BIM-based fall hazard ontology and benchmark model for comparison of automated prevention through design approaches in construction safety

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Abstract. Due to the continuous changes in its complex and dynamic work environment, work in the construction industry is one of the most dangerous. Many of the existing workplace safety planning techniques are still based on 2D drawings and manual expertise. This effort is cumbersome as the progressing work quickly results in outdated safety plans. Researchers have put much effort into automating the planning process, but their result's soundness and completeness are incomparable. This work describes our BIM-based ontology of construction hazards and mitigation interventions for fall from height hazards based on EU and US regulations. We extract the variations of the rules and capture the concepts in spatial artifacts. We carefully created a benchmark model that allows for soundness and correctness assessment which enables comparison of different automated PTD approaches.

1. Introduction

Construction is one of the most dangerous industries due to the continuous change in the environment (Pinto et al., 2011). Over time, the previously safest route may have turned into a very dangerous route, e.g., because of changes in the tower cranes planned tasks, missing fall protection equipment, or debris in the designated pedestrian walk path. Consequently, the workers are responsible and must be aware of, consider, and adapt to new hazardous situations that may not be a part of the safety plan due to the low temporal resolution adopted when undertaking initial safety planning. Safety planning is currently a manual and labour-intensive task. In particular, the standard planning process only covers the overall site layout in a coarse temporal resolution because it would be impossible to generate a new safety plan on every state change of the construction site. The lack of temporal precision and, therefore, the demand for the workers to take over the situation planning, result in thought-provoking statistics.

Furthermore, current manual safety assessment is done on an overall procedure, typically once at the beginning of a construction project and often based on 2D cad drawings of the construction site and building layout. Additionally, safety planning may be subject to human biases, and the safety expert may even oversee potential hazards. Often, it is chosen to make the complete construction site, including indoor areas, subject to an injunction of hardhats even though only parts of the construction site are subject to *strike from the above* hazards. Finally, the overall request may result in safety equipment fatigue.

A report on labour statistics in the US from (BLS, 2020) shows that fatalities in the private construction industry correspond to 21.2% (1008) of fatalities (4764). Furthermore, the report indicates that the predominant reason for fatalities in the construction industry is falls, slips, and trips, which correspond to 36.5% (368). These findings motivate the research and development of automated safety design and planning, also referred to as Prevention Through Design and Planning (PtD/P). With the emerging research of automating the task, manual work is reduced, and consequently, the temporal resolution is expectedly rising. Furthermore, an automated programming-based approach may be less biased and prone to produce errors

https://doi.org/10.7146/aul.455.c231

depending on the accuracy of the rule implementation. In general, assessment of truth is a non-trivial task but especially a comparison of the automated approaches.

To get the full benefit of an automated approach, it needs to be sufficiently fast and operate on an updated version of the Project Intent Information (PII) considering the current stage of the construction site captured in the Project Status Knowledge (PSK). PII and PSK are introduced in (Sacks et al., 2020) as a part of the Digital Twin (DT) concept. In our previous work (Teizer et al., 2022), we outline a holistic approach to interact with a DT in PtD/P and other safety aspects. The emergence of DT is an enabling factor for automated safety design and planning, where the temporal precision can be enhanced. It also enables further insight into the historical data of the construction crew and specific scenarios that need extra attention in the design.

The current research in the domain of automated safety design and planning is often based on individual models, which makes the comparison of approaches complicated. Furthermore, it is our understanding that a common standardized approach of defining hazards in construction would be beneficial in combination with a benchmark model that can be used for correctness assessment. Our research questions for this study are therefore:

> *RQ 1* Can we formalize *fall from height* hazards as defined in Germany, Denmark, and the US construction safety regulations, where considered mitigation strategies are guardrails and cover boards using spatial artifacts extracted from building information models?
>
> *RQ 2* Would such a formalization be accessible to industry practitioners and readily exploited in current workflows?
>
> *RQ 3* Can various approaches to formalizing fall safety hazards be put on a “level playing field” so strategies can be directly compared in terms of soundness and completeness?

