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FORMALIZING VIRTUAL CONSTRUCTION SAFETY TRAINING: A SCHEMATIC DATA FRAMEWORK ENABLING REAL-WORLD HAZARD SIMULATIONS USING BIM AND LOCATION TRACKING

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SUMMARY*: Virtual construction safety training (VCST) as an active training method has considerable potential to be more effective than existing passive learning methods. VCST can also become equivalent to or part of on-the-job training once the system has been tested and is comparable to real-world training methods. However, including such real-world scenarios is commonly integrated into VCST by experts creating made-up scenarios. This approach requires considerable resources from different domains and may not represent the scenarios with sufficient realism, risking the relevance of and efforts spent on creating the training system. Despite several existing approaches to integrate real-world data, no formalization of the relevant Data Modeling (DM) concepts, their relations, and their functionalities within VCST have been published. Such a formalization, however, can ease the creation of training developers and enable them to simulate scenarios from real-world construction sites. This research proposes that VirtualSafeConDM formalize such concepts using existing ontologies. VirtualSafeConDM is developed using an existing data schema development method based on the Linked Open Term methodology. It comprises four steps: (a) Specification of requirements as Competency Questions (CQs), (b) knowledge acquisition and conceptualization from existing ontologies such as IfcOwl or a hazard ontology, (c) implementation in a C# library for the game engine Unity, and (d) the evaluation of the proposed VirtualSafeConDM. The evaluation contains a manifold qualitative approach. The consistency of the VirtualSafeConDM is evaluated through consistency checks. The extendibility and clarity are evaluated using a qualitative criteria-based method. Last, the usability and coverage are evaluated using a task-based method of answering the CQs. This task-based evaluation approach includes the creation of a real-world hazard-integrated virtual training environment (RHI-VTE) based on a metro renovation project in Germany. The authors recreated a task where a worker and several machines were active. The case study demonstrates that VirtualSafeConDM connects to real-world data sources using an as-built Building Information Modeling (BIM) model and Real-Time Location System (RTLS) data to expose trainees to hazards based on historical real-world construction activities. This integration formalizes hazard entities, allowing for comprehensive behavior analysis. Secondly, VirtualSafeConDM ensures efficient knowledge transfer across construction domains and use cases.*

KEYWORDS*: Active personalized learning, behavioral assessment, construction safety, construction workers, game engines, ontologies, personalized feedback, real-world hazards, serious games, training and education, virtual reality, virtual training environments.*

REFERENCE*: Kilian Speiser & Jochen Teizer (2024). Formalizing virtual construction safety training: a schematic data framework enabling real-world hazard simulations using BIM and location tracking. Journal of Information Technology in Construction (ITcon), Special issue: 'Managing the digital transformation of construction industry (CONVR 2023)', Vol. 29, pg. 980-1004, DOI: 10.36680/j.itcon.2024.043*

1. INTRODUCTION

Active training methods can be up to three times more effective than passive training methods such as classroom teaching, videos, or textual training (Burke et al., 2006). In construction, on-the-job training, as one of the active training methods, has several limitations. First, it can be inflexible as it requires replications of construction sites and equipment and can be limited in the reproducibility of specific scenarios such as emergency evacuation. Second, on-the-job training exposes the trainee to hazards. These hazards are then significantly mitigated in the training site, questioning the relevance of the training task due to missing hazard exposure.

Virtual Construction Safety Training (VCST) can provide active training similar to on-the-job training but in a safe environment, as the hazards only exist virtually. Several studies investigated VCST using Virtual Reality (VR) with head-mounted displays (Jacobsen et al., 2022; Sacks et al., 2013) or desktop-based virtual training (Speiser and Teizer, 2023). However, existing approaches often overlook the opportunity to assess the actual safety behavior of workers, instead focusing solely on changes in intention. This observation refers to the well-documented intention-behavior gap, which suggests that human actions often deviate from their intended plans (Ajzen, 1985). In the realm of VCST, evaluation methods often rely on subjective assessments or post-training interviews and surveys (Salinas et al., 2022). Unfortunately, these methods primarily measure changes in intention or require manual assessment, failing to reflect behavioral shifts. For example, a worker answering that they will follow a safe path does not entail that they will do so at the construction site, where other factors (affective and psychological) come into play.

VCST presents a promising solution to overcoming the intention-action gap by enabling the assessment of behavior in practical tasks. By collecting and analyzing data during training sessions, particularly concerning interactions with hazards, the safety behavior of trainees can be captured and quantified (Golovina and Teizer, 2022). In contrast to interviews, which reflect only the intentions of trainees, behavior-based assessment methods offer a more representative measure of behavioral improvements. Therefore, leveraging VCST with the capability of data collection and analysis is crucial for accurately evaluating the efficacy of safety training. However, in order to capture data that represents the behavior of the trainee reflecting real-world situations, the training scene must include scenarios considering many aspects, such as the task, the technology, the behavior of other agents, and the surroundings. Creating these scenarios requires vast resources from different domains.

Connecting the VCST to real-world data sources could minimize the required resources for the creation of the training scenes. Several studies have included Building Information Modeling (BIM) models (Golovina, Kazanci, et al., 2019; Park and Kim, 2013) that represent the surroundings to integrate more realistic hazards, connect them to a digital twin (Speiser and Teizer, 2023a) or propose a framework for content-sharing (Bao et al., 2024). Previous work included dynamic scenes based on 4D BIM models updating the training scene based on a schedule (Speiser and Teizer, 2024a) or including sensor data using the Internet of Things (IoT) (Speiser et al., 2023). Nevertheless, similar to other aspects in the domain of construction safety, such approaches are point solutions without connection to knowledge from other domains or use cases.

VCST must connect to such knowledge sources from other domains to incorporate content reflective of real-world scenarios. By integrating pre-existing construction safety knowledge, the demand for resources in scenario generation reduces as redundant re-collection and re-entry of data are eliminated. Furthermore, the assimilated knowledge, grounded in real-world hazard information, may represent a step towards bridging the intention-behavior gap. Consequently, the fusion of existing knowledge from various construction safety contexts and other domains facilitates seamless knowledge sharing.

This study proposes VirtualSafeConDM, a schematic data model addressing the described problems by integrating existing ontologies and schemas into a real-world hazard-integrated virtual training environment (RHI-VTE). The study aims to create a data model covering several requirements, such as real-world hazard integration and data collection reflecting interaction with real-world hazards. VirtualSafeConDM integrates existing machine-readable knowledge schemas to allow for the smooth consumption of safety-related knowledge and the sharing of the generated knowledge in the RHI-VTE. To validate the practical feasibility of the approach and underline its usability, the VirtualSafeConDM is instantiated and evaluated in a case study from a real-world railway renovation project in Germany.

2. RELATED WORK

2.1 Existing efforts in advancing virtual training

VCST represents an active training method that can quantify behavioral shifts, similar to on-the-job training. Vast approaches for construction safety training exist, and active methods like on-the-job training can be more effective (Burke et al., 2006). Moreover, in on-the-job training, safety behavior can be quantified directly by assessing the actions of the trainee. In other training methods, such as classroom lectures and videos, an assessment of behavioral shift is not measurable, but interviews or exams can evaluate the shift in intention. Example: A trainee may answer in a test that they will wear a ventilated helmet with an air supply when performing welding work. However, only on-the-job training can verify that they will wear such protective equipment when factors from the environment may affect the worker's decisions (e.g., stress, fatigue, time pressure, noise). This effect refers to the so-called intention-behavior gap, and VCST can close this as it can expose trainees to lifelike simulations of construction tasks and potential hazards (Li et al., 2018; Nykänen et al., 2020; Sacks et al., 2013; Zoleykani et al., 2023).

Such behavioral assessment, however, can only be meaningful if the hazards and the environment in the training scene reflect real-world scenarios. Several studies have included BIM models to include such real-world data (Golovina, Kazanci, et al., 2019; Park and Kim, 2013). Another approach is the utilization of a digital twin (Speiser and Teizer, 2024a; Teizer et al., 2024). Nevertheless, integrating construction training into the context of digital twins has not been fully explored. Kaarlela et al. (2020) utilized a digital twin for safety training in an industrial environment, and Sun et al. (2023) integrated a digital twin for training crane lifting operations. Another study proposed a framework for integrating construction safety training into a digital twin (Harichandran et al., 2021). However, this framework has not been implemented; it has only been discussed on a conceptual level. The concept has been refined and applied in several case studies, indicating promising results (Speiser and Teizer, 2023b, 2023a). In these works, the authors use the definition of the Digital Twin for Construction (DTC) introduced by Sacks et al. (2020) and utilize the as-planned and as-performed information to recreate a training scene using real-world knowledge. Lastly, the only existing approach to include IoT data in VCST utilizes Real-Time Location Systems (RTLS) for simulating construction workers and machinery (Speiser et al., 2023).

When integrating real-world data, behavioral safety performance can be relevant, but existing approaches merely assess VCST using subjective methods or based on surveys. Many studies evaluate the performance of the trainees using interviews (Akanmu et al., 2020; Kim et al., 2021) and questionnaires (Eiris et al., 2020; Sacks et al., 2013; Wolf et al., 2022). A disadvantage of this approach is that they are subjective and quantify intention rather than behavior. Other studies assess the performance based on the number of identified hazards (Shamsudin et al., 2018; Wolf and Teizer, 2022). Other approaches involve collected data, such as the time for completing a task (Kim et al., 2021; Lucena and Saffaro, 2022) or the time until a hazard is recognized (Comu et al., 2021; Wu et al., 2023). It is crucial to quantify the behavior, and in VCST, it is simple to collect data capturing the behavior of the trainees. Nevertheless, most studies do not exploit this opportunity (Salinas et al., 2022). Studies addressing the worker's behavior analyze the position of the trainees (Getuli et al., 2020), and Speiser and Teizer (2023a) integrate methods to detect and quantify proximity between hazards and trainees based on previous efforts (Golovina, Perschewski, et al., 2019). For measuring behavioral safety performance, it is essential to include the spatial-temporal context. Besides the approach mentioned above, Getuli et al. (2021) propose a method to include hazardous spaces in virtual environments along with other relevant spatial entities.

