querying (Pauwels and Terkaj, 2016; Pauwels et al., 2017). In practice, BIM models are retained as the geometric and instance backbone and aligned through shared identifiers to a domain safety ontology. Data is linked such that BIM supplies the *what* and *where* as instance data, while the ontology supplies the domain meaning and the rules that follow from it, allowing a reasoner to derive the hazards and controls applicable to a given safety-related task. The specific ontology models proposed for construction safety, and their scope and limitations, are examined in the following subsection.

Within the BIM safety literature, coverage is uneven across the asset lifecycle. Review evidence indicates that work is overwhelmingly design-centric, with fall-related hazards dominating because they are the most readily represented geometrically, and with comparatively little addressing the operation and maintenance (O&M) phase (He et al., 2026). This is relevant because O&M is where the present study is positioned: facilities maintenance workers face elevated risks of falls, electrical injury, crushing, and cuts, yet the onus typically rests on the individual to assimilate a large body of generic training and documentation and apply the relevant parts to each task (Wetzel and Thabet, 2015). Wetzel and Thabet (2018) demonstrate the transfer of safety-relevant information into a BIM-based repository for facilities maintenance while noting the interoperability and data-structuring difficulties that continue to constrain uptake. The framework proposed here builds on the BIM–ontology coupling described above, using the element-level hazard data held in the model as the basis for personalising the safety information a worker receives at the point of site access.

2.4 Ontology models in construction safety

Gruber (1993) defined ontology as "an explicit and formal specification of a conceptualization." In recent years, ontologies have been adopted in many business and scientific communities as a way to share, reuse, and process domain knowledge. The main areas, in which ontological modelling is applied, include communication and knowledge sharing, logic inference and reasoning, and knowledge reuse. Zhang et al. (2015) initially proposed a construction knowledge ontology where safety related knowledge and project specific information were linked to support job hazard analysis and visualization of hazards as a first step towards automated safety planning using BIM. Since then, combinations of formalized safety knowledge alongside project information through BIM have evidenced the capability of such approaches to enhance safety management. As an example of utilising an ontological approach, Xing et al. (2019) proposed a mechanism by which to formalise safety risk knowledge in metro construction to support safety risk identification. In this case the researchers leverage an ontological approach to enable improved risk identification processing in an otherwise "*ill structurally stored*" and "*disorganised format*". Here the proposed ontology (SafetyRiskIdentification-Onto) is applied such that safety risk information is more readily available to those who need and are responsible for it, in both a timely and contextual fashion. A similar approach is used in prefabricated building construction by Shen et al. (2022). The researchers though stop short of explaining by what mechanism the information would be reported back to those to whom it would be useful.

More recently, Johansen et al. (2023) present a 4D BIM-based model and construction safety ontology covering falls from height and struck by a falling object, which are the two most frequently occurring construction site accidents. The ontology model is designed to enable a construction safety community to test and compare alternative automated hazard identification methods. The study implements empirical evaluation in an attempt to evidence differences in the safety perception among different construction schedules on the same project. IFC data schema is proposed as a mechanism by which to benchmark and reuse hazard data which incorporate hazard representation alongside safety ontologies. Pandithawatta et al. (2023) also propose a construction safety ontology for automating JHA. The intensive nature of JHA development as well as the reliance on experience knowledge are argued as drivers for automation. The value of the ontology in enabling query response is demonstrated by establishing clear relationships between job steps and external conditions to determine primary and secondary hazards before outputting control measures. Indeed, ontologies have supported structuring safety data in an effort to facilitate key information at the right time to the right stakeholders. From a safety training perspective, learning from accidents and hazard risks is essential in preventing their recurrence and training tools need to be facilitated access to such information. Pedro el al. (2024) recently formulated an ontology-based framework that enhances learning approaches, in this case a virtual reality scenario, with safety data contributing to improved safety outcomes. This work has major implications not only for workers on the jobsite, but also in tertiary construction safety education, which often fails to prepare learners for the safety challenges and demands of construction jobsites.

2.5 Research gaps

The literature highlights persistent safety challenges in the construction industry, particularly during both new builds and operations and maintenance (O&M) phases. Despite regulatory frameworks and technological interventions, high rates of injuries and fatalities continue due to hazardous environments and complex operational processes. Existing approaches often neglect the nuanced relationship between workers' safety perceptions, compliance behaviours, and the organizational safety climate. While there is growing recognition of the importance of cultivating a positive safety climate through training and managerial responsibility, the sector still lacks integrated strategies that account for both the societal and technological dependencies influencing safety outcomes. As such, a research gap exists in understanding how safety perception and climate can be leveraged more effectively to reduce incidents, especially when paired with technological advances like smart construction tools.

Another critical gap lies in the personalisation of health and safety (H&S) training. Despite the emergence of technology-enhanced learning (TEL) and virtual reality (VR)-based training, current H&S education remains largely generic, failing to address the diversity of learners and the specific contexts of construction sites. Standardized instruction overlooks individual capabilities and environmental variables that impact learning effectiveness. Although BIM-integrated systems and safety ontologies have advanced data structuring and hazard visualization, the mechanisms for real-time, context-aware personalisation of training remain underdeveloped. Furthermore, while ontologies support knowledge reuse and risk identification, their integration into adaptive training systems that dynamically tailor content based on site conditions and individual profiles is still limited. Thus, further research is needed to bridge TEL, ontologies, and personalized, data-driven H&S training frameworks.

3. RESEARCH METHODOLOGY

The primary goal of the study is to develop an ontology-enabled access verification system that integrates health and safety data following a personalized approach. To accomplish this goal, this research adopts a design science research method (DSR), which has been applied to the field of construction information successfully (Hevner et al., 2010). DSR has been widely used as a robust methodology for applied research in the construction domain due to its emphasis on iterative problem solving. This study follows the DSR process with the sequential steps of problem identification, objective definition, solution design, demonstration, evaluation, and communication (as partially illustrated in Figure 1). This approach provides a systematic approach for the development of an artifact that enables the research goals.

Reflecting the three gaps identified above, this study is guided by three research questions: RQ1: Can a framework and underpinning ontology roadmap the levels of personalised safety information, instruction, and training and formalise what constitutes a personalised experience for construction site access verification? RQ2: To what extent do domain experts regard such a personalised, ontology-enabled solution as valuable and as appropriate to the current operation and maintenance delivery environment? RQ3: What level of personalisation is realistically supportable given the current maturity of hazard identification, hazard-data management, and safety-training standardisation?

The problem identification step, from which the study's objectives are derived, centred on an analysis of how construction safety training is currently specified and delivered to visiting contractors at the point of site access, indicated as H&S Training Process Analysis in Figure 1. This examined the existing site access verification arrangements and the predominantly one-size-fits-all training route, and characterised the trajectory from generalised, legally required training towards a personalised provision. Considered alongside the reviewed literature, the analysis established the practical basis of the problem, that being safety training is delivered generically rather than according to the worker, task, and built-environment context. Thus, informing the objectives and requirements subsequently formalised in the AccVerOnt ontology and its supporting framework.