In addressing these research questions our contributions in this paper are:

> *C1* We present a new concept and formal definition of a shared benchmark BIM model, with a precise formal definition of sound and complete *fall from height* analysis.
>
> *C2* We develop a new, freely available benchmark BIM model, with the precise sound and complete analysis according to DK, DE, and US construction safety standards facilitating a “success” score calculation by following our prescribed safety criteria.

2. Related Work

The domain of construction code and regulation checking is an ongoing research topic. The most commonly investigated rule is regarding *fall from heights* hazards as these are responsible for most fatalities in the construction industry (Collins et al., 2014; Li et al., 2022; Melzner et al., 2013; Schwabe et al., 2019). To explore automated prevention through design, one must first define a link between the construction regulation and the Building Information Model (BIM) and afterward define the logic that can check whether the regulation is violated in a given BIM model. The drive behind the efforts has been the fact that the current practices are cumbersome and affected by manual assessment. With the emergence of Digital Twins (DT), the knowledge gap between the current state of the construction site and planning has been made smaller. As presented in DTCS (Teizer et al., 2022), the digital twin and automated safety assessment even allow the decision-makers at the construction site to analyze different approaches in terms of cost, time, safety fitness, etc., before making a choice.

2.1. Linking construction safety codes to building information models

We need a way of formally capturing construction regulations and building codes such that the computer can (1) interpret the natural language formulation of the content and (2) link this content to concepts in BIM for automated safety analysis in construction. There are several construction safety ontologies that capture object concepts and their relationships (Lu et al., 2015; Wang and Boukamp, 2011; Zhang et al., 2015a; Zhou et al., 2016). Some of these ontologies are used for safety rule checking, i.e., to determine if some safety hazards are present in the BIM model under investigation. The above examples successfully point out the areas where the safety expert needs to be cautious and apply temporary prevention equipment. However, these automated approaches are not applied in actual construction hazard planning, which may be due to a lack of knowledge and descriptiveness of ontologies.

2.2. Construction hazard identification

Takim et al. (2016) and Zhang et al. (2015b) are examples of automated fall hazard identification, which are based on maximum elevation height, and maximum slab openings, that are allowed before prevention measures must be applied. In Tekbas and Guven (2020), the prevention measures are injected into the BIM model using Dynamo, the Revit programming interface. Even though those mentioned above are already significant contributions, their correctness and soundness cannot be assessed without going through the identified hazards individually. The reason is that there is no easy way to compare the results of the different approaches in an environment that contains identified edge cases. Another reason is that the algorithms are often benchmarked on the number of identified hazards but not compared to the number of existing hazards. Benchmarking is commonly used in other domains such as machine learning and computer vision, where a portion of the data, i.e., test data, is used as ground truth to assess the correctness and soundness of a trained model (Deng et al., 2009; Xuehui et al., 2021). The adoption of benchmarking provides the stakeholders with a deeper insight into the quality of the hazard identification provided.

3. Methodology

By comparing different approaches to defining domain languages for construction safety analysis and assessment, we have chosen to follow a similar approach to the one presented in (Zhang et al., 2015a) and later adopted in (Li et al., 2022). The approach is based on IDEF5 (Peraketh et al., 1994), which consists of five subsequent steps that will generate three resulting outputs, i.e., a graphical representation of the ontology language, a structured text representation, and a procedure with a guideline for information extraction.

3.1. Step 1: Organizing and Scoping

The purpose of initiating a formal standardization of a construction safety domain language is to provide an approach that can be used in our future research and the community to streamline the efforts on automated construction safety assessment. We initiate the domain language with the most straightforward and predominant spatial artifact (i.e., *movement*, *fall*, and *fall hazard space*) and envision the vocabulary extending over time when work progresses in the community. We base our ontology on the Industrial Foundation Classes (IFC) to permit interoperability. Additionally, the IFC structure is similar to graph databases used in the emerging Digital Twins (DTs).

3.2. Step 2: Data Collection

We collect the natural language formulation of the construction safety codes from the European Union, Denmark, Germany, and the US regulation. We have chosen the EU regulation to get an overview of Europe, Denmark (where we are located), and Germany to compare similarities within the European countries. Besides the European regulations, we have chosen to consider the US regulations as it should reveal differences and similarities between the two continents.