The benefits of VR training are evident in psychomotor performance, knowledge acquisition, and spatial ability improvement (Abich et al., 2021). Several studies highlight the improved effectiveness of virtual training compared to traditional lecture-based approaches (Adami et al., 2021; Jacobsen et al., 2022). However, Adami et al. (2023) emphasize the need for further investigation, particularly regarding the applicability of these findings to construction workers. Other studies find that extensive resources are required to create virtual training scenarios (Golovina, Kazanci et al., 2019).

A reusable framework connecting to existing knowledge from the safety domain and other domains and use cases could reduce these resources in training creation. The framework could integrate real-world knowledge and, therefore, provide an environment for measuring behavioral shifts instead of intention. For such a framework, the knowledge from the construction safety domain must be captured. Hence, the following section describes the different approaches to formalizing safety knowledge in construction.

2.2 Formalizing construction safety knowledge

Previous efforts have formalized construction safety knowledge using various approaches. There are regulations, laws, and technical specifications defined by authorities or institutes describing required safety concepts for safe construction processes. Several approaches define the different types of hazards and conditions for when such hazards exist. On the other hand, there are mitigation measures to control the risk of hazards that can cover safe behavior, such as moving vehicles at low speed or wearing protective equipment, but can also entail requirements to properties of elements such as scaffoldings of certain steel quality or certifications of a fire extinguisher. As these concepts are typically formalized in written text, several studies propose ontologies for converting them into machine-readable formats for specific use cases.

The first studies propose monolithic ontologies that do not connect to existing systems. For instance, Zhang et al. (2015) propose an ontology for job hazard analysis in masonry works. Similarly, Lu et al. (2015) developed an ontology for safety rule checking. The second iteration of safety ontologies integrates existing concepts for specific tasks. The first ontology to connect to the Industry Foundation Classes (IFC) targets the design of fall protection systems (Guo and Goh, 2017). Shen et al. (2022), in contrast, integrate existing ontologies but miss a connection to higher-level concepts outside the safety domain.

For safety knowledge required during the planning stage, Li et al. (2022) cover a spatial analysis in BIM to detect fall hazards and ankle sprain hazards (trips). Johansen et al. (2023) refine that ontology and extend the scope with struck-by hazards. The ontology connects to IFC and an existing ontology describing a digital twin (Poveda-Villalón et al., 2024). The shortcomings are that it only includes certain hazard types and focuses on the planning stage. Another approach includes the hazards as quantifiable risks where 29 different hazard types and suitable mitigation measures can be linked with IFC entities (Farghaly et al., 2022). Nevertheless, safety concepts related to the construction processes and inspection are not addressed.

Limited research exists regarding safety training ontologies. Pedro et al. (2023) introduce an ontology focusing on training content derived from accidents, which covers the nature of work and types of hazards at a meta-level. However, this ontology lacks the inclusion of mitigation measures and is restricted to specific hazard types. In contrast, another strategy involves an ontology-driven data model that incorporates IFC while considering spatial and temporal hazards (Speiser and Teizer, 2023b). Particularly noteworthy is their proposition of a geometric depiction of hazard zones, employing safety parameters aligned with safety regulations.

In VCST, safety knowledge must be included, but VCST is also a dynamic system that allows for user interaction. These systems have different requirements, such as creating performance assessments. Such requirements set the scope of the required content in such a knowledge base and how this knowledge can be generated in VCST. For this reason, our research proposes the VirtualSafeConDM. This data model implements existing ontologies into a data schema, capturing knowledge from the construction safety domain and reflecting the safety behavior of workers.

3. OBJECTIVES AND RESEARCH QUESTIONS

This research aims to tackle critical challenges in VCST. First, it aims to ease the creation and adoption of training scenarios. Second, it seeks to generate knowledge about safety behavior based on collected data on the trainee's safety behavior. As outlined in the previous Section, a notable issue exists within the realm of VCST: the resource-intensive scene creation. Current methods involve hard-coding scenes, necessitating the recreation of entirely new scenes for modifications. While some literature suggests flexible frameworks, there is a lack of formalization in machine-readable formats covering various aspects. Moreover, most VCST platforms fail to capture behavioral feedback effectively. To truly reflect trainee behavior, the inclusion of real-world hazards is imperative. Not only does this enhance realism, but it also facilitates behavioral analysis. Nevertheless, little research has explored integrating real-world data into VCST platforms.

This paper introduces VirtualSafeConDM to address these challenges. VirtualSafeConDM is a data model designed to simplify VCST creation. By integrating existing knowledge concepts, VirtualSafeConDM facilitates seamless data transfer. Additionally, it enables the incorporation of real-world hazards, thereby enhancing training realism. VirtualSafeConDM achieves this objective in two ways. Firstly, it connects to real-world data sources, such as as-built BIM models and RTLS data, to expose trainees to hazards based on historical real-world construction activities. This integration formalizes hazard entities, allowing for comprehensive behavior analysis.

Secondly, VirtualSafeConDM ensures efficient knowledge transfer across construction domains and use cases. Leveraging existing ontologies and schemas minimizes redundant data entry and enables smooth data sharing. This approach not only accelerates scene creation but also promotes consistency and extendibility.

In summary, this paper proposes a data model that revolutionizes VCST by leveraging real-world data sources and streamlining scene creation. The research aims to address the following questions:

RQ1: How can existing ontologies and schemas be effectively integrated into VCST platforms to facilitate seamless data transfer and knowledge sharing?
RQ2: What methodologies can be employed to create virtual training scenes and quantify safety behavior based on real-world hazards?

4. RESEARCH METHOD

This research focuses on formalizing the data structures for VCST so that training developers have a generic framework to create training scenes. The research extends the previous efforts of the authors, where IoT data from RTLS devices has been integrated into VCST to simulate real-world hazards (Speiser et al., 2023). In this work, however, the RTLS integration is only a minor part of a data structure covering several aspects of VCST. It extends the proposed method to include RTLS data by proposing abstract data structures, allowing for the framework to be extended and more robust. As mentioned before, ontologies have a similar objective, but in this research, we propose the data model VirtualSafeConDM as virtual safety training requires functionalities beyond data structures. The research method for constructing the data model comprises four stages: (1) specification, (2) knowledge acquisition and conceptualization, (3) implementation, and (4) evaluation. While this methodology was initially presented for defining ontologies (Zheng et al., 2021), its suitability was demonstrated for developing data models (Schlenger et al., 2022).

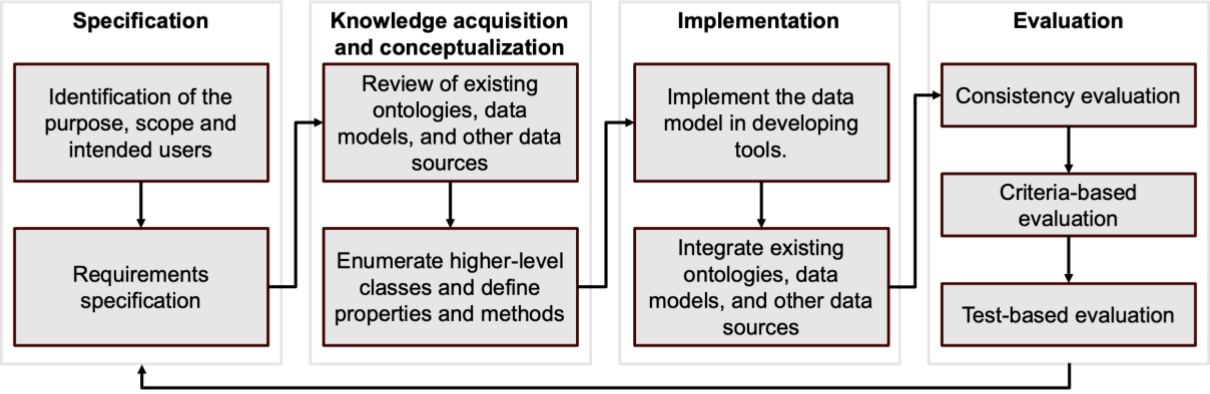

Figure 1: Research method for developing and evaluating VirtualSafeConDM.

4.1 Requirements specification

First, the purpose, scope, and intended users were specified (Uschold and Gruninger, 1996). The three variables were specified based on the results of the literature review. As previously mentioned, the literature revealed that current approaches in virtual safety training are (1) hardcoded with little flexibility, (2) based on made-up scenarios without real-world data, and (3) have limitations measuring safety behavior rather than intention. Based on these findings, the data model's purpose is to provide a framework for safety training developers (intended users) to create training scenes with less effort by integrating knowledge from other domains as well as data from real-world sources. Moreover, the data model specifies rules and functionalities on how hazards can be integrated into such training so that behavior-based feedback can be generated automatically.

The scope of VirtualSafeConDM includes relevant entities related to VCST based on existing ontologies and data models so that safety training can be generated with less effort and more flexibility and so that the behavior of the trainee can be evaluated. It, therefore, includes relevant entities from IFC, working activities, hazards, and safety incidents. The hazards are limited to a sub-selection of the hazards causing the most fatalities, namely, falls from leading edges, trips, electrocution, and struck-by incidents related to operating machinery (Harris et al., 2023). As mentioned before, the hazards are integrated into a machine-readable format to assess the safety performance. The proposed behavioral assessment is limited to hazards that can be described in a spatial-temporal context where the shape of the hazards can be geometrically identified, and the temporal occurrence is known. While the authors believe that most hazards can fulfill this assumption, further research needs to investigate if there are constraints. For instance, it is not clear if hazards like lifting heavy loads, particularly psychological hazards like stress or health hazards such as heat exposure, can be described in a spatial-temporal context.