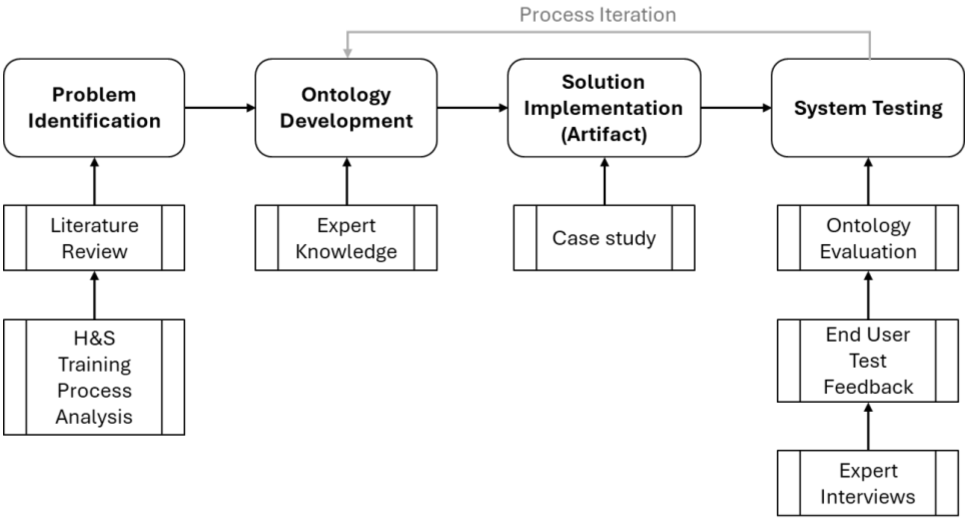

Figure 1: Research methodology for this study (based on design science research steps).

3.1 Ontology Development Methodology

There are many documented methodologies for developing ontology models (Jiang et al. 2020), many of which are widely researched and evaluated. In the case of the identified core ontology development for construction safety studies reviewed as part of the literature review for this research, methontology is adopted by the two most recent studies, Johansen et al. (2023) and Pandithawatta et al. (2023). This study will follow up on the same methodology that has been successful in previous studies, and the ontology development will follow up 'methontology' to conceptualize, develop, and evaluate the proposed ontology, AccVerOnt (Access Verification Ontology).

This approach presents a well-structured framework to develop ontologies from scratch by enlisting and tracking the activities necessary in an ontology development process. These activities are classified into six stages: ontology specification, knowledge acquisition, knowledge conceptualization, knowledge formalization, ontology evaluation, and ontology verification and validation. First, its scope is specified in the ontology specification stage by describing and assembling the general aspects such as ontology domain, the purpose of ontology, its intended users, level of formality, and several key terms. A conceptual model is then developed in the second phase – involving organization and modelling of the raw data gathered in accordance with the scope during the knowledge acquisition stage in a more formal and structured form. A glossary of terms describing physical and conceptual objects related to each knowledge domain is created in tabular or graphical form. A conceptual model (taxonomy) is converted to a formal model (computable) in the ontology formalization phase. Domain specific concepts and sub-concepts are defined in this stage.

Finally, to test the correctness and coherence and detect the incompleteness, inconsistencies, and redundancies, the formal ontology is evaluated. The evaluation process is carried out during each phase, between the phases, and at the end and it involves validation and verification. Verification refers to ''building the system right" and involves a technical process that ensures that the ontology is built correctly as per the requirements established during the specification phase. Whereas validation refers to ''building the right system." It ensures that the ontology corresponds to the system that it represents and guarantees that the designed ontology performs correctly with an acceptable level of accuracy by checking the quality of the solutions when the system is queried.

3.2 System Evaluation

The core final evaluative component of the methontology will be undertaken based on expert insight and knowledge collected via the means of interviewing and a short-associated questionnaire, implementing a mixed but predominantly qualitative approach. In addition, expected end users will be questioned regarding safety perception of the new proposed solution.

According to Saunders and Townsend (2016), interviews are classified into three types: (1) structured, (2) semi structured, and (3) unstructured interviews. Structured interviews implement a set of pre-determined standardised questions. Unstructured interviews implement a set of unstandardized questions usually to explore a topic with which the research has strong familiarity. Interviewees are encouraged to respond freely regarding questions put to them. Semi structured interviews occupy the centre position between the two and the researcher is guided by a list of questions and related themes. This research incorporates semi structured interviews with a range of participants as part of the evaluation phases of the research design.

This study has interviewed participants of high senior roles in the fields of facilities management, estate management, construction technology, H&S management and compliance, construction retrofitting, BIM, and learning management systems. A total of 16 interviewees have provided their expert opinion onto the following 4 key areas: 1) importance of individualized construction safety training; 2) the reality of the perceived solution delivery knowledge (ontology); 3) the value of the proposed framework; and 4) the readiness/maturity of the delivery environment for a solution roll out. The gathered data is then evaluated through a reflexive thematic analysis (RTA). According to Clarke & Braun (2017), thematic analysis is a method for identifying, analysing, and interpreting patterns of meaning, collectively called themes as identifiable within qualitative data. RTA allows the researchers to be part of the knowledge generation process, which is relevant to reduce subjectivity in the interviewee's views on innovation and domain knowledge.

4. PROPOSED SOLUTION

This section focuses on the development of the digitally enabled construction safety framework and related ontology following the aforementioned methodology. The purpose of the framework is to demonstrate an approach by which a personalised safety instruction and training may be made functional and leveraged to support improvements in site access verification arrangements for the O&M built asset lifecycle phase. The proposed solution seeks to build on existing research in the personalized safety instruction management (PSIM) system domain. The solution seeks to extend the principles of PSIM, that being the provision of personalised safety instruction and training considering the features of both the job and the individual worker (Tang et al., 2019). The existing research position as established in the PSIM literature will be extended to include features which enable additional contextual H&S information and training to be communicated dynamically to the individual operative and according to specific job information. Thus, the extension being proposed "personalises" the individual user experience for the purposes of providing highly contextualised and timely instruction and training. In addition, the solution will have the ability to check certain individual credentials, such as a trade-specific safety certificates, thus digitising hitherto administrative 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 verified (clear for access) site access status to the individual worker profile and as such to the individual. This is to ensure that construction workers presenting for construction classification jobs on client estates at O&M phase are best informed in a timely and contextual fashion as to the specific hazards which may be encountered during the course of the specific job instance.

4.1 AccVerOnt: Access verification ontology

Following the steps mentioned in section 3, formulation of the access verification ontology (AccVerOnt) is carried out. The purpose of AccVerOnt is to structure, model, and store relevant H&S related site access verification (SAV) systems knowledge and use it to enable the development of an access verification process design specifically for construction classified projects being undertaken during the O&M phase of the built asset lifecycle. The ontology focuses specifically on the O&M phase of the built asset lifecycle and is concerned exclusively with construction classified tasks. The level of granularity is directly linked with UK Government regulation pertaining to construction classified tasks, and the associated H&S legislation which applies to such tasks. In addition, the ontology is concerned with best practice for the domain. The conceptualization of AccVerOnt is illustrated in Figure 2, with each domain is described below.

The knowledge used to populate AccVerOnt is acquired, following the METHONTOLOGY support activities, from three principal sources: the reviewed literature, domain expert input, and existing ontologies and schemas identified for reuse. The literature review establishes the regulatory underpinnings of construction H&S and the role of enabling technologies, while engagement with domain experts and practice grounded the ontology in the reality of site access verification delivery environment. On this basis, the domain is structured around the safety documentation and classifications used in practice: regulatory and best-practice job safety documentation, namely Risk Assessment and Method Statements (RAMS) and permits to work, are represented as classes within the Job domain and can be set as completion requirements for an individual, and Uniclass, the predominant open, non-proprietary classification in UK BIM, is adopted to link the ontology to the BIM model, allowing hazard data to be structured and stored at both spatial (area) and object (element) level. Existing safety ontologies and schemas identified through the integration step are reused or adapted where appropriate rather than rebuilt, and the resulting draft domain concepts formed the input to the conceptualisation phase.