3.3. Step 3: Data Analysis

Based on each of our chosen country and continent regulations, we extract two kinds of information: (1) their definition of when fall protective equipment must be applied, (2) The dimensions of hazard space for different mitigation strategies, and (3) example implementations of fall protection systems. The extracted and analyzed information is assumed to make our ontology applicable for at least the included countries and continents.

3.4. Step 4: Initial Ontology Development

Our initial ontology is based on the current state of the art, which we refine to ensure further applicability and consensus in the research domain. The ontology focuses on fall hazard scenarios. Based on our data analysis (step 3), we extract the variating factors and define a vocabulary of variables that we extract from the regulation. Subsequently, we define the ontology using spatial artifacts and the vocabulary. Additionally, we propose a strategy to integrate the spatial artifacts into IFC, which exclusively depends on existing IFC-classes, meaning that the ontology is compliant with the IFC4 tools and workflows.

3.5. Step 5: Ontology Refinement and Validation

To refine and validate our ontology, we develop a benchmark model. Based on the regulations, we carefully create scenarios that will, or will not, require fall hazard mitigation equipment depending on the regulation. We are utilizing the benchmark model to validate our ontology and expectedly refine it during this process. Additionally, we will refine the ontology based on other continents and countries and feedback from practitioners in future research studies.

4. Otology development

4.1. Safety regulation collection and analysis

We analyze the European (ES, 2018), Danish (BFA, 2020), German (BG-Bau, 2021), and US regulations (OSHA, 2019). To ensure that the proposed ontology is representative, we extract the factors that are present in them. We compile the variating factors into a vocabulary and extract their values for comparison, as shown in Table 1. Figure 1 shows a graphical representation of the vocabulary variables, which are limited to *falls from height*, where mitigation approaches include safety guardrails and cover panels. Hence, we are not investigating safety nets.

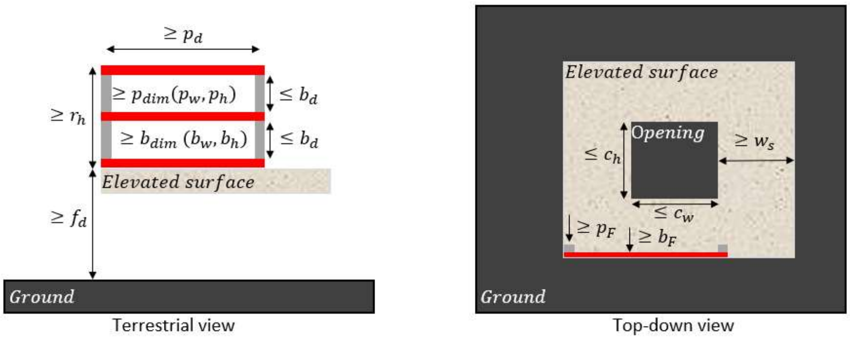

Figure 1: Illustration of values in Table 1 (horizontal boards colored in red and vertical poles in grey)

4.2. Definition of ontology for fall from heights

After extracting the variables that change in the European, Danish, German, and US regulations, we define our ontology that captures the construction regulation. Our ontology shown in Figure

2 is based on spatial artifacts, which captures concepts pertaining to human experience and behaviour as semantically rich regions of empty space. In a BIM model, spatial artefacts are derived from IfcElements and their spatial relationships. Depending on the point of view, the surface of a slab (for example) may simultaneously introduce a walkable space, fall space, and tumbling space. Thus, extraction of the spatial artifacts is based on the construction regulation, the element relationships according to specific points of view, the location of the IfcElement instance, and the geometry of the IfcElement instance; the location and geometry are extracted from instance's IfcProductRepresentation. Additionally, the relationship between spatial artifacts may introduce *hazard spaces*, e.g., Fall hazard space. Each hazard is mitigated via mitigation equipment, which is a subclass of IfcElement. The individual mitigation strategies have test procedures specified in the safety regulation. The test procedure indirectly captures the attributes of the mitigation system, e.g., dimensions, pole- and bord distances, etc.