Based on the specified scope and purpose, the functional requirements of the data model were identified through user stories and structured interviews. The interviewees were three domain experts with at least twelve years of experience in construction and a minimum of nine years in construction safety. They all operate in global construction firms (see Table 1).

Table 1: Structured interviews with three domain experts supported the formalization of requirements.

ID	**Domain**	**Field of work**	**Experience in years in**	
			Construction safety	**Construction**
1	Safety Manager	Safety Management on a strategic level	12	18
2	Site Manager	Safety Management on an operational level	9	12
3	Site Manager	Construction safety research	17	22

Based on the defined user stories and the interviews, Competency Questions (CQs) were formalized. CQs are questions formulated in natural language that VirtualSafeConDM must be able to answer (Grüninger et al., 1995). Table 2 shows the CQs that ease the conceptualization of the VirtualSafeConDM as they highlight crucial entities, attributes, and relationships.

Table 2: Competency questions (CQs) formalizing the requirements for VirtualSafeConDM.

Domain	**ID**	**Competency Question (CQ)**
Training	CQ1.1	What hazards were active during the session?
	CQ1.2	What did the construction site look like during the recording?
	CQ1.3	What resources were active during the session?
Hazards	CQ2.1	Where did the hazard occur?
	CQ2.2	What type does a hazard have?
	CQ2.3	What causes the hazard?
	CQ2.4	Is the hazard mitigated?
	CQ2.5	How can a hazard be mitigated?
	CQ2.6	What is the shape of the hazard zone?
	CQ2.7	What safety rule specified the shape of the hazard zone?
	CQ2.8	Can the hazard zone be geometrically specified?
RTLS	CQ3.1	What resource does the trajectory refer to?
	CQ3.2	How does the machine move?
Performance	CQ4.1	How many safety incidents occurred during the training session?
	CQ4.2	Where did the safety incidents occur?
	CQ4.3	How severe were the safety incidents?
	CQ4.4	What type of hazard relates to the incident?
	CQ4.5	What corrective measures could have prevented the incident?
	CQ4.6	How well did worker X perform compared to worker Y?

4.2 Knowledge acquisition and conceptualization

Following the specification, the subsequent phase determines domain knowledge for the data model (Fernandez et al., 1997). During this stage, relevant domain knowledge of VCST was initially reviewed as part of the literature review. Subsequently, in the conceptualization phase, the acquired knowledge from the literature review was compiled into relevant terms for the VirtualSafeConDM, establishing a class hierarchy, defining class properties, and specifying functionalities.

In this process, the majority of terminologies were directly sourced from related existing ontologies and schemas to ensure clarity and eliminate ambiguity within the data model. Subsequently, leveraging these listed terms, a generic schema was initially formulated, encompassing definitions of primary classes and properties. This approach aimed to facilitate the development of VirtualSafeConDM within a theoretical framework, formalizing the structure and ensuring coherence in the vocabulary utilized (Holsapple and Joshi, 2002).

A notable distinction between an ontology and VirtualSafeConDM lies in the inclusion of behavioral functionalities of several concepts. For instance, beyond mere semantic descriptions, VirtualSafeConDM also incorporates functionalities that entities implement, such as actions to be taken if trainees enter hazardous spaces. This aspect necessitates consideration of constraints posed by programming languages or software architecture.

4.3 Implementation

Since existing ontologies encompass a significant portion of the specific knowledge relevant to our project, we opt to re-use and align our VirtualSafeConDM with them. This approach enhances the reliability and diminishes the effort required to define redundant concepts and relationships. Throughout the literature review, we examined numerous related ontologies. Subsequently, during the implementation phase, we imported and mapped these ontologies with the modules of VirtualSafeConDM. Specifically, we used IFC, a hazard ontology (Johansen et al., 2023), a safety ontology (Farghaly et al., 2022), as well as a digital twin ontology (Poveda-Villalón et al., 2024), and a digital twin data model (Schlenger et al., 2022).

VirtualSafeConDM has been implemented in a language-specific context. As the virtual training is intended for Unity, VirtualSafeConDM has been implemented in C#. Here, Unity-specific behavior and properties are assigned to include further functionalities specified in the requirements. It is essential to highlight that the implementation process is iterative in both stages as consistency flaws arise throughout the implementation.

4.4 Evaluation

The evaluation of the data model aims to validate that VirtualSafeConDM satisfies the requirements specified in the first steps of the development method. Several approaches exist, including data-driven evaluation (Brewster et al., 2004), automated consistency checking, criteria-based evaluation (Delir Haghighi et al., 2013), evaluation by humans, task-based evaluation (Delir Haghighi et al., 2013), and gold standard evaluation (Dellschaft and Staab, 2006). An appropriate evaluation method must be chosen since some methods may not be applicable. For instance, gold standard evaluation is not feasible as there are no comparable existing data models. In this study, a mixed approach using three levels of evaluation was chosen. A similar method has been successfully demonstrated in developing an ontology for building permit processes (Fauth and Seiß, 2023).

Previous researchers have defined criteria to evaluate ontologies (El-Diraby et al., 2005; El-Gohary and El-Diraby, 2010; Fauth and Seiß, 2023; Zheng et al., 2021). Similarly, we defined the following five criteria and used different methods to evaluate each of them (see Table 3): Consistency, extendibility, clarity, coverage, and usability. For these five criteria, four evaluation approaches were performed. First, consistency checks intend to identify flaws in the design of the data model. This evaluation is a parallel process occurring during the implementation of the data model. As C# is a pre-compiled language, it allows us to evaluate the consistency before runtime. Second, the criteria-based evaluation is a qualitative assessment of the extendibility and clarity. The third approach evaluates the coverage of the data model by answering the CQs. In the last step, a task-based evaluation approach aims to assess how the data model realizes tasks within the defined scope. In this research, a case study involving an as-built BIM model and RTLS data was used to instantiate VirtualSafeConDM in an RHI-VTE to assess its usability.

Table 3: Evaluation method for the selected criteria.

Criterium	**Evaluation method**			
	Consistency checks	Criteria-based evaluation	Answering of CQs	Task-based evaluation
Consistency	X			
Extendibility		X		
Clarity		X		
Coverage			X	X
Usability				X

5. DATA MODEL INTEGRATING REAL-WORLD HAZARDS

This Section delves into the details of the proposed data model by introducing the core entities shown in Figure 2. VirtualSafeConDM adheres to the SOLID principles to ensure high flexibility and extendibility (Martin, 2002). To increase the extendibility, several features are implemented as interfaces. In other cases, however, abstract classes are used to generalize concepts. Lastly, the data model connects to the IFC standard using relationships. Such relationships allow us to connect to existing ontologies without limiting the features of VirtualSafeConDM.

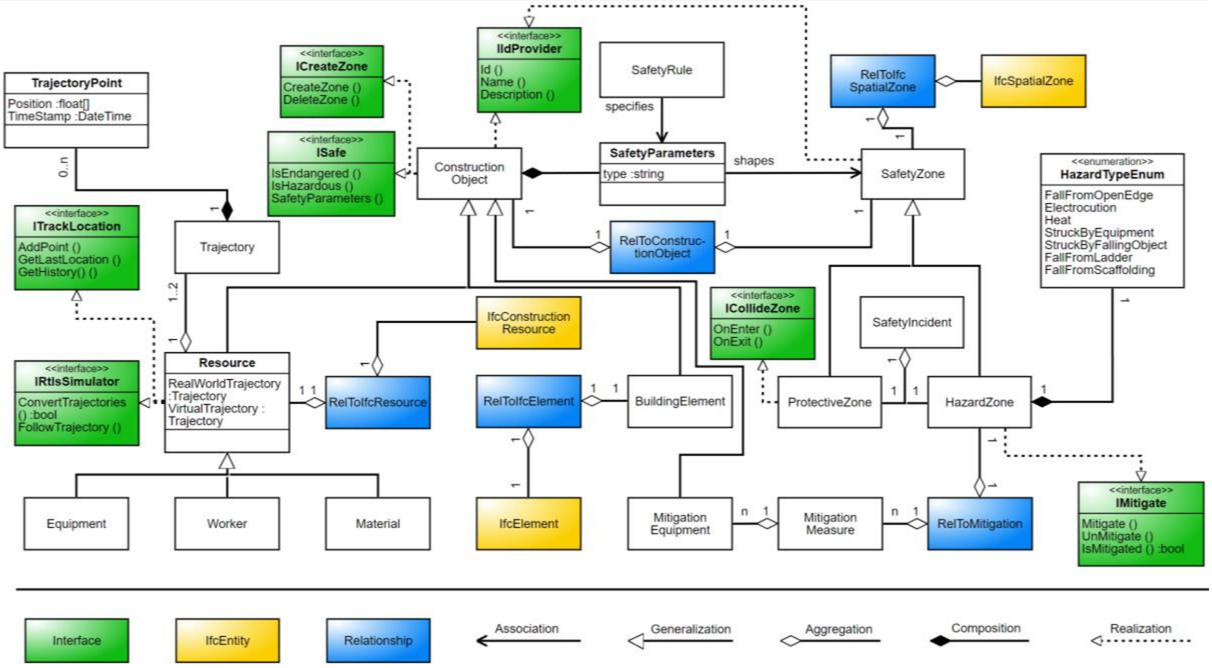

Figure 2: The proposed schema for VirtualSafeConDM, including the classes, interfaces, and relationships.