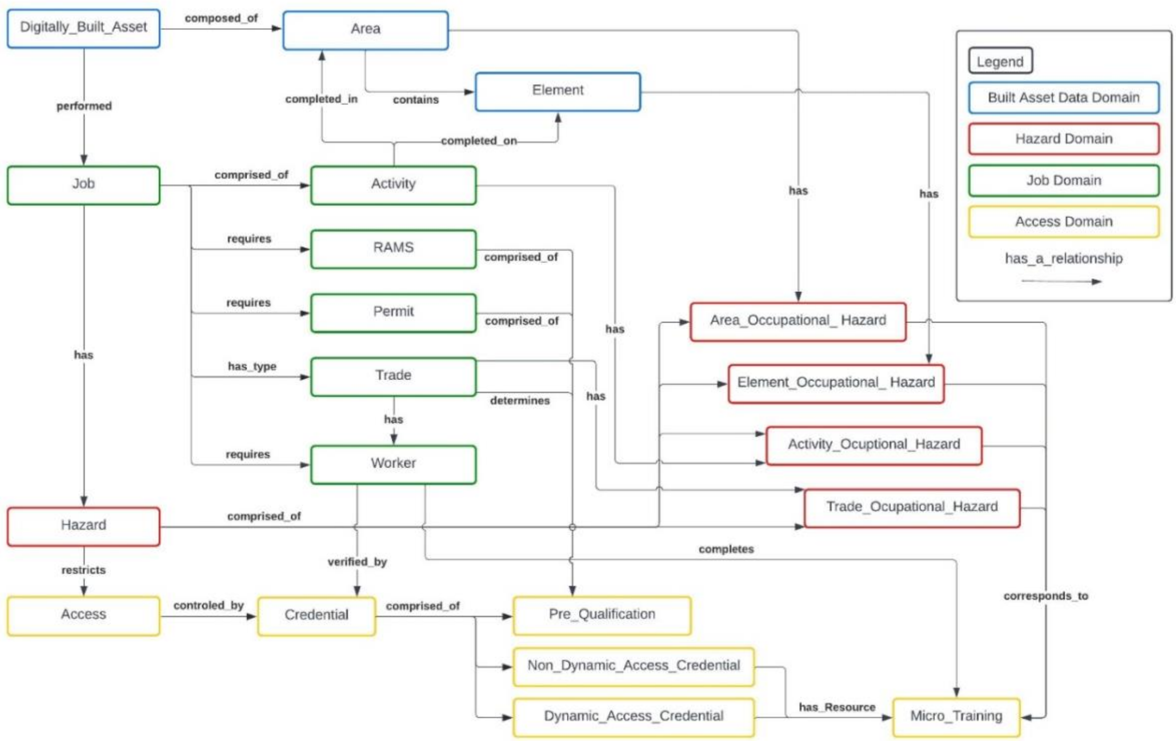

Figure 2: Ontology concept for AccVerOnt.

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.

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.

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.

Access Domain: The ‘Access ‘domain is made up of data classes 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.

4.2 Digitally enabled framework for site access verification

The framework presented in Figure 3 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.

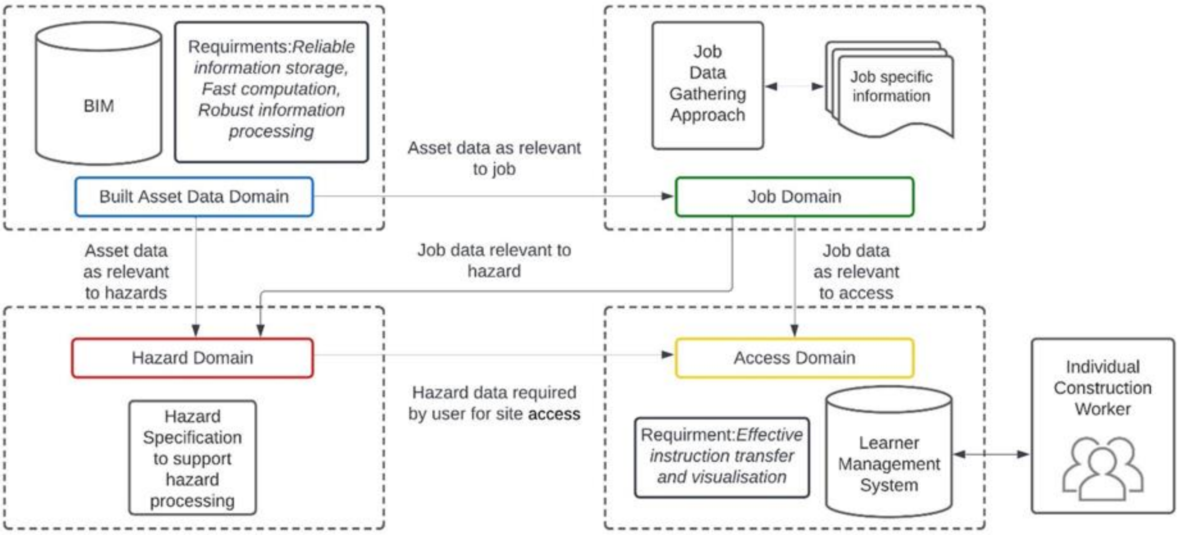

Figure 3: Framework for improving safety in construction classified projects at the operational phase of built assets.

The Built Asset Data domain underpins the framework by enabling hazard data to be structured, stored, and queried according to job specifics. BIM is identified as a critical process for hazard data storage, leveraging Uniclass for non-proprietary classification. This ensures data can be organized by area (where work occurs) and element (building components worked on). BIM's capacity for robust hazard information processing and querying supports construction safety and framework functionality. By integrating BIM with hazard data, the framework facilitates hazard mitigation and system operability, serving as a key interface between the digitally built asset and hazard/job domains.

Table 1: Sample 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

The Job domain is central to the framework, enabling hazard relevance to be determined for specific job instances and individuals. It facilitates personalisation by gathering, storing, and linking job-specific data, including job details (start/end dates, area/element worked on, trade type, job ID) and contractor identifiers like email addresses. While current practices typically use contractor names, email addresses can enhance data linking for personalisation. By integrating job data with hazard and built asset domains, the framework enables querying for hazard relevance to specific jobs. This ensures estate access is contingent on personalized criteria, enhancing safety and task-specific data application.

The Hazard domain is concerned with the assignment of hazard data, as relevant to the individual, via the job domain and according to the specifics of the job to be completed. The Hazard domain relies on data as appropriate from the Built Asset Data domain, regarding area and element data, and relies on data from the Job domain regarding activity and trade data. The data assigned at the Hazard domain as determined by data supplied by the Built Asset and Job domains is subsequently supplied out the Access domain. Here corresponding training content is able to be made available to the individual such that completion data may be able to be recorded, such that any required credentials as set are able to be demonstrated and recorded as having been met (or not). An illustration of data relation across the domains (Built Asset Data, Job Data, and Hazard Data) is shown in Table 1.

Finally, the Access domain establishes an effective hazard information, instruction, and training transfer as a learning management system (LMS). LMS platforms can be adapted to assign personalized hazard data to users by linking hazard IDs with relevant training content. This allows the system to publish task-specific safety training and set completion requirements for credentials. The LMS ensures that training completion and credential validity can control access to work sites. By integrating data from the Job, Hazard, and Built Asset domains, the LMS aligns hazards with personalized safety content.