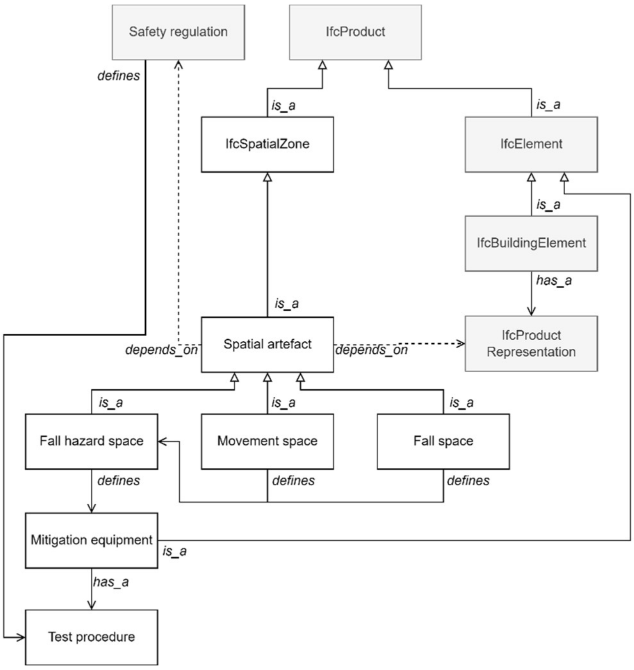

Figure 2: Diagram of our BIM-based ontology of construction hazards and mitigation interventions.

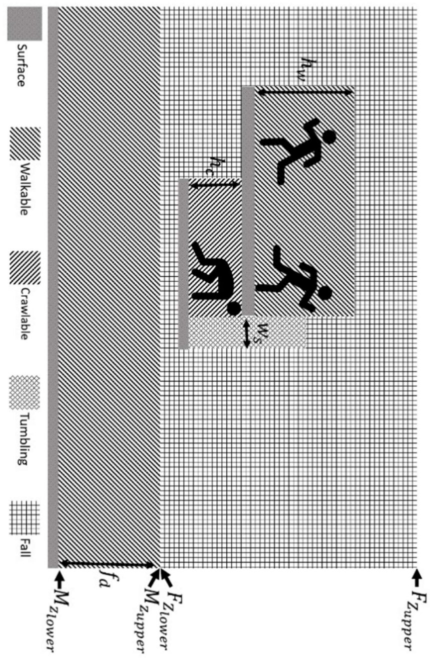

Figure 3: Illustration of spatial artefacts extracted from IfcElements.

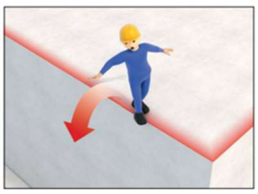

Figure 4: Leading edge.

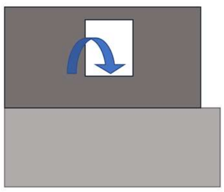

Figure 5: Offset leading edge.

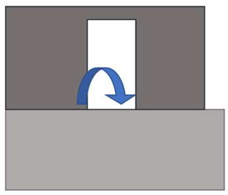

Figure 6: Offset top leading edge.

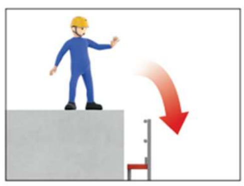

Figure 7: Tumbling space.

4.3. Integration into Industry Foundation Classes

Figure 3 presents our latest version of IFC integration, which is based on the work presented in (Li et al., 2022). The integration utilizes the IfcProperty class and the IfcRelReferencedInSpatialStructure class to capture information about which products in the BIM model directly generate a given spatial artifact. This version is fully compliant with IFC4 and can be processed by all IFC4 compliant tools. Each spatial artifact is implemented as an instance of the IfcSpatialZone class. The spatial artifact type is expressed as an instance of IfcProperty that selects an enumerated value.

Table 1: Variable vocabulary defined through analysis of scoped regulations.