5.1 High-level concepts and entities in construction safety and training

Occupational safety and health (OSH) is defined as one or more means, methods, practices, processes, or operations that are required or suitable for ensuring safe and healthy workplaces and employment conditions (OSHA, 1970). Based on this definition, construction safety revolves around identifying hazards at the construction site and implementing measures to mitigate them effectively. While the terms and definitions vary, the two primary concepts are the identification of hazards and corrective measures to mitigate the hazards. A hazard is controlled once appropriate mitigation measures are in place (Erkal and Hallowell, 2023). However, incidents may still occur, necessitating incident reporting and subsequent analysis to determine preventive measures for future hazards.

In this study, we refer to a *hazard* as a »potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation« (EU-OSHA, 2024). The *mitigation measures* control such hazards so that the risk is minimized. Yet, safety or health events may occur despite having measures in place. In this study, we refer to these events as safety incidents, which refer to the definition of OSHA. Safety incidents include such events with severe consequences but also near misses. Near misses, also known as close calls, are safety or health events where »potential hazard or incident in which no property was damaged, and no personal injury was sustained, but where, given a slight shift in time or position, damage or injury quickly could have occurred. « (OSHA, 2022). This definition results in OSHAs conclusion that the difference between an accident and close calls lies in timely intervention or chance. A *safety incident* in this work includes all types of hazardous events, including close calls.

In safety training, personalized feedback can improve the effectiveness of active training methods. Hence, the actions of a worker must be analyzed. In this work, this analysis focuses on the spatial-temporal interaction with hazards and the occurred safety incidents, which are separated into close calls and actual hits. The following sections discuss the main entities of VirtualSafeConDM using the described concepts in the previous paragraphs. Figure 2 illustrates the different components using the Unified Modelling Language (UML): (1) the construction objects, (2) the safety zones, (3) safety parameters, and (4) safety incidents. The following paragraphs will describe each of them in detail and elaborate on the relationships between them.

5.2 Construction objects

ConstructionObjects are physical entities found within a construction site, which are either consumed during the construction process (*Resource*) or are permanent or temporary elements contributing to the geometrical description of the construction site (*BuildingElement*). This definition draws inspiration from the IFC schema, where *IfcConstructionResource and IfcBuildingElement* are the respective entities. Hence, *RelToIfcElement* and *RelToIfcResource* relate elements from both specifications. These and all other relationships in the data model are represented through references to the objects; thus, unique identifiers are required. The provision of these functionalities is ensured through the *IIdProvider* interface that all relevant entities of the data model implement.

ConstructionObjects can be classified as hazardous or endangered. Depending on this classification, a resource can either cause a *HazardZone* (if hazardous) or a *ProtectiveZone* (if endangered). Although VirtualSafeConDM does not impose limitations on user specifications, the most common use case would involve designating a pedestrian worker as endangered while considering most other resources as hazardous. Section 6 will provide further examples.

Resources encompass objects consumed during the construction process. In VirtualSafeConDM, we distinguish between *Materials*, *Equipment*, and *Workers*. A *Resource* implements the *ITrackLocation* interface to monitor its location during operational activities. The tracked locations are stored in the *VirtualTrajectory* property of the resource as a collection of *TrajectoryPoints*. Additionally, a *Resource* adheres to the *IRtlsSimulator* interface, providing methods to simulate resource actions in the virtual environment based on RTLS data collected in the real world. The *ConvertTrajectory* method utilizes raw data to instantiate the *RealWorldTrajectory* property of this Resource. Subsequently, the *FollowTrajectory* method simulates movements using the *RealWorldTrajectory*. The FollowTrajectory method needs to incorporate knowledge specific to the resource, as demonstrated in previous research, such as that involving a forklift (Speiser et al., 2023).

BuildingElements encompass all temporary or permanent elements within the construction site, including existing building structures and construction site equipment like scaffolding, safety barriers, or signage. Mitigation Equipment is another specification of *ConstructionObjects* that represents objects within the construction site and is aimed at mitigating hazards. In this data model, hazards are a specification of *SafetyZones* described in the subsequent Section.

5.3 Safety zones

A *SafetyZone* is a temporary spatial description of a zone on the construction site with safety-related implications. Within the IFC framework, the *IfcSpatialZone* class plays a similar role. Thus, establishing a *RelToIfcSpatialZone* relationship can capture this connection.

SafetyZones are classified into two types: *ProtectiveZone* and *HazardZone*. A *ProtectiveZone* signifies an area safeguarding endangered objects within the construction site, typically workers. Conversely, *HazardZones* provide spatial descriptions of hazardous areas within the construction site, each identified by a specific hazard type. In this data model, the hazard types are limited to five of the most common hazards in construction sites: Fall, Struck by, Electrocution, and Heat.

As previously discussed, mitigation equipment is employed to address such hazard zones. Given the potential for multiple mitigation measures, mitigation equipment is grouped according to these measures. The *RelToMitigation* linkage includes the connection between hazard zones and mitigation equipment for two key reasons. Firstly, within the training environment, partial removal of mitigation equipment can expose trainees to hazards, a process implemented within the *IMitigate* interface. Secondly, insights from expert interviews highlight the interest among safety trainers in understanding which measures could have prevented accidents. Thus, the link is required to see the possible corrective measures for safety incidents, as described later in Section 5.5.

5.4 Safety parameters

Construction objects have the potential to generate a *SafetyZone*, encompassing both hazardous and protective zones. For instance, a worker requires a protective zone, while equipment such as an excavator may create a hazardous zone.

In general, each *ConstructionObject* can establish a safety zone. Typically, building elements, equipment, and materials tend to create hazard zones, whereas workers are associated with creating protective zones due to their hazardous and endangered nature, respectively. Nonetheless, the data model accommodates hazardous workers as well as endangered building elements. To facilitate the creation of *SafetyZones* based on *ConstructionObjects*, the utilization of *SafetyParameters* is indispensable.

SafetyParameters conceptualize a geometric description of a safety rule within the temporal context of the construction site. For instance, a safety rule might dictate that no worker should approach within 1.5 meters of liquid gas containers. Consequently, the gas container (classified as *Material*) incorporates safety parameters in the form of a cylinder with a radius of 1.5 meters, accounting for the size of the gas tank. This cylinder serves as the blueprint for shaping the corresponding *SafetyZone*, in this instance, a *HazardZone* categorized under the *HazardType* Explosion. The same principle applies to instances of *Equipment*, *Worker*, and *BuildingElement*. Further elaboration on examples will be provided in Section 6 as part of the case study. While the concept of *SafetyParameters* may cover any geometric representation, this study limits the implementation to generic geometries, including cylinders, cuboids, and capsules.

However, it is essential to note that *SafetyParameters* describe a geometric representation of a safety rule without the temporal and spatial context of the instantiated resource. It indicates that the *SafetyZone* may be generated with accurate dimensions but not with the correct temporal and spatial context. Therefore, to ensure the safety zone aligns correctly with time and location, the resource's location at the time of safety zone creation is retrieved from the *VirtualTrajectory*. Subsequently, when the resource changes location, the *SafetyZone* is dynamically adjusted accordingly. To manage the generation, removal, and updating of safety zones, the *ConstructionObject* implements the *ICreateZone* interface, governing these functionalities.

5.5 Safety incidents

Safety incidents form the cornerstone for evaluating trainee feedback, as revealed through structured interviews with safety domain experts. These experts emphasized the significance of knowing the location, time, number, and severity of safety incidents during training. Additionally, they expressed interest in understanding the hazard type associated with safety incidents, along with the corrective measures that could have prevented accidents. Building upon this insight, we have integrated various functionalities addressing these requirements.

A *SafetyIncident* in the context of VirtualSafeConDM occurs when a hazard zone intersects with a protective zone. Given that these zones adhere to safety regulations, we define this event as a close call. In reality, an accident on this occasion could only be averted through timely intervention or chance (OSHA, 2022). Consequently, we aim to track not only incidents resulting in actual collisions but also near misses, enabling us to offer more nuanced feedback on trainee performance.

To facilitate such functionalities, hazard zones must implement the *ICollideZone* interface. This interface incorporates two methods defining the actions following a collision between a protective zone and a hazard zone. While our previous research proposed methods for capturing comprehensive information regarding close calls and calculating severity, this study maintains flexibility by including this interface. In the data model implementation described, we distinguish between near misses and actual collisions. For example, a worker nearing an open edge constitutes a close call, whereas the worker falling from the open edge represents an actual collision, with the severity property of the safety incident indicating this distinction.

The accumulation of safety incidents throughout the training experience is vital for evaluating a worker's safety performance. As previously mentioned in Section 2.1, existing studies often overlook the comprehensive collection of safety-related data. While data collection commonly focuses on hazard identification, detecting and assessing unsafe behaviors holds immense potential, particularly in synthetic data generation, where the construction domain often lacks valuable datasets.

6. CASE STUDY

The objective of the case study is to validate VirtualSafeConDM's ability to consume real-world data and expose a trainee to real-world hazards based on real-world data while collecting behavioral data reflecting the trainee's interaction with the hazards for evaluation of performance. The following section, therefore, describes how the Real-world Hazard-Integrated Virtual Training Environment (RHI-VTE) is generated using the Unity game engine. It first overviews the real-world task and then delves into the data input creation from BIM and RTLS. In the next step, the scene generation in Unity is described before the trainee's mission is finally introduced.

6.1 Experimental setup

The case study is based on a real-world task from a metro renovation project that was recorded in June 2023 in Munich, Germany. The case study includes the staging area where material supplies are stored (see Figure 3). In the specific 15-minute period, several activities were ongoing. There were three machines active: A wheel loader moving gravel, another wheel loader moving materials, and a forklift loading materials on a train wagon.

Figure 3: (a) The selected construction site for evaluation of VirtualSafeConDM is a loading stage for a metro renovation project where a (b) wheel loader and (c) forklift were transporting materials at the tracked task.