4.3 Solution architecture

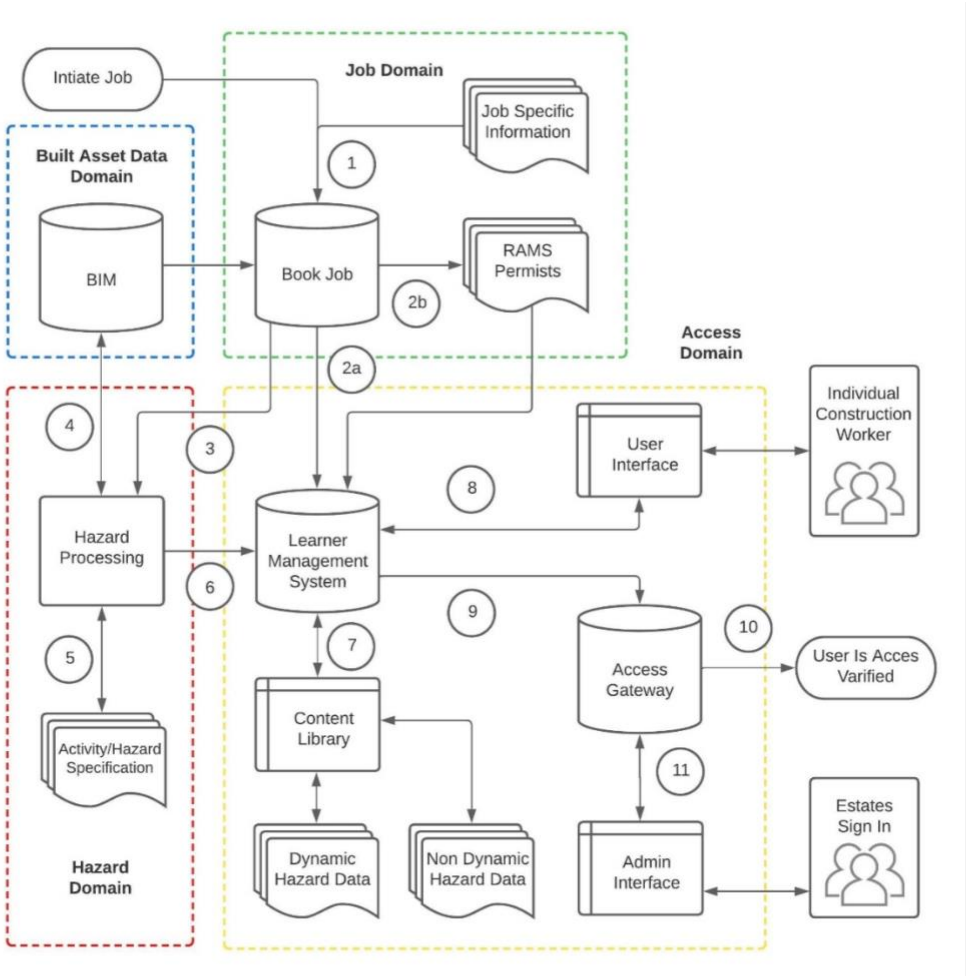

Figure 4: Solution architecture.

Figure 4 shows a representation of the architecture by which individual construction worker safety information instruction and training personalisation journey is proposed to be made possible. The architecture is built on the proposed technology enabled safety framework. This solution can be implemented through the following sequence: 1) book a job instance and assign the required data for processing as required by the ontology (job dependent); 2a) send the data to the LMS so that safety information can drive personalized instruction and training; 2b) pass RAMS and required permit data to the LMS under the job instance; 3) initiate hazard processing leveraging activity and hazard specifications; 4) query BIM in regard to hazard data at the areas and elements relevant to the job instance; 5) query activity and hazard specification to establish hazard data as being relevant (or not) to the job activity type; 6) send the hazard data to the LMS; 7) assign relevant content (dynamic and non-dynamic) based on the job instance and hazard data; 8) user completes required content and accesses/uploads relevant documentation; 9) user completion data passed to the estate gateway for user access verification; 10) user estate access is verified for the job instance; 11) estates check for individual user access verification status.

Figure 5 shows the solution from an end user perspective of the LMS according to a work-based scenario whereby a user was assigned to a job located on the roof of a building. The job scenario required work to be done on a roof-mounted component of a mechanical ventilation system. 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, as such 'Working at Height' hazard is reported. The information model also contains 'Risk of Shock' hazard data as assigned to the mechanical ventilation. 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. Figure 5 shows how the corresponding hazard safety training content is displayed and accessed on the personal home page of the individual construction worker. Note that hazard data duplicated in the report (Risk of Shock), on account that hazard occurs and is assigned both to the Element and Activity listed under the 'Job' data, is not duplicated in the corresponding hazard safety training. Note also that the user personal homepage also contains a RAMS review credential, this is comprised of the Risk Assessment and Method Statement data as assigned to the 'Job' under the RAMS class. Once all training is completed, site access verification would be checked by the estates manager and its outcome communicated to the user.

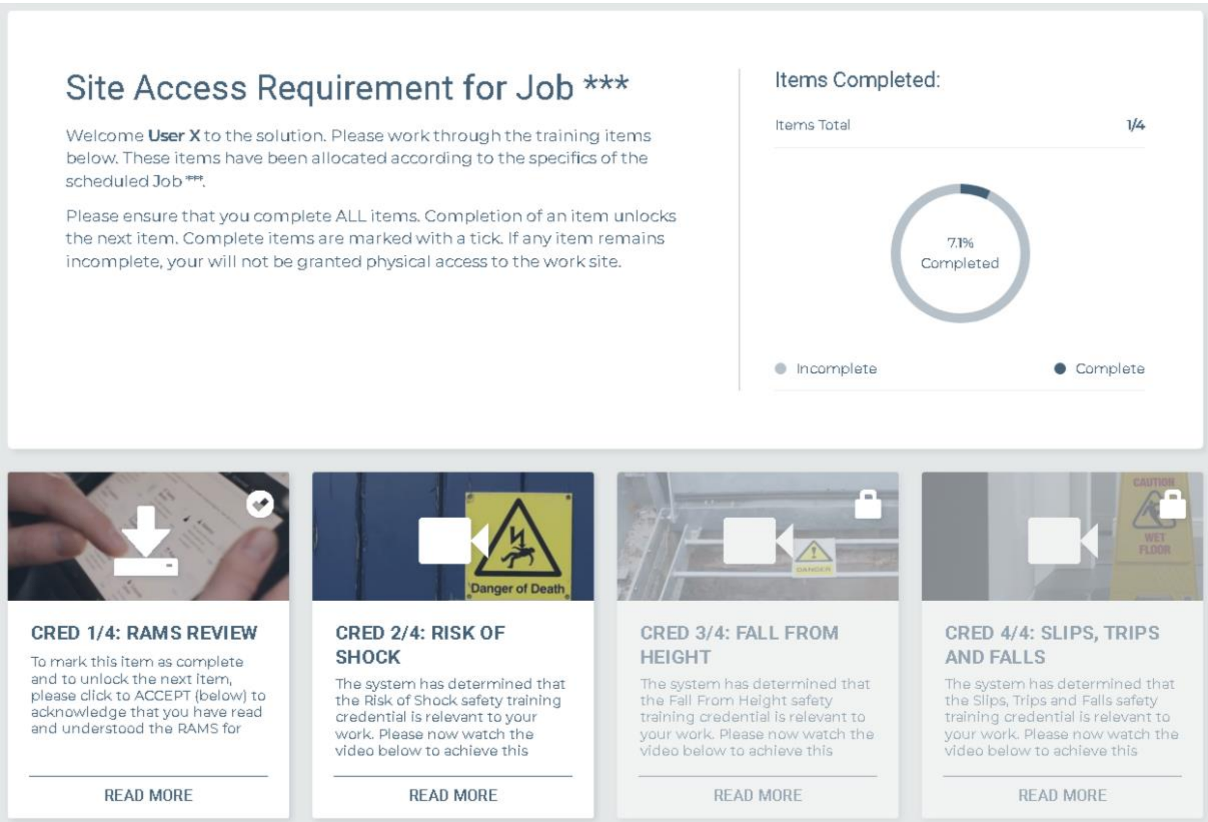

Figure 5: Individualised hazard safety training content.

5. SOLUTION EVALUATION AND DISCUSSION

According to the adopted research methodology, the proposed framework and associated ontology are evaluated. As per the research design, this phase is undertaken by the means of an applied research thematic analysis (RTA) performed on expert interview data as gathered through an expert interview process and its associated research questionnaire. The evaluation process also incorporates an end user test of a pilot version of the associated solution as enabled by the proposed framework.

5.1 Expert panel and questionnaire

So that expert participant competencies could be established, a questionnaire is completed by each participant after their participation in the interview process. Here, the participants self-selected at least one or more competencies from a predefined list of qualifying competencies which participants believed applied to them. Note that as part of the purposeful sampling approach and prior to enrolment in the expert interview process, participants confirmed that a minimum of one of the qualifying competencies is applicable to them. Prior to questioning, each expert session opened with a standardised presentation, providing an overview of personalised safety training for site access verification and the proposed framework and its underpinning ontology at a conceptual level. This overview ensures that participants share a common understanding of the domain and the proposed solution. The same standardised presentation and interview format are applied consistently across all expert sessions.