Natural language formulations	Attribute	Symbol	US	EU	German	Danish
The minimum distance, from an elevated surface to a lower surface which an item or a human being could fall onto, which would require a form of fall protection equipment.	Fall distance	f_d	1,8m	1m	1m	1m
The minimum width of a surface, which an agent is allowed to be present on	Surface width	w_s	56cm	60cm	60 cm	60cm
The minimum Height of a space, which is considered walkable	Walk height	h_w	NA	NA	NA	NA
Minimum height of a space considered crawlable	Crawl height	h_c	NA	NA	NA	NA
Maximum width of hole in a surface, where chosen mitigation will be a coverboard, i.e., maximum width of cover boards	Cover width	c_w	1m	NA	NA	NA
Maximum height of hole in a surface, where chosen mitigation will be a coverboard, i.e., maximum height of cover boards	Cover height	c_h	1m	NA	NA	NA
Minimum height of guardrail (aka., Safety railing, safety barrier)	Railing height	r_h	1,1m	1m	1m	1m
Maximum distance between vertical poles of guardrail installation	Pole distance	p_d	2,4m	NA	2m	2,25m
Maximum distance between horizontal boards in guardrail installation	Board distance	b_d	$r_h/2$	0,47m	0,47m	0,47m
Best practice width of applied vertical poles in guardrail installation	Pole width	p_w	5cm	NA	3cm	4,5cm
Best practice height of applied vertical poles in guardrail installation	Pole height	p_h	10cm	NA	15cm	7cm
Best practice width of applied horizontal boards/rails in guardrail installation	Board width	b_w	2,5cm	NA	3cm	3,2cm
Best practice height of applied horizontal boards/rails in guardrail installation	Board height	b_h	15cm	NA	15cm	15cm
Minimum continues force that vertical poles in guardrail installation should withstand	Pole force	p_f	890N	300N	300N	300N
Minimum continues force that horizontal boards in guardrail installation should withstand	Board force	b_f	890N	300N	300N	300N

Table 2: Overview and description of spatial artifacts for fall hazard identification and analysis.

Spatial Artefact	Specialized subclasses	Description	Illustration	Constraints
Movement space		Regions in which an agent (e.g., construction worker, manager, and visitor) can travel.		
	Crawlable space	Regions in which an agent can travel crawling.	Figure 3	$h_c \leq height < h_w \; and \; width \geq w_s$
	Walkable space	Regions in which an agent can travel upright	Figure 3	$height = h_w \; and \; width \geq w_s$
Fall space		Regions in which an object or agent will fall by f_d.	Figure 3	$F_{z_{lower}} = M_{z_{lower}} + f_d$
Fall hazard spaces		Regions in which an agent is subject to a fall hazard		
	Leading edge space	Regions where the movement space in its full height intersects with a fall space	Figure 4	$M_{z_{lower}} \geq F_{z_{lower}} \wedge M_{z_{upper}} \leq F_{z_{upper}}$
	Offset leading-edge space	Regions where a portion of the movement space intersects with a fall space	Figure 5	$M_{z_{lower}} + offset_{lower} < M_{z_{lower}} + r_h$
	Offset top leading-edge space	Regions where a portion of the movement space intersects with a fall space	Figure 6	$M_{z_{upper}} - offset_{upper} < M_{z_{lower}} + h_c$
	Tumbling space	Regions in which an agent can tumble over fall prevention equipment on lower surface	Figure 7	$z_{upperSurface} - z_{lowerSurface} < f_d \wedge width_{lowerSurface} < w_s$

The enumeration of spatial artifact types is implemented as an instance of IfcPropertyEnumeration, with the name "PEnum_SpatialArtefactType". The relationship with existing products in the IFC model that are used to directly generate the spatial artefact is expressed via an instance of IfcRelReferencedInSpatialStructure; for example, a slab on which a person can walk may be used to derive a movement space.

For representing mitigation strategies (e.g., coverings, harnesses, safety nets) we adopt a similar approach by creating instances of the existing class IfcCivilElement and assigning a property enumerated value (with a custom property enumeration listing the mitigation strategies) to indicate the mitigation strategy class.