During this task, the workers were exposed to several hazards listed in Table 4. These hazard types represent examples of the so-called fatal four categories in construction sites: falls from heights, electrocution, struck-by, and trips. Additionally, a heat hazard is present.

Table 4: Hazards in the case study.

ID	Type	Cause	Safety Rule	Mitigation
1	Trip	Uneven surface	Workers must not enter the railway area.	Guardrails and signage
2	Electrocution	Power generator	Power sources must be guarded and indicated as hazardous.	Guarding the generator and signage
3	Struck-by	Machinery traffic	Areas with traffic must be indicated by signage, and safe walkways must be established.	Safe walkways, crossings, and signage
4	Fall from height	Unprotected leading edges	Open edges with fall height higher than 1m must be guarded.	Hole cover
5	Explosion (pressure and heat)	Gas cylinder	A worker must keep at least a 1.5m distance from liquid gas containers.	Securing the gas bottle and signage

The first objective of the case study is to recreate these hazards in an RHI-VTE so that trainees can be exposed to real-world hazards. For that reason, the real-world situation throughout the task is captured using a BIM model for the static objects and RTLS data for the simulation of dynamic objects (machinery). The data is then integrated into a training environment in Unity, where the VirtualSafeConDM is used to create the training scene. In the next step, an avatar is added to the scene, a mission for the trainee is added, and interaction abilities are added. The complete training scene is then tested by a trainee completing the training. The following sections delve into each of the steps in creating and testing the training environment.

6.2 Real-world hazards from BIM

A BIM model represents the static environment of the RHI-VTE. Recreating BIM models automatically has been studied, and promising results have been shown using point clouds where geometry (Rashdi et al., 2022) and also semantic information could be included (Werbrouck et al., 2020). In this study, however, the BIM model was manually created using the authoring software Autodesk Revit 2023. Figure 4 shows the BIM model, including the existing structures as well as temporary construction site equipment. Moreover, the BIM model provides several hazards. In this study, the hazard zones are modeled manually, but research has shown how such efforts can be automatized (Johansen et al., 2023; Speiser and Teizer, 2024b).

Adhering to safety regulations, any open edge posing a fall risk must be safeguarded. The BIM model includes a fall hazard with an open edge at a maintenance hole (see Figure 4 b). To address this, we model a cover atop the openings and delineate a fall hazard zone accordingly. The BIM model furthermore includes two hazards relating to utilities, as shown in Figure 4f and Figure 4g. First, a safety rule specifies that no worker must get closer to gas tanks than 1.5 meters. For that reason, the gas bottles are guarded by guardrails, and signs are added. The guardrails and the signs are the mitigating equipment. Similarly, a hazard zone is created, and the safety *ZoneType* is set to "Heat". Similarly, a power generator is controlled using guardrails and signage.

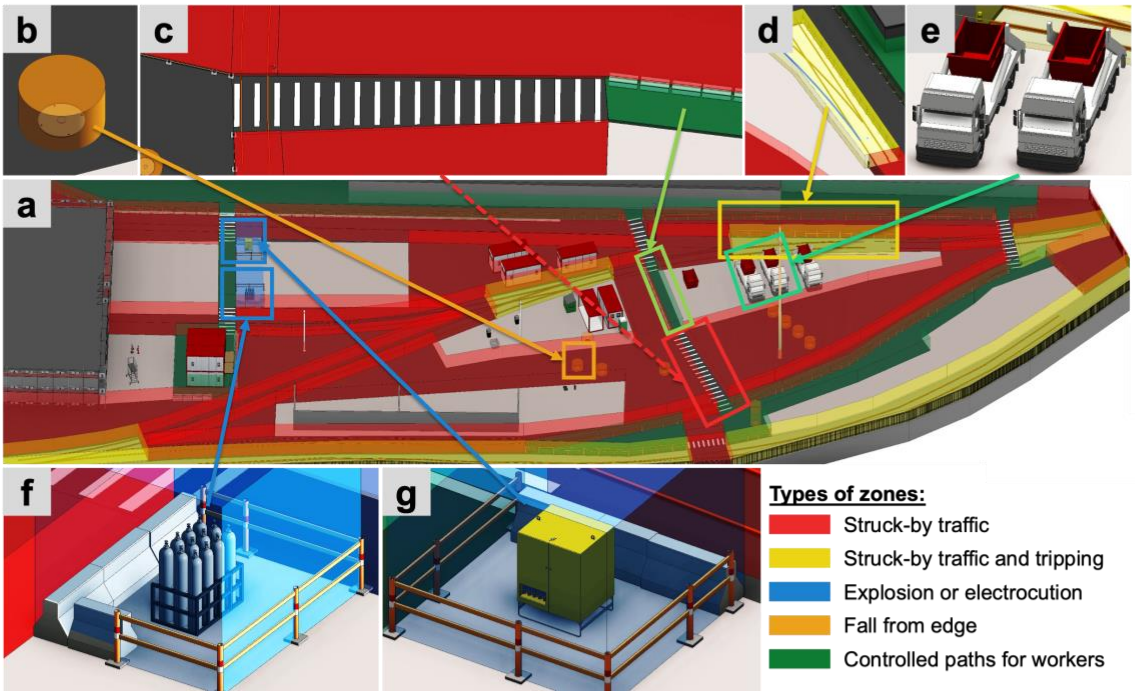

Figure 4: (a) The BIM model in Revit and examples for (b) areas with maintenance holes and rail tracks where tripping and struck-by incidents may occur, (c) fall hazards, (d) a crosswalk for pedestrian workers, (e) construction equipment functioning as a placeholder for equivalent machinery in the form of a model, and (f-g) specific hazard related objects.

There are several areas in the BIM model where rails represent uneven surfaces. These areas are highlighted in yellow in Figure 4. These areas are considered areas with higher tripping risk. Hence, the workers must not enter these zones. The areas are modeled in the BIM model, and the hazard type parameter is set to "Trip". The mitigation equipment is guardrails and signage.

The last hazard is related to operating machinery. All areas where such machinery could be present are modeled as hazardous zones. On the other hand, the mitigation of the hazard is to establish safe pathways for pedestrian workers. Hence, the BIM model includes safe paths and separates the safe path from the traffic zones using guardrails, concrete barriers, and signage. Signage is needed as the pedestrian workers must cross through the traffic zones. All safe walk paths are modeled and will be exported as *SafetyZone* (in contrast to the Hazard Zone). Figure 4 shows the traffic zones in red and the safe walkways in green.

As mentioned before, the connection between the hazard zone and the mitigation equipment is essential. As Revit does not directly allow for creating relationships, an additional parameter is added to all the mitigation equipment, "RefToSafetyZone". The value of this parameter is set to the IfcGuid of the corresponding SafetyZone. Similarly, another parameter is added to the HazardZones referencing the object in the BIM model causing this hazard zone. For instance, the hazard zone related to the gas cylinders will specify the IfcGuid of the gas cylinders.

The BIM model also includes the machinery. However, they will be replaced later in the Unity scene with more realistic representations. Nevertheless, their existence is essential so that the data model can instantiate them in Unity. These elements are later exported to IFC as IfcElement, although they should be included as IfcResource. However, Revit does not support such entities.

While the safety zones for the previous hazards were modeled in Revit, the safety zones for the workers and equipment are instantiated in Unity also to prove the ability of the data model to create safety zones using the *SafetyParameters*. To include this feature, the objects in Revit must provide additional information. The resources also have some parameters assigned based on the safety specifications. These parameters implement the *SafetyParameters* from the data model. While this information would typically not be part of the BIM model itself, we still save the information here for simplicity reasons. The machinery is modeled, and as they are hazardous, a parameter is set to true while the endangered parameter is set to false. The dimensions of the *SafetyParameters* are defined as a cuboid with a 1m offset from a bounding box around the equipment. Lastly, the hazard type is set to Struck-by.

In the last step, we export the Revit model into an IFC file using the IFC4 schema and the Architectural Exchange requirement. To ensure that the properties are exported correctly, we define the property export rules for the IFC export in a .txt file as described in the Revit user manual.

6.3 Real-world hazards from dynamic resources

While the BIM model includes static hazards, VirtualSafeConDM also supports dynamic hazards. In this task, several pieces of machinery were active, representing hazards to pedestrian workers. The three vehicles, two-wheel loaders, and a forklift were performing tasks in the staging area. To recreate their behavior in the RHI-VTE, a recently introduced approach was followed, integrating data from RTLS (Speiser et al., 2023).

For data collection, the vehicles were equipped with a Real-Time-Kinematic Global Navigation Satellite System (RTK-GNSS). RTK-GNSS is a technology for location tracking with high accuracy and reliability in open spaces, improving regular GNSS accuracy through an additional base station and decreasing the error. The sensors on the machines are connected to mobile phones and store the recorded data locally on the phones. The raw data is stored in .csv files, and each line includes the resource ID, a timestamp, and the coordinates at the given time. The resource ID corresponds to the ID of the *IfcResource* element created in the BIM model. To ensure correct visualization relative to the project base point of the BIM model, the location data was transformed into the local coordinate system using the Python library PYTRANSFORM. Figure 5 illustrates the recorded trajectories projected onto a satellite image, which are later superimposed with the BIM model described in the previous section.