In addition, as part of the questionnaire, participants are asked to reflect on the four key interview areas: 1) importance of the individualised construction safety training concept as a component of construction classified H&S approaches; 2) the reality of the perceived solution delivery environment (accuracy of the framework and associated ontology); 3) value of the proposed solution and opportunities to improve; 4) readiness/maturity of the delivery environment for a solution roll out. The feedback data is initiated by the researcher asking each respondent to rate a particular area or item on a scale of 1-10. This mechanism is applied both as a means to facilitate reflection here and to collect illustrative quantitative data regarding expert response.

Table 2: Expert participant self-identified core competencies.

	Experience		Role Classification					Core Competencies of Participants										
Job Title	Yrs Experience in Sector	Yrs Experience in Post	Construction Supply	FM Supply	EM/FM Estates	Construction Technologies	LMS	FM	Estates Management	Construction Design	Construction Scheduling	Construction Technology	Compliance	H&S	Retrofitting	BIM	LMS	Site Induction Total
Technical Manager	28	8	✓										✓	✓				144
Procurement Manager	6	2	✓					✓	✓		✓	✓		✓		✓		46
Head of HSEQ	20	2		✓				✓					✓	✓			✓	900
H&S Business Partner	13	5			✓			✓		✓		✓	✓	✓			✓	1000
Asbestos Compliance Manager	10	1			✓			✓										1500
ESHQ Group Lead	8	8		✓				✓		✓			✓	✓				N/A
Senior Facilities Manager	7	3			✓			✓	✓	✓					✓			43
CEO	20	5				✓				✓		✓	✓	✓				N/A
H&S Training Consultant	10	7		✓				✓	✓				✓	✓				N/A
Senior Digital Consultant	8	3		✓												✓		N/A
Head of Governance and Compliance	20	2			✓				✓				✓	✓				1200
Head of H&S	15	1			✓									✓				130
eLearning Manager	12	12					✓										✓	N/A
Head of Maintenance	50	3			✓			✓	✓	✓		✓		✓	✓			540
H&S Manager	50	4			✓				✓					✓				12000
Estates Safety Coordinator	34	15			✓								✓	✓				534
Total	311	81	2	4	8	1	1	8	6	5	1	4	8	12	2	2	4	18037

The results of the core competencies questionnaire are given in Table 2 above. The table also includes data about the participant's experience (both in the sector as well as current post) and, where applicable, gives data about the number of individual contractors for whom each participant has legal responsibility in respect of visiting contractor site/estate inductions on a per annum basis. The total inductions for which participants collectively have some degree of legal responsibility for is 18037, a figure which represents approximately 0.84% of the total UK construction workforce (2.1 million). The participants held a collective tally of 251 years' experience in the sector with a collective tally of 81 years' experience in current posts. The distribution of competencies is varied, but has a clear predetermination to FM, compliance, and H&S.

Table 3 shows the estate experts self-selected rating of current organisational position against the personalisation safety information, instruction, and training pathway (expressed as 'Personalisation in Safety Training Position'). Of those representatives, two estimate the organisational position to be at legally required training, three identify the organisational position at industry standard, and three position the organisation at baseline personalised training. The average current rating being 'Industry Standard'. When they are asked to rank organisational aspiration against the personalisation safety information, instruction, and training pathway (expressed as 'Personalisation in Safety Training Aspiration'), one of the eight estate side expert participants expresses no organisational desire to improve the current rating, while seven participants express an organisational desire to improve the rating by a minimum of one level and a maximum of four levels. The average aspiration rating is 4.25 indicating that of the estate's representatives taking part in the research there is a desire to increase the safety personalisation journey for visiting contractors. Table 3 also shows the participant ratings for each of the core discussion areas. Participants are asked to rate each area on a scale of 1-10 (1 being the lowest). When rating the safety training personalisation concept, participants gave an average rating of 8.25. Regarding the appropriateness of the proposed ontology relative to the participant perception of the ontological domain, participants rated the ontology on average 7.125. Regarding the value of the proposed solution (and the enabling framework) the participants rated an average of 8. Participants rate the potential to further enhance the solution an average of 8.063 and finally rated the potential of ubiquitous technologies to speed up adoption of the solution in the absence of a fully digitised built environment such to drive the proposed solution as 7.875.

Table 3: Expert participant post position and aspiration and key theme ratings.

	Position Expressed by Estate Reps.		Participant Rating of Key Interview Themes				
Job Title	**Current PST Position**	**PST Aspiration**	**Concept**	**Ontology**	**Value of the Solution**	**Potential for Improvement**	**Potential to Speed up Adoption**
Technical Manager			8	7	7	9	8
Procurement Manager			10	10	10	10	10
Head of HSEQ			7	5	5	5	5
H&S Business Partner	3	4	8	6	9	8	8
Asbestos Compliance Manager	2	5	10	9	10	9	10
ESHQ Group Lead			8	8	7	7	7
Senior Facilities Manager	3	5	7	7	8	9	7
CEO			8	6	7	9	9
H&S Training Consultant			10	8	10	8	8
Senior Digital Consultant			8	7	9	8	6
Head of Governance and Compliance	1	3	8	8	8	9	9
Head of H&S	1	5	8	7	9	6	8
eLearning Manager			10	9	9	9	9
Head of Maintenance	2	5	10	9	8	8	8
H&S Manager	3	5	8	7	8	8	7
Estates Safety Coordinator	2	2	4	1	4	7	7
Average	2.125	4.25	8.25	7.125	8	8.063	7.875
Standard Deviation	0.781	1.09	1.521	2.027	1.658	1.248	1.317

5.2 Reflexive thematic analysis

In order that the qualitative data gathered via the expert interview process can be evaluated and reported as a means to address the related research questions, a reflexive thematic analysis (RTA) approach is applied. The approach accounts for the reflexive interpretations of the researchers (as experts in the process) as well as allowing for the researchers to perform the role of knowledge generator, itself a particularly important component of the defined approach. The knowledge generator role assumed during this process by the researchers is of particular importance to this study on account that the main research focus is on a domain innovation. While experts in the domain may be able to formulate a view on the innovation, the domain experts can not necessarily perform the role of innovation expert in the absence of the knowledge generator (the researchers). The reflexive analysis as performed is presented as a six-phase process: 1) data familiarisation, 2) code generation, 3) theme generation, 4) theme review, 5) theme definition, 6) RTA report.

Data Familiarisation: this phase allows to gain rich understanding of the interview data by manual analysis of the interview transcripts. Digital copies of the transcripts were subject to multiple read-throughs, with multiple notes and annotations added about initial causal observations. The key emergent concepts at this phase are four-fold. First, a general propensity of the participant group toward the concept of personalisation of safety information, instruction, and training is evident. Participants appear to value the general concept and recognise the potential of such to add value to the construction H&S at O&M phase domain. Secondly, there appears to be an acknowledgement of the challenges pertaining to a potential roll out of the proposed solution into the operational environment. Multiple participants on both the supply and estate side discussed the challenges associated with "staying up to speed with regulation", as well as "initial hazard identification". Thirdly, there appears to be a propensity of participants on the supply side toward cost, especially on the human resource cost for visiting contractors to estates where such a process may be implemented. Finally, there appears from the initial familiarisation phase to be a number of technical concerns relating to any potential implementation of the proposed solution, with one supply side representative quoting "an already complex delivery environment" on the supply side.