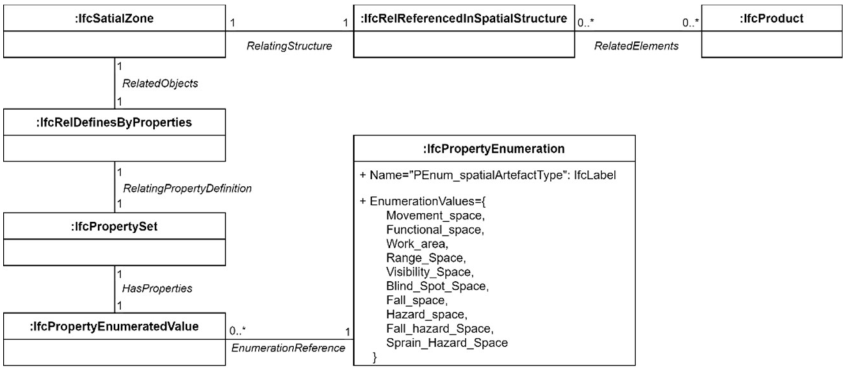

Figure 8: UML class diagram depicting how instances of spatial artifacts for safety analysis are expressed in standard IFC4.

4.4. Validation of ontology

Figure 11 shows the results of our automated approach of prevention through design, specifically for fall hazard identification and prevention. The algorithm is running on an IFC file exported from CAD software. The result, which is also IFC-format, is imported into the same CAD software for subsequent internal correctness and soundness assessment. As part of future work, the ontology will be further validated in a series of studies and workshops where industry experts are interviewed to assess the analysis soundness and completeness, and to assess how this analysis fits into their current practices, workflows, and tools. Additionally, we will assess the expandability, portability, and scalability of our approach, e.g., by extending the current coverage to other continents and hazard types.

5. Definition of the benchmark model

Figure 9 shows the benchmark model that has been carefully designed to include edge case scenarios of the regulations that have been investigated for this work. Specifically, it consists of two parts separated by the stamped line. The first part in front of the dashed line shown in the detailed view in Figure 9 is designed such that the first platform's elevation (f_d) is below the threshold for all analysed regulations, the second platform's elevation (f_d) is high enough to be subject to the EU regulation, and the third platform's elevation is subject to both EU and US regulation. Additionally, the platforms have been designed with smaller outgoing platforms, whose widths (w_s) are chosen to be subject to individual regulations, described in the figure. Lastly the platforms include two openings, where one is bigger than the allowable coverable dimensions (c_w and c_h) stated for the US regulation; i.e. the larger opening requires guardrails, and the other smaller opening requires a covering. This dimension is not stated for the EU regulation, and it is assumed to have the same measure requirements. The other part of the model (behind the stamped line) is designed to capture special cases such as openings in walls and slabs, leading edges, coverable gabs, tumbling spaces, leading edges that are non-orthogonal to the model space, and obstacles in the movement space.

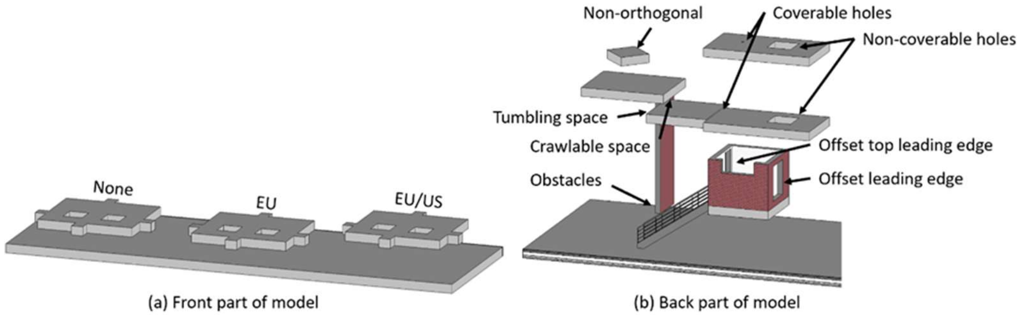

Figure 9: 3D view of benchmark model (a) front and (b) back with description of included scenarios.