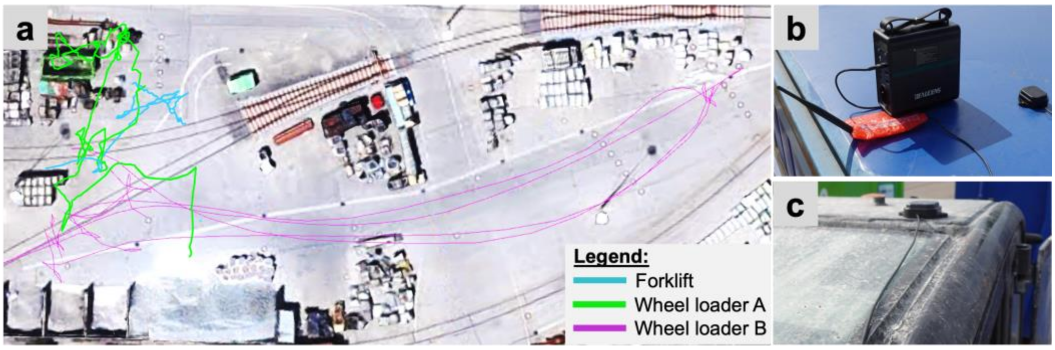

Figure 5: (a) The recorded trajectories of the tracked machinery using the (a) RTK-GNSS base station and (c) rovers assembled on the roofs of the operators' cabins. The trajectories are superimposed on satellite images included in Unity using Cesium. The image does not reflect the state of the site on the day of recording.

6.4 Instantiating VirtualSafeConDM in Unity

With the input data set, we can now import the files into Unity. The IFC model is imported using the IfcImporter asset. We add the BIM model to the scene and add a script to the root object of the BIM model. This script interprets the information added to the BIM model as well as the RTLS data once the training starts. To include all relevant features of VirtualSafeConDM, the script follows the procedure shown in Figure 6.

The script iterates through all the elements of the BIM model. If the element is defined as *IfcSpatialZone* and the parameter *IsHazardous* is set to true, a *HazardZone* is instantiated. If the element is set to *IsEndangered*, a

ProtectiveZone is instantiated.

If the element is a *Resource* (*Material*, *Worker*, *Equipment*), the script will first create a new instance of the corresponding class and add it to the object in Unity. In the case of pedestrian workers and machinery, the game objects are replaced with graphically more accurate representations. The machinery is replaced with the correct machine type, and the worker with an avatar that allows it to be animated. In the second step, if the resource is hazardous, a *HazardZone* is added to the object, and if it is endangered, a *ProtectiveZone* is added using the *CreateZone* method. This method also ensures that the zones exist but are not visible to the trainee. Once the training starts, the zones will be hidden. Nevertheless, collisions will still be detected. While the previous examples in the BIM model had the geometry of the zones modeled, in this case, the safety zones are created based on the *SafetyParameters* information.

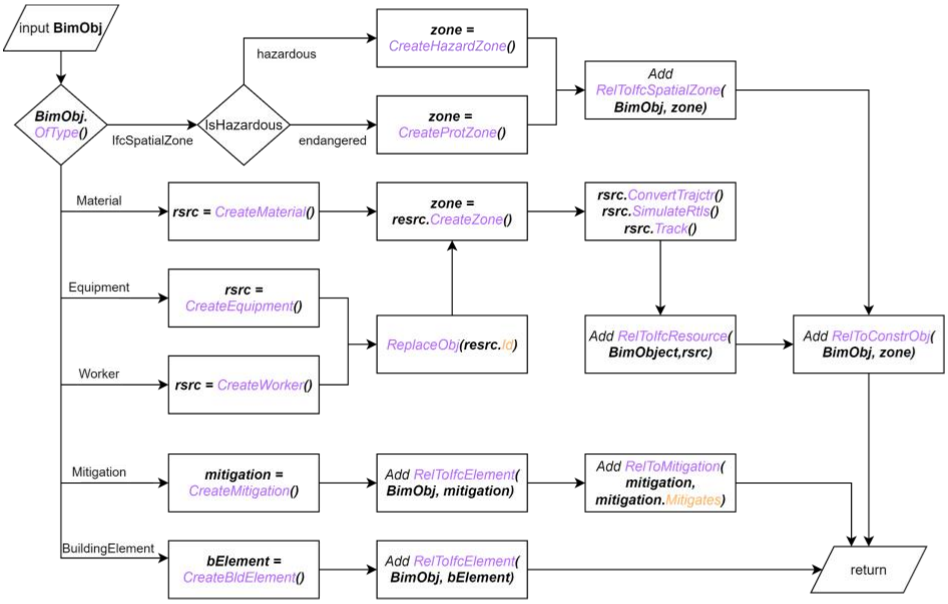

Figure 6: The process for evaluating the information from one individual element of the BIM model and instantiating the corresponding VirtualSafeConDM entity.

Last, the corresponding RTLS data is requested from the .csv file and added to the *RealWorldTrajectory* property by calling the *ConvertTrajectories* method provided in the *IRtlsSimulator* interface. If real-world data is provided, the *FollowTrajectory* method will simulate the motions of the resource based on the trajectory. If there is no real-world data provided, the resource is considered static and will not move during the training experience. The *RecordTrajectory* method starts tracking the locations of the resource during the training experience and stores this information in the *VirtualTrajectory* property. It is essential to point out that the *FollowTrajectory* method must include information about the technical specification of the specific vehicle, as the algorithm to simulate motions may differ depending on the vehicle. If the element represents mitigation equipment, a *MitigationEquipment* component is added to the object, and a *RelToMitigation* between the mitigation and the *HazardZone* is created.

6.5 Hazard interaction and trainee's mission

While the previous steps were purely enabling the visualization of the task, this point integrates the interaction possibilities of a trainee with the generated environment. The trainee's mission is to collect seven objects on the construction site and carry them to material storage. During this activity, the hazards described above were active in the same location as in reality and followed the exact trajectory using the RTLS data; however, the mitigation equipment was partially removed. Hence, the training scenario exposes the worker to real-world hazards.

An avatar is added to the scene, and a protective zone around the worker is added in the shape of a capsule around the avatar with a 1m diameter and a 2m height. To enable interaction possibilities, the *FirstPersonStarter* Asset is used to provide essential functionalities for navigating an avatar using a keyboard and a mouse in front of a desktop (desktop-based VR). This can quickly be replaced with more immersive systems such as an HMD display. The trainee in this scene must navigate through the scene and collect seven objects. During the activity, the functionalities of detecting hazard interactions are tested.

Additionally, the functionality of the VirtualSafeConDM to capture this knowledge is evaluated. Figure 7 illustrates the final training scene in Unity with the avatar. A researcher tests the scene. It is purposely chosen as the objective of this study is to evaluate a framework for creating training scenes and specifically not to evaluate the effectiveness of virtual safety training. Hence, it is not primarily relevant to test the framework with construction workers, despite recent research suggesting that the effectiveness with workers may not reflect the effectiveness of researchers (Adami et al., 2023).

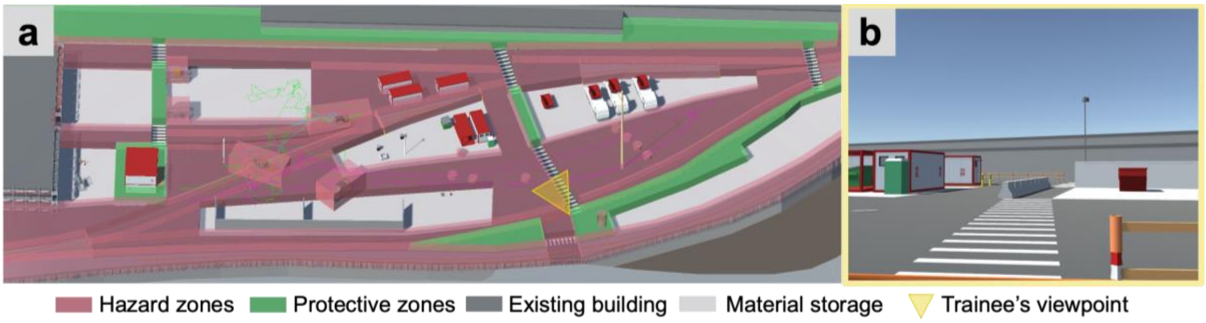

Figure 7: (a) An overview of the complete training scene with the hazard and protective zones and (b) a first-person view of the trainee that navigates the scene where the hazard and protective zones are hidden for collecting data to reflect the trainee's safety behavior.

Based on the implementation of the VirtualSafeConDM described in Section 5, the RHI-VTE can then detect trainee interactions with hazards. Once the training session has ended, all instantiated entities are exported into the knowledge base in the form of a graph consisting of nodes and edges using the JSON format. This graph was then evaluated using the Python library NetworkX to visualize and query the graph, as shown in the following section.

7. EVALUATION

The training scene has been generated and tested using a simple task as described above to evaluate the core functionalities of the proposed data model. The following sections summarize the results from the evaluation of the data model.

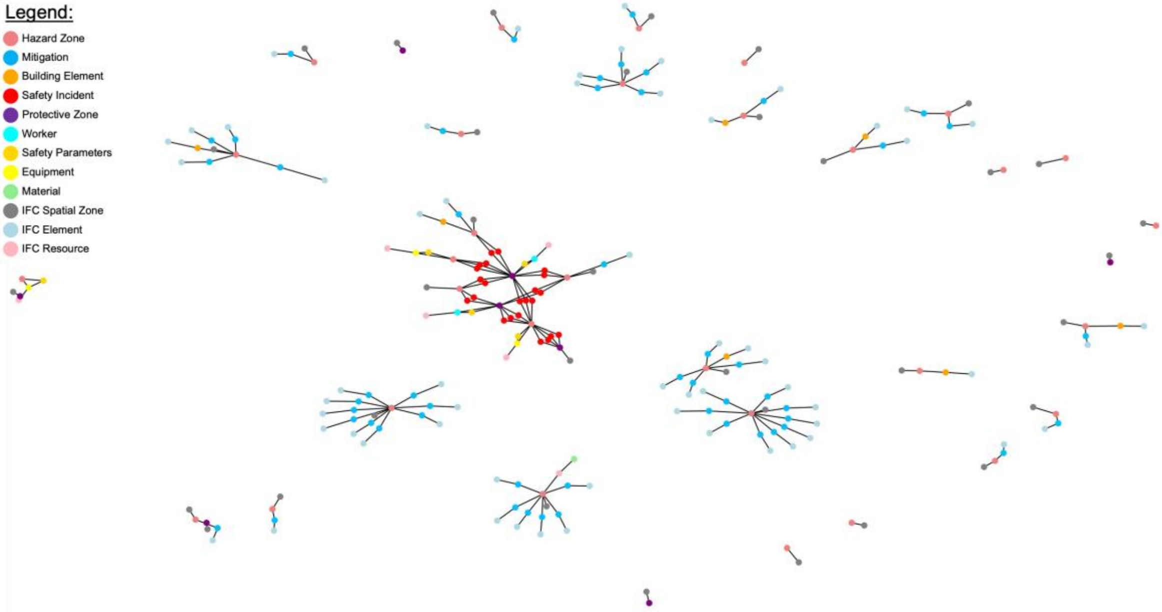

Figure 8: Components of the graph that include at least one node of the type HardZone or ProtectiveZone.