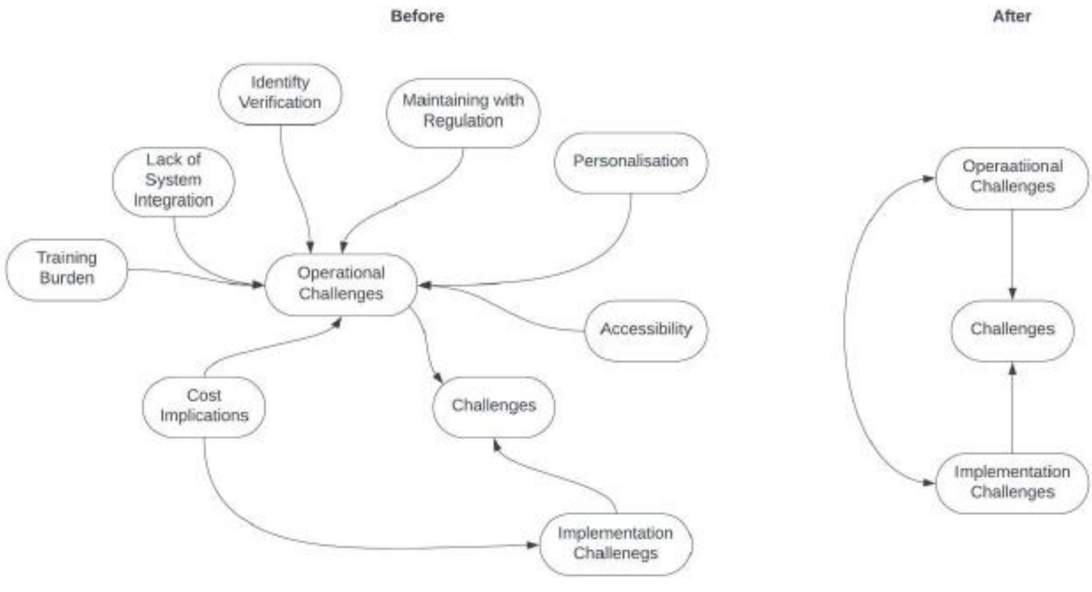

Figure 6: Sample of Code Condensing on the 'Challenges' Category.

Code Generation: In order to generate an initial code list, an OpenAI tool (Atlas TI) is employed. This enables to focus efforts on the thematic analysis from an existing machine drafted code base. Before feeding the expert interview transcripts into the OpenAI tool, some basic language classification is required. Each transcript is reviewed to remove ambiguous language instances as used by the participants during the interview process and language that may not be able to be interpreted by the coding reasoner, such as uses of the terms "they", "them", "their" and "they're", where the participant is referring to a particular group but where there is nothing explicit in the written text such that the generative pre-trained transformer OpenAI tool could link the statement to the intended group. This is also to ensure consistency in the language used across the interviews. Upon completion of the language classification review, the transcripts are fed into the reasoner for analysis. The initial OpenAI generative pre-trained transformer code list is enormously expansive. 763 codes are attributed to 508 data items (quotations) across 12 categories. As part of phase two, the expansive code base is condensed through an iterative process. The manual iterations are looking for patterns in the code base which may enable multiple codes from the expansive list to be dismissed, merged, or renamed, as well as addressing the limitations of the OpenAI algorithm. For example, it does not appear to be able to distinguish positive comments from negative comments or to differentiate meaning in similar or same language. The iterative code reduction process brought down the number of categories from 10 to 5 and the number of codes from 763 to 19 in 6 manual iterations.

Theme Generation: with lower number of codes and categories, the remaining data is reviewed again to determine a set of candidate themes. The foci are set on thin codes, where only a single or a couple of data items are attributed. Condensing the codes available aim to rationalize and provide a more concise thematic analysis inferring only on robust categories. An example of code condensing that generate a theme is shown in Figure 6. For all categories, a similar approach is followed to reduce the codes and relationships within all categories. As a result of this phase the researcher arrived at seven candidate super-ordinate themes (hitherto described as categories), and 24 subordinate themes (hitherto described as code classifications).

Theme Review: Each category brought forward to this stage is considered as a candidate super-ordinate theme, each code is considered as a sub-ordinate theme. As part of this iteration, merging super-ordinate and sub-ordinate themes is considered so as to further condense the emerging thematic framework. The result of this phase is a thematic framework which visually represents the decided upon super-ordinate themes. When taken together, the super-ordinate themes (henceforth themes) and sub-ordinate themes (henceforth sub-themes) collectively create an explicit narrative that is consistent with the broader data items (quotations as identified). As a result of this review phase, five functional themes are proposed (with two non-functions but contextualising/categorising themes also retained). A total of 19 sub-themes are proposed. **Table 4** presents the proposed themes, sub-themes, and data item instance data.

Table 4: List of Themes and Associated Data Items.

Theme	Sub-themes	Total Data Items	
Benefits / Efficiency	*Auditing*	5	20
	Automation	3	
	Efficient Communication	9	
	Productivity	3	
Benefits / Value	*Challenging Outdated Process*	5	42
	Effective Communication and Information Access	5	
	Personalisation	14	
	Responsibility	9	
	Value of Training	9	
Challenges	*Hazard Data Management*	9	48
	Hazard Identification	9	
	Implementation Challenges	3	
	Operational Challenges	27	
Information Management	*Data Quality*	11	13
	Data Standards	2	
Safety	*Hazard Response*	2	20
	Competency	5	
	Culture	4	
	Hazard Mitigation	9	

A thematic framework is then put forward as a visual representation of the selected themes and their relationships. A graphic representation is given in Figure 7. It is interesting to note that the relationship between *challenges* and *benefits* is indirect, going through *safety* and *information management* while the *value* of the proposition is directly linked to *safety* and the *efficiency* of the proposition directly comes from the *information management*.

Theme Definition: a detailed analysis of the themes reported in the previous phase is reported here. The definition aims to present in a tabulated manner the basis for analysis pertaining to each theme and subtheme. In order to enable data items (as gathered from the expert interview process) to be contextualised in a fully transparent manner, each member of the participant group is classified according to data gathered via the associated expert questionnaire under one of this three categories: Construction/ FM Supply Representative (total five participants), Owner/Operator Representative (total eight participants), and Technologist (including Digital Consultant, Digital Construction expert and LMS/Learning Technologies expert – total three participants). This enables data items as presented to be attributed to specific stakeholder groups in order that any propensity to a theme by a participant group may be discussed as relevant to the overall findings of the evaluation, and of the researcher in general. Each theme is reported in both an analytical and illustrative style. Under the tabulated reporting format, the number of associated data item occurrences is given; first as a total number of occurrences (across the participant group and for the specific sub-theme) then by each participant group (of which there are three). Note that where multiple data items (quotations) by the same individual have been attributed to a sub-theme, the number of data item occurrences given by unique participants is given in brackets next to the number of associated data item occurrences. The definitions for all themes are presented in the supplementary documentation S1, and the findings are developed in the following section.

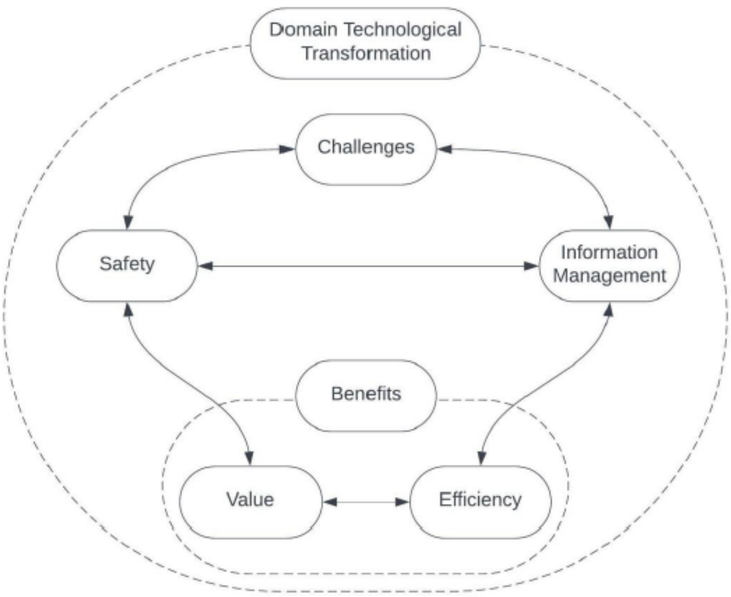

Figure 7: Resulting thematic framework.