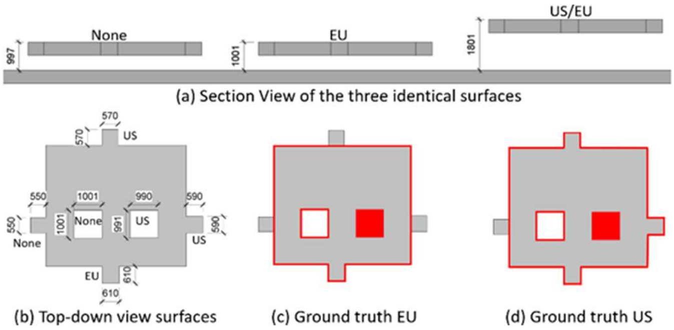

Figure 10: (a) 2D section and (b) top-down view of f_d and w_s in scenarios and their application in (c) EU and (d) US regulations from Figure 9 (a).

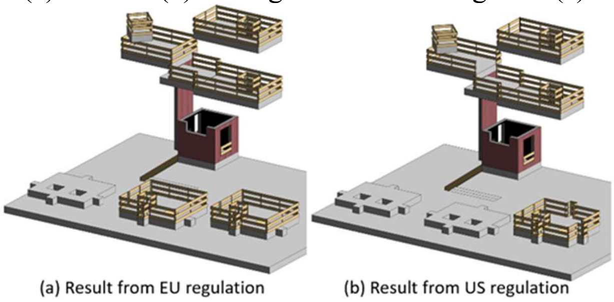

Figure 11: Safe design based on (a) EU regulation and (B) US regulation.

6. Discussion

We have created the ontology based on the *fall from height* safety regulations of two regions, Europe and the US. Additionally, we have performed internal validation through an internal safety expert assessment. This assessment will be extended in future work to incorporate external industry practitioners. Furthermore, the ontology will be tested against other countries and continents.

We provide a benchmark model consisting of two parts: the front part, which contains edge cases of the analysed regulations, and the back part, which consists of different IfcElements that create the various spatial artifacts described in our ontology. The benchmark model does not yet contain any sloped surfaces, which is another aspect to be addressed in future research.

The ontology and benchmark model have been developed to be utilized in our own prevention through design algorithm. We have included the results in Figure 11, but as this is not the main contribution, we have not described this in detail. Nevertheless, it has been the basis for the internal soundness and completeness assessment. This has been done on the input (regulation, benchmark model, and ontology) and output (safety enhanced model). One final direction we are pursuing is automatically generating benchmark BIM models directly from a formal logic-based description of hazards (such as *falls from height*), taking inspiration from automated test case generation in software engineering (Larsen et al., 2010), spatial grammars and generative design (Mckay et al., 2012), and declarative spatial reasoning (Bhatt et al., 2011; Schultz et al., 2017). This will involve adapting notions of equivalence class partitioning, boundary testing, and coverage to the construction safety domain, e.g., what we refer to as *edge cases* corresponds to strategies in boundary testing.

7. Conclusion

We analyzed the construction regulations pertaining to *falls from height*, specifically for cases where guardrails and cover panels are used as a mitigation measure. We formalized the rules and their variating factors into tangible definitions using spatial artifacts that can be extracted from building information models. Our ontology has been defined in close relation to Industry Foundation Classes, and its integration has been proposed such that our work is accessible and exploitable in industry practitioners' current workflows and tools. Additionally, we provide a freely available benchmark model for comparing different PTD approaches in the community.

Our future research will include case studies that can determine the soundness, completeness, expandability, portability, and scalability of our approach, focusing on the design aspect. Furthermore, we envision extending this with planning, which incorporate timing (scheduling) and processes (tasks and their dependencies). We invite the community to take part in the investigation of these topics to drive the efforts of streamlined contributions.

Acknowledgement

The research presented in this paper has received funding from the European Union's Horizon 2020 research and innovation program under grant agreements no. 958398 and no. 958310.

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