7.1 Complete graph

The training was performed once by a researcher, and the data was collected throughout the training. On completion, the graph was exported with a total size of 9,384 nodes and 13,065 edges, of which the vast amount of data relates to the trajectories of the resources. There is also a high number of *IfcBuildingElements* and *ConstructionObjects*. Thus, the plot of the complete graph is too complex.

Figure 8 illustrates the exported graph after removing all components of the graph that do not include at least one node of type *HazardZone* or *ProtectiveZone* and, thus, do not include knowledge that is relevant for describing the results. Besides, the trajectories have been removed.

The graph provides knowledge on how many hazard zones are in the construction site and how they are mitigated. The graph additionally contains information about the exact location of these elements during the training experience. As these results are presented on a high level, the following sections go deeper by looking at specific nodes of the graph. This graph should have all the knowledge to answer the competency questions defined in Section 4.1. As this is not feasible to validate based on the figure, the following sections describe individual parts of the graph evaluating the answering of the competency questions.

7.2 Hazard evaluation

The hazard zones from the BIM model and the RTLS data have been instantiated correctly. The following paragraphs show the results for several subgraphs, describing the different concepts of VirtualSafeConDM.

The gas cylinders present an entity of the class *Material* and are represented as *IfcConstructionResource* within the BIM model. The graph indicates that the hazard zone for the gas cylinder has been created correctly (see Figure 9). The hazard zone is created based on the geometric definitions in the *SafetyParameters* (a cuboid with a 1.5m distance to the gas containers. The mitigation equipment (barriers, guardrails, and rack) is also connected to the hazard, representing the mitigation measures. This example successfully demonstrates the creation of a hazard zone using the *SafetyParameters* specification in BIM.

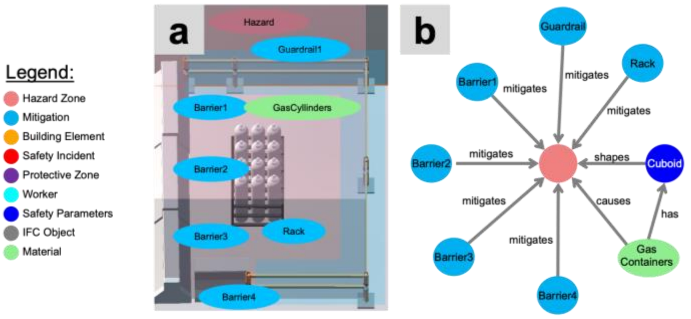

Figure 9: The gas cylinders cause a hazard zone, which is described by a cuboid based on the safety regulation (1.5m distance). The mitigation includes barriers and guardrails.

The remaining semi-static hazard zones are the ones relating to tripping and the traffic zones. They have a different character as they do not emerge from the elements but are directly modeled in the BIM model. Nevertheless, the hazard zone entities are created and linked to the corresponding IFC entities of type IfcSpatialZone. Figure 10 illustrates the concept for one of the trip hazard zones. The trip hazard zones are caused by the rails (*BuildingElement*), and mitigation equipment is in place to control the hazard.

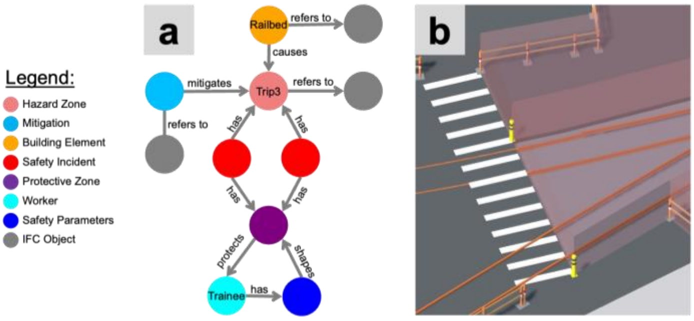

Figure 10: (a) The subgraph includes the trainee who is surrounded by a protective zone whose geometry is shaped by the SafetyParameters. During the session, the trainee caused two safety incidents (close calls) related to the zone with the railbeds (b). These incidents may relate to missing mitigation equipment.

The hazard zone in Figure 9a also demonstrates the successful collection of the trainee's safety behavior. The trainee collides twice with the hazard zone during the training experience. Hence, two safety incidents were added to the trainee's protective zone. The protective zone is shaped by the safety parameters assigned to the worker. In this case, a capsule with a height of two meters was defined.

The dynamic hazards caused by the resource have also been instantiated correctly, followed the paths, and safety incidents are stored once a worker collides with them. Figure 11 illustrates the machines that have been added, and the trajectory was superimposed. They follow the trajectories based on a successfully introduced method from the authors' previous research (Speiser et al., 2023). The trainee triggered nine incidents related to the machines, of which five related to the large wheel loader (see Figure 8).

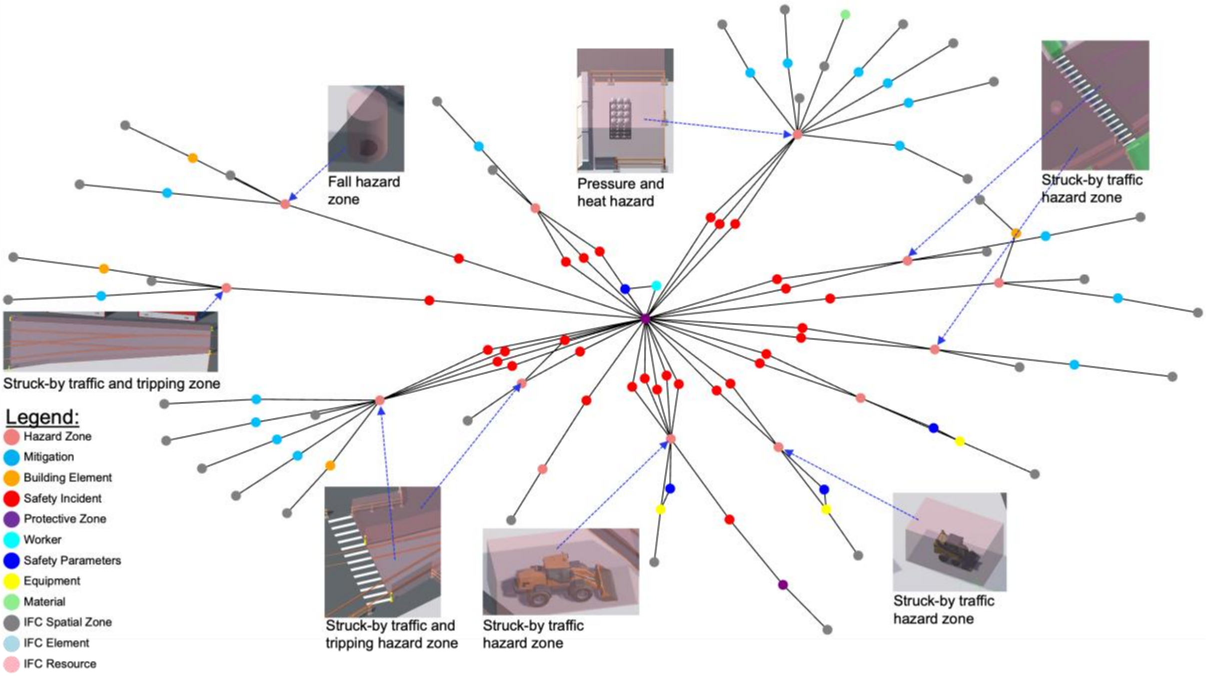

Figure 11: Safety performance knowledge graph comprising the safety incidents from the training session and related hazard zones.

7.3 Performance feedback

Safety performance assessment represents an essential component of safety training. To provide such feedback, the generated knowledge graph must be able to answer the requirements for the performance, formalized in CQ4.1-4.6. The knowledge shall be visualized in dashboards or feedback cards, as illustrated in previous research.

However, this study will only look at the graph and evaluate if knowledge is available.

Figure 11 illustrates the graph containing all knowledge relevant to assessing the safety performance of the trainee. The number of safety incidents (CQ4.1) and the type of hazard causing the safety incident are visually available (CQ4.4). Similarly, the connection to the *Mitigation* allows us to answer CQ4.5. The location of the safety incident is represented by a *TrajectoryPoint* connected to the safety incident (CQ4.2). To find the severity, the node safety incident node includes another property that is not visible in the figure but is assigned to each incident. The remaining CQ4.6, addressing the comparability of several performances, is not addressed in this research. However, the number of safety incidents for each training session could be an applicable measure.