RTA Report: Note that the expert group represents three distinct domain stakeholder groups. Of the eight participants representing the estate owner/operator group, two estimated the organisational position (of their employer) to be at legally required training, three identified the organisational position at industry standard, and three positioned the organisation at baseline personalised training. When expressing organisational desire to increase the organisational personalisation position, all but one expressed a desire to increase the organisational by at least one level. When rating the safety training personalisation concept, all participants collectively gave an average rating of 8.25/10. Regarding the value of the proposed solution (and the enabling framework) the participants rated an average of 8. The expert participant group demonstrated a comprehension of the personalisation concept and associated framework such that all of those for whom the rating was appropriate were able to rate the organisational position on such (according to the information, instruction and training personalisation pathway), with the majority expressing an appetite to improve the organisational position in this regard. When rating the value of the personalisation concept the average rating of 8.25 suggests that the group recognises inherent value in the concept, and in the proposed framework (average rating of 8). To this end then the researcher acknowledged prior to undertaking the RTA that the expert group collectively attributes value both to the personalisation concept and to the enabling framework.

Indeed, the RTA process identified multiple themes and sub themes (categorised under the overarching benefits theme) which offered a qualitative contextualising feature to the quantitative data reported through the associated questionnaire. Under the benefits overarching theme, the respective value and efficiency themes together with the associated sub themes demonstrated a recognition by multiple members of the expert group from across the three participant groups, that the proposed framework was capable of improving the ability of the owner/operator to efficiently communicate necessary hazard information, via automated means and in a fully auditable way out to those to whom it was relevant. In doing so, according to multiple data items across the respective participant groups, there were many opportunities to add value into the domain. Indeed, opportunities to challenge outdated processes, and provide effective communication, as well as information access were recognised as being positive features of the proposed framework. The concept of personalisation as a means to target information toward those that need it and in a timely fashion was also recognised as a value adding feature, as was the value of training generally in this regard. Connected to the overarching benefits theme are the safety and information management themes. The connectivity between themes is recognised both in respect of data item co-occurrences and from a researcher qualitative observational perspective. The safety theme, despite having relevance to the value theme is classified as a theme in its own right on account of the concept existing in the operational domain as a regulatory requirement (something which is legally expected and required) rather than as a theme or a concept which is deemed to add value per se. The information management theme is also observed to be connected to the benefits theme via the efficiency theme on account that effective information management is an operational requirement of a functional delivery environment for the proposed framework. The safety theme was identified as having the potential to contribute to an enhanced safety culture at both a supplier and owner/operator level, while at the same time as recognising the potential of the framework to aid hazard mitigation and improve hazard response. Competency checking was also regarded as a sub theme here, in those appropriate competencies according to the task in hand (as able to be assessed and enabled by the framework) have the potential to contribute to workforce safety. The information management theme was concerned with the quality of data in respect of built environment hazard data stored to the BIM environment. As such the data standards theme (as recognised in the framework) was recognised as being of significance here. Both the safety and information management themes, as well as being linked directly in that information management is an enabler of the safety theme as discussed, are also related to the challenges theme.

The challenges' theme represents on overview of the challenges (as perceived by the participant group) of a roll out of the proposed solution to the delivery environment. Of the most significant challenges as identified were operational challenges. Here a range of issue relating to the cost of implementation of such a solution both from a direct financial perspective for the owner/operator and from an indirect financial (i.e. human resource) perspective for the supplier were investigated. Indeed, implementation of the any such solution was recognised as being significantly challenging on account that both hazard data identification and subsequent hazard data management would be significant challenges for the owner/operator. In respect of cost to supplier considerations around volume and potential repetition of training, concerns were raised both from a resource perspective and in respect of "boredom" with excessive safety training potentially leading to decreased quality of outcomes and a dilution of message. In relation to the challenges theme a discussion pertaining to the potential to "start small" with a focus on the core construction hazards before building out was explored.

It is clear then according to the themes as interpreted by the researcher from the available data that the concept of embedding hazard data into BIM such to automate the process of hazard assignment to a particular job so as to enable the personalisation of communication of hazard information, instruction and training is recognised as holding much in the way of potential. The general feeling though of the participant group was that the current operational position in the proposed delivery environment is not yet sufficiently well placed to support a fully personalised solution as proposed. The complexities associated with hazard identification and hazard data management at that level simply outweigh the potential benefits of a fully personalised solution as able to be facilitated right now. Instead, the idea of rationalising the concept, down to a realistic and workable level, where core hazards (those which present the biggest risk) may somehow be able to be implemented perhaps at the baseline individualised, while not explicitly expressed in any of the data items, was reflected in the qualitative theming of the discussion and is reflected also in the quantitative data obtained through the associated questionnaire.

In conclusion, the observations made by the researcher through the predominantly qualitative approach were that despite the propensity of the expert group toward the concept of safety information, instruction and training personalisation, the challenges associated with operationalising such at the fully personalised level are too many in number and too great in complexity in respect of the delivery environment as is. In that case then focus of development for the concept should be at the baseline personalised level, building on the operational position observed during pilot study three (chapter two).

5.3 End user testing

The end user testing is undertaken by a total of 22 prospective end users, individuals who after commercial deployment, are reasonably be expected to use the solution in an operation and maintenance site-access context. A qualitative standardised safety perception measure is adopted to assess safety perception in end users. The focus for the scope of this research instrument being to consider any differences in safety perception as identified when comparing pre- and post-WSS data as collected. The 50-item WSS instrument as adapted from Hayes et al. (1998) is applied to collect qualitative safety perception data from participants before (pre-WSS) and after (post-WSS) having used a representative digital version of the proposed solution. The variable of interest is the difference between post- and pre-intervention safety perception (post-pre), which would measure the impact of the intervention. This variable is available for the whole 50-question survey as well as 5 sub-sections (Own Job, Supervisory, Coworkers, Estates Managers, and Estates Safety Policy), the sub sections being a means to link safety perception to specific categories as associated with work safety. The scores presented are the mean sum of scores. The scores are on a 1-to-5 Likert scale, with each sub-section scored between 10 and 50, and the overall score ranging from 50 to 250. For the full sample group, a Z-score adjustment and interquartile adjusted sample are also presented to exclude potential outliers in the population based on two well-known outlier removal processes. All results are listed in **Table 5**.

Table 5: End User Test Statistical Results.

		OwnJob Post-Pre	Supervisory Post-Pre	CoWorkers Post-Pre	EstatesManagers Post-Pre	EstatesSafetyPolicy Post-Pre	Sum Post-Pre
Full Sample	Average	-0.5	1.8	-1	-0.3	0.7	0.7
	Standard Deviation	5.7	5.1	2.9	4.9	3.9	13.8
	Min	-19	-11	-6	-15	-6	-40
	Max	7	10	7	7	9	23
	No. of Observations	22	22	22	22	22	22
Z-score Adjusted Sample	Average	0.3	2.4	-0.7	-0.1	0.7	2.7
	Standard Deviation	4.1	4.4	2.7	4.9	4	10.6
	Min	-10	-8	-5	-15	-6	-23
	Max	7	10	7	7	9	23
	No. of Observations	21	21	21	21	21	21
IQR Adjusted Sample	Average	0.5	2.5	-0.6	0.7	1	4
	Standard Deviation	4.1	4.5	2.7	3.7	3.8	9.1
	Min	-10	-8	-5	-7	-6	-13
	Max	7	10	7	7	9	23
	No. of Observations	20	20	20	20	20	20

When reviewing the pre- and post-scores for the full sample group, the scores indicate a marginal improvement in safety perception, by an average of 0.7 points (out of 250). Both sub-samples with no outliers showed a larger mean improvement in safety perceptions (2.7 and 4). It is noted by the researchers though that considering the 50-250 scale, the magnitude of improvement is still modest. The main sub-section identified as driving the improvement in safety perceptions is the supervisory subsection. It is possible to suggest that this could imply a link between safety perception and the solution as tested in as much as it is reasonable to consider the tool supervisory in nature.