The knowledge in this graph allows us to quantify the safety behavior of the trainee. The trainee caused a total of 29 safety incidents. Six incidents relate to three different zones of the railway where tripping and being struck by a trafficking railway could occur. Nine incidents relate to the machinery, with the forklift and small wheel loader causing two incidents each and the large wheel loader causing five incidents. Moreover, the trainee entered four different traffic zones with a total of 8 times. Three incidents relate to the hazard caused by the liquid gas containers, and one incident relates to the unprotected leading edge. While not shown in Figure 10, the spatial information of the occurrence of the incidents is also given. A safety trainer may conclude shortcomings in the trainee's safety behavior and may provide personalized training for them based on this quantification.

7.4 Criteria evaluation

Clarity refers to the ability of an ontology to clearly convey the intended meaning of defined terms, ensuring they are unambiguously specified (Gomez-Perez, 1995). As the proposed data model is based on ontologies, we assume that the same applies to the VirtualSafeConDM. To ensure the clarity of the proposed data model, most concepts and definitions are re-used from existing ontologies and concepts, specifically the open standard IFC, the Cogito ontology, a hazard ontology, and a previously published data model. Hence, the concepts and relationships are unambiguous and convey the purpose.

Similarly, the fact that most concepts refer to existing concepts underlines that VirtualSafeConDM is extendible. Besides, adhering to the SOLID principles when developing the model, particularly when including interfaces and polymorphism, allows for extension (Martin, 2002).

VirtualSafeConDM is consistent because it has been implemented in the game engine Unity using the programming language C#. The nature of C# would not allow the program to execute if the data model was not implemented consistently. The case study in the prototype also shows that VirtualSafeConDM satisfies the criteria of usability.

The coverage of the VirtualSafeConDM is validated by answering the CQs. All CQS defined in Section 4.2 can be answered from the created knowledge graph during the training session. CQ1.1- CQ1.3 can be answered with the data input. In the prototype, the BIM model includes all the knowledge needed to answer these questions. Similarly, CQ2.1-CQ2 can be answered from the data input. However, in this case, the BIM model only includes the knowledge related to the semi-static hazards, and the RTLS data includes the knowledge about the dynamic hazards. Specifically, with respect to the dynamic hazards connected to RTLS data, CQ3.1 is answered by the knowledge graph, and the implemented algorithm to simulate the resources answers CQ3.2. Lastly, the CQs regarding performance were addressed in the previous Section.

8. DISCUSSION

The approach outlined in this study offers a general and usable framework for training creators to build more realistic training scenarios in virtual reality. By integrating information from real-world sources in the form of IFC and RTLS, the study demonstrated the feasibility of creating training scenes that simulate real-world hazards. The integration of these data sources allows for the recreation of historical safety incidents in virtual settings, providing a foundation for relevant training scenarios. This flexibility in scene creation enables training creators to adapt scenarios to specific training objectives and needs, ensuring that virtual training experiences are tailored to address relevant safety challenges in the construction industry. Overall, the integration of IFC and RTLS data serves as a practical and effective approach to developing virtual training scenes that accurately reflect real-world conditions, offering a novel platform for safety training in the construction industry.

VirtualSafeConDM can overcome the intention-behavior gap by incorporating real-world hazards into an RHI-VTE. Traditional safety training methods often rely on passive learning approaches, which may not accurately influence how individuals behave in real-life hazardous situations. However, by integrating data from sensors and BIM models, the RHI-VTE created in this study closely reflects on-site conditions. By exposing trainees to lifelike simulations of construction tasks and hazards, the approach ensures that trainee behavior is quantified in realistic scenarios, thus bridging the gap between intention and behavior. This alignment between training scenarios and real-world situations may enhance the effectiveness of safety training programs by providing trainees with the opportunity to practice and refine their safety skills in a safe yet realistic environment. Therefore, the approach not only enhances the realism of training scenarios but also facilitates more accurate quantification of trainee behavior, ultimately leading to improved assessment opportunities for safety behavior.

While VCST platforms offer opportunities for assessing safety behavior in simulated environments, challenges in accurately replicating human behavior and decision-making processes remain. Trainee responses in virtual scenarios may not always reflect real-world actions, leading to potential discrepancies between simulated and actual safety performance. Validating the transfer of learning was not within the scope of the work but requires further investigation through broader evaluation campaigns with more trainees of different backgrounds, e.g., construction workers, equipment operators, novices, and experts. Validating this approach faces challenges in practice, but Harris et al. (2020) discuss approaches to demonstrate Construct Validity and Fidelity in virtual training to evaluate the transfer of learning. The critical point is that the effectiveness of training can always only be measured once clear training objectives are set Harris et al. (2020). This work, however, provides a general framework where specific training objectives would not contribute to the purpose of this work.

The integration of existing knowledge specifications and ontologies in the framework enables knowledge re-use and seamless knowledge sharing of the training results. By integrating existing ontologies from a digital twin, a hazard ontology, and IFC, the framework includes pre-existing safety knowledge. These ontologies provide structured representations of safety concepts, hazard types, mitigation measures, and other relevant concepts, facilitating efficient knowledge exchange and interoperability. Additionally, the use of ontologies enables the framework to capture and represent complex relationships between safety elements, ensuring that training scenarios are accurately modeled and reflect real-world conditions. Furthermore, ontologies inherently support knowledge sharing by providing a common vocabulary and semantic framework for communication and collaboration among stakeholders. This allows for the seamless transfer of training results, insights, and best practices across different projects, organizations, and domains. Overall, by integrating existing ontologies, the framework enables effective knowledge re-use and sharing, enhancing collaboration and interoperability in construction safety.

VirtualSafeConDM includes novel concepts that have not been part of previous ontologies. For instance, an existing ontology focuses on fall spaces but does not address dynamic equipment or the detection of safety incidents, but VirtualSafeConDM does. Nevertheless, further adjustment is required regarding the inclusion of other sensor data. VirtualSafeConDM uses the location and constant shape described by the safety parameters. However, the safety parameters could change, e.g., the boom and bucket of an excavator constantly move and would require dynamic updating of the hazardous zone. Future work should investigate how such behavior can be integrated using more detailed sensor evaluation algorithms.

VirtualSafeConDM is extendible as it implements generic concepts and interfaces that can be added and removed. For instance, RelToIfcElement links resources to elements of an IFC model. Similarly, the safety zones are linked to IfcSpatialZones. It is preferred to include such relationships rather than inheriting directly from them to be more open to other approaches. In the last few years, more schemes for interoperable data exchange have emerged, and limiting the scope of IFC could prevent innovations.

The case study indicates that VirtualSafeConDM is a starting point for a domain-specific safety extension of the IFC schema. The presented data schema integrates several concepts into the IFC language. Nevertheless, until today, there is no Model View Definition (MVD) in IFC that specifies safety requirements, nor does the IFC schema particularly address safety concepts. At the same time, VirtualSafeConDM and other previous work fit the concepts of construction safety into IFC.

The VirtualSafeConDM covers the set requirements established through the expert interviews, but further aspects are left out. For instance, it remains unsolved whether VirtualSafeConDM can facilitate long-hauling training on a personalized level. While our previous work introduced a method to create personalized training (Speiser and Teizer, 2024a), the long-term consequences of VCST remain a research gap. In this study, a data schema that eases the creation is demonstrated and will also provide a framework for training creators to create long-hauling training, but future research must address this.

Another aspect that is not addressed in our study is the integration of technologies to enhance immersion in VR. Such technologies as treadmills, head-mounted displays, scent diffusers, or thermal simulations may create other requirements for the data model that are not satisfied. Similarly, the data model is targeted at single-trainee sessions. However, collaborative sessions must also be supported, which future research needs to investigate.

In summary, the research questions presented at the beginning have both been answered within the scope of the research. VirtualSafeConDM integrates existing knowledge specifications into a schema for VCST. The reference to IFC and the integration of relevant safety concepts ensure a flexible extension to needs. Second, the case study using the IFC model and RTLS data has shown that VirtualSafeConDM supports creating a training scene and collects data that can be processed to quantify the safety behavior of a trainee. The assessment of this quantification remains for future research.

9. CONCLUSION

Active training methods have been shown to be significantly more effective than passive methods in various fields, including construction safety training. However, traditional on-the-job training, while effective, presents limitations such as content inflexibility and user exposure to real hazards. VCST offers a promising solution by providing active training in a safe virtual environment. Despite its potential, existing VCST approaches often fail to adequately assess safety behavior, relying instead on subjective measures or post-training surveys. Bridging this gap between intention and behavior is crucial for accurately evaluating safety training efficacy.

This study proposed VirtualSafeConDM, a data model that integrates existing ontologies and schemas to create Real-World Hazard-Integrated Virtual Training Environments (RHI-VTEs). By leveraging BIM models and RTLS data, VirtualSafeConDM enabled the creation of training scenes that accurately reflect real-world conditions while ensuring safety. The model facilitated the seamless sharing and re-use of safety knowledge.

The significant contributions of the VirtualSafeConDM are (1) the integration of existing ontologies and schemas such as IFC, to ease the generation of training scenes, (2) integrating functionalities to collect data related to the interaction of the trainee with hazards during the training session, (3) integrating real-world hazards using BIM and RTLS to create more relevant training scenarios, and (4) enabling further enhancements due to the implementation in Unity, a commonly used tool for developing construction safety training.

The evaluation of VirtualSafeConDM through a case study demonstrated its practical feasibility and usability. The model successfully captured safety behavior during training sessions, providing valuable insights into trainee performances. However, further research is needed to address challenges such as personalized training or evaluating the effectiveness of the training method through broader campaigns with more trainees of different backgrounds. Additionally, the integration of emerging technologies like VR enhancements requires ongoing investigation. Another essential research path includes investigating the effectiveness of such training environments when it comes to the transfer of learning.

In summary, VirtualSafeConDM offers a versatile framework for developing safety training scenarios in the construction industry. By addressing the intention-behavior gap and enabling knowledge sharing, VirtualSafeConDM contributes to advancing safety practices and improving outcomes in construction safety.

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