5.4 Discussion

As a result of the RTA data, the participant group had predetermination to the safety information, instruction, and training concept. Indeed, on average owner/operator representatives expressed a desire on average to improve the level of safety training personalisation currently employed on the estates for which they were responsible. When taken on average estate owner/operator representatives expressed a desire to elevate the safety personalisation by a minimum of one level, with the average aspiration in this regard being at the semi personalised level (4/5). Despite the apparent propensity toward the proposed framework and an apparent acceptance of its potential to provide value back to visiting contractors as well as estate/owner organisations as expressed through the benefits themes as well as the safety and information management themes, a number of significant challenges sub themes suggest that the maturity of the delivery environment is not sufficient such that the solution may be able to be rolled out at the top level of the safety personalisation pathway (fully individualised). This is despite there being data items assigned under the benefits themes to suggest that conceptually the fully individualised level had much in the way of benefits to offer back to the domain in regard to SAV.

Two significant challenges associated with the delivery of a fully personalised solution out into the operational domain are related to [Hazard] Data Management and Hazard Identification. The challenge of initially identifying hazard data such that said data could be stored back to and structured for querying in the BIM environment is too significant in terms of resource allocation required for such. Related to this, maintenance of hazard data as required to drive the solution at the fully individualised level would be equally resource intensive and as such would likely be possible but certainly not desirable in an operational environment. Multiple attempts to address such challenges as identified by multiple expert participants can be found in literature (Zhang et al., 2015; Ding et al., 2016; Xing et al., 2019, Jiang et al., 2020, Pandithawatta et al., 2023). Construction safety ontological development could be attributed as having the potential to address, over time, the expert concerns. A hazard ontology that facilitates the automated construction safety requirement analysis is identified as the most appropriate of the available domain ontologies to support the process of hazard identification (Johansen et al. (2023)). With this in mind then it is possible to link the expert data with the existing domain research (specifically construction safety ontology development), with both recognising the scale of the challenge of hazard identification, and the potential of the novel interfacing established and emerging technology enabled solutions to address such.

Concerns about the ability of the operational environment to effectively deal with safety training repetition is identified as a key operational challenge by the interviewed experts. which it was suggested would emerge from the implementation of fully personalised safety solutions pertaining to SAV across multiple client sites. Experts acknowledged that without more construction safety training industry standardization, this identified challenge would be difficult to address from a safety personalisation pertaining to SAV perspective. Two potential solutions emerged from the expert discussion in relation to such:

1) The solution be considered for roll out in the first instance with a focus on core construction hazards, such as those being attributed to the highest volume of accident, injuries, and deaths. In doing so, multiple expert participants suggested, it may be possible to minimise the operational burden at the supply side by reducing the volume of micro training credentials set as access credentials for visiting contractors on the client side.

2) The second solution involves standardisation, where industry-recognised training—such as the UKATA asbestos awareness certification—can be used as a pre-qualification across multiple client sites. This approach offers significant potential to reduce repetitive safety training by allowing a standard credential to substitute for duplicative site-specific components.

The propensity of expert industry representatives toward the proposed solution as a driver of novel construction worker site access verification process and protocol is highest at the level which is commensurate and compatible with the state of the delivery domain in regard to both technical capability (respect of hazard identification and management in the digital construction domain) and standardisation of construction safety training. However, looking at the current delivery environment, the general propensity of the expert participant group at this time is strongest at the baseline individualised level. To increase the propensity of expert industry representatives towards semi-individualised and/or fully individualised solutions, potential considerations are:

1) Automation methods pertaining to hazard identification and data storage/maintenance will be necessary, as well as continuous data compliance/verification with regulatory requirements implemented at scale.

2) In addition, standardisation in the construction industry safety training space would need to be significantly advanced such that is necessary to minimise duplication of training for end users.

A coordinated and concerted call to action is needed by relevant stakeholders, including the UK HSE, to standardise hazard safety training content development and verification. A model exists in the UKATA Asbestos Awareness qualification which may be leveraged to demonstrate a potential future where automated SAV solutions are commonplace across client estates, with standardised safety certification and verification processes being implemented at a scale such that the complexities of the advancing built environment do not negatively affect industry safety statistics and in particular the safety outcomes for those tasked with the implementation, maintenance, and eventual decommissioning of such. Advancement in this domain would give rise to a more fertile delivery environment in respect of construction safety information, instruction, and training personalisation. A situation which may offer incentives to researchers and practitioners to further develop knowledge and understanding into the automation of hazard identification, hazard data management, and hazard data maintenance against the required regulatory standards. In which case the appetite to increase the construction safety personalisation position of estates across the UK and more generally around the world may be able to be realised at pace and at scale.

6. CONCLUSION AND FUTURE DIRECTIONS

This research presents both theoretical and practical contributions to the domain of construction safety, particularly in the context of emerging smart and sustainable technologies. First, it is demonstrated that the increasing integration of smart and sustainable technologies is contributing to a more complex hazard profile within the built environment, necessitating adaptations to existing regulatory frameworks. Second, the study identified a critical gap in the domain of technology-enabled safety solutions for visiting contractors, leading to the development of the AccVerOnt ontology and an associated construction safety framework. These tools are positioned to support future research and development, offering a structured knowledge base for hazard management innovation and a framework for interpreting and advancing safety solutions in complex construction delivery environments. On a practical level, the research contributes a technically demonstrated solution architecture for site access verification (SAV), demonstrated through an applied case study. This demonstration establishes technical and conceptual feasibility rather than proven effectiveness: the small expert (n=16) and end user (n=22) samples, together with the marginal end user improvement observed, mean that broader empirical validation of effectiveness remains a matter for future work. This architecture can serve as a foundation for industry practitioners seeking to implement or improve safety verification processes. Furthermore, the construction safety personalisation pathway, developed and validated through expert evaluation, serves as both a practical tool for organisational assessment and a theoretical model for future academic inquiry. It enables organisations to evaluate their current safety training personalisation level and explore opportunities for advancement, while also providing researchers with a structured approach to classify and analyse personalisation strategies within the construction safety domain.

Future research should consider investigating the development of construction safety-related ontologies, particularly in the domains of automated hazard identification and hazard data maintenance. These areas hold significant potential for enhancing construction safety information delivery, instruction, and training personalisation. Additionally, existing maintenance scheduling tools that incorporate UK regulatory framework requirements—such as SFG20—could be explored in relation to their applicability for supporting personalised safety training and instruction. Leveraging such systems may offer a pathway to more integrated and regulation-aligned training solutions within the construction sector. To evaluate the full potential of the proposed solution, a complete implementation that includes all relevant ontology components should be developed and assessed with a larger and more diverse end-user sample. Such testing would enable more robust evaluation of the framework's effectiveness, scalability, and usability in practice. Importantly, testing should extend beyond controlled or scenario-based environments and into live operational settings. A practical approach would involve implementing the solution in contexts where baseline individualised training solutions are already in use. This would minimise deviations from existing practices and thereby enhance the likelihood of user participation and engagement. Finally, consideration should be given not only to the personalisation engine itself but also to the format and delivery of the online training content. Opportunities exist to tailor training to individual learning needs, preferences, language proficiencies, and learning styles, thereby optimising user experience, and improving learning outcomes across diverse construction workforces.

DECLARATION OF COMPETING INTEREST

Authors recognize that there is no conflict of interest associated with the paper.

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