COGITO

CONSTRUCTION PHASE
DIGITAL TWIN MODEL

cogito-project.eu

D4.1 – Preventive Health & Safety Application

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D4.1 – Preventive Health & Safety Application v1

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Authors

Name	Beneficiary	Email
Jochen Teizer	AU	teizer@cae.au.dk
Christos Chronopoulos	AU	chrichr@cae.au.dk

Reviewers

Name	Beneficiary	Email
Frédéric Bosché	UEDIN	f.bosche@ed.ac.uk
Giorgos Giannakis	Hypertech	g.giannakis@hypertech.gr

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Disclaimer

Executive Summary

The COGITO Deliverable D4.1 "Preventive Health & Safety Application v1" aims at documenting the first version of the currently developed Health and Safety Application called SafeConAI and consequently at reporting on the first iteration of the COGITO Task T4.1 "Health & Safety Prevention through Design and Planning" development activities.

In summary, the Preventive Health and Safety Application, called SafeConAI and its domain model (SafeConDM) contribute to the automated assessment of building models from the perspective of construction safety. The SafeConAI application enhances the resulting model in two ways. First, by injecting the identified environment features and hazardous spaces to the BIM model, and second, by integrating the mitigation measures of the identified hazards. Specifically, the developed algorithms approximate the environment features of the models and identify the spatial artefacts (e.g., walkable spaces, fall hazard spaces) in accordance with the safety regulations. In the current version of the prototype we analyse the European (ES, 2018) Danish (BFA, 2020), German (BG-Bau, 2021), and US regulations (OSHA, 2019). Finally, all the identified hazard spaces are replaced by actual safety hazards mitigation equipment. In the case of fall hazards for instance, safety guardrails are generated. Those elements are injected to the safe BIM model. We have developed the SafeConAI application to currently interact with IFC but it will further developed to interact with the COGITO DT Platform data structure.

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List of Acronyms

Term	Description
AI	Artificial Intelligence
BIM	Building Information modelling
CM	Construction Management
COGITO	Construction Phase diGItal Twin mOdel
CS	Construction Site
CW	Construction Worker
DM	Domain Model
DTCS	Digital Twin for Construction Safety
DTP	Digital Twin Platform
HSE	Health and Safety Employee
IFC	Industry Foundation Classes
PTD	Prevention Through Design
PtD/P	Prevention Through Design and Planning
SKPI	Safety Key Performance Indicator

1 Introduction

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 analyse different approaches in terms of cost, time, safety fitness, etc., before making a choice.

Safety planning is currently a manual and labour-intensive task. In particular, the standard planning process only covers the overall site layout and does this 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. With the emerging research of automating the safety planning 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.

1.1 Scope and Objectives of the Deliverable

Throughout this deliverable we report on the current stage of the prevention through design and planning (PtD/P) software, called SafeConAI, and its underlying domain model, called SafeConDM.

1.2 Relation to other Tasks and Deliverables

This deliverable is related to other COGITO Tasks and Deliverables. It builds upon the outcomes of T2.4 "COGITO System Architecture Design" that have been documented in D2.4 "COGITO System Architecture v1" and D2.5 "COGITO System Architecture v2" for the development of the Preventive Health and Safety Application.

1.3 Structure of the Deliverable

Section 2 briefly summarizes the related work within the domain of construction code and regulation checking. In Section 3 we present our concept of Digital Twin for Construction Safety (DTCS) and describe our internal data model SafeConDM (zones, artefacts, and spaces), and how we integrate SafeConDM into Industry Foundation Classes (IFC). Additionally, we present the approximating algorithms that generate spatial artefacts and identify hazard zones. The identified hazard zones are used to create a safe Building Information Model (BIM), which is an enhanced model, where the potential hazards have been eliminated through the inclusion of hazard mitigating equipment such as safety barriers, cover panels, and harness anchor points. Finally, Section 4 concludes this report.

2 Digital Twin for Construction Safety

In this section, we describe how we build our Digital Twin for Construction Safety (DTCS), as a part of the COGITO ecosystem. The DTCS has been adapted from (Harichandran et al., 2021; Teizer et al., 2022) and modified to fit the structure of COGITO.

Figure 1 shows the overview of our DTCS (shown in the lower-left corner of the diagram). The DTCS is, as shown, dependent on other domain knowledge Digital Twins (DTs), which are interconnected in a network that allows the exchange of information and knowledge of interest. The digital twin should also be able to perform tasks for each other. For example, we envision that the main Digital Twin Platform requests DTCS to do a safety enhancement and assessment of a 4D BIM model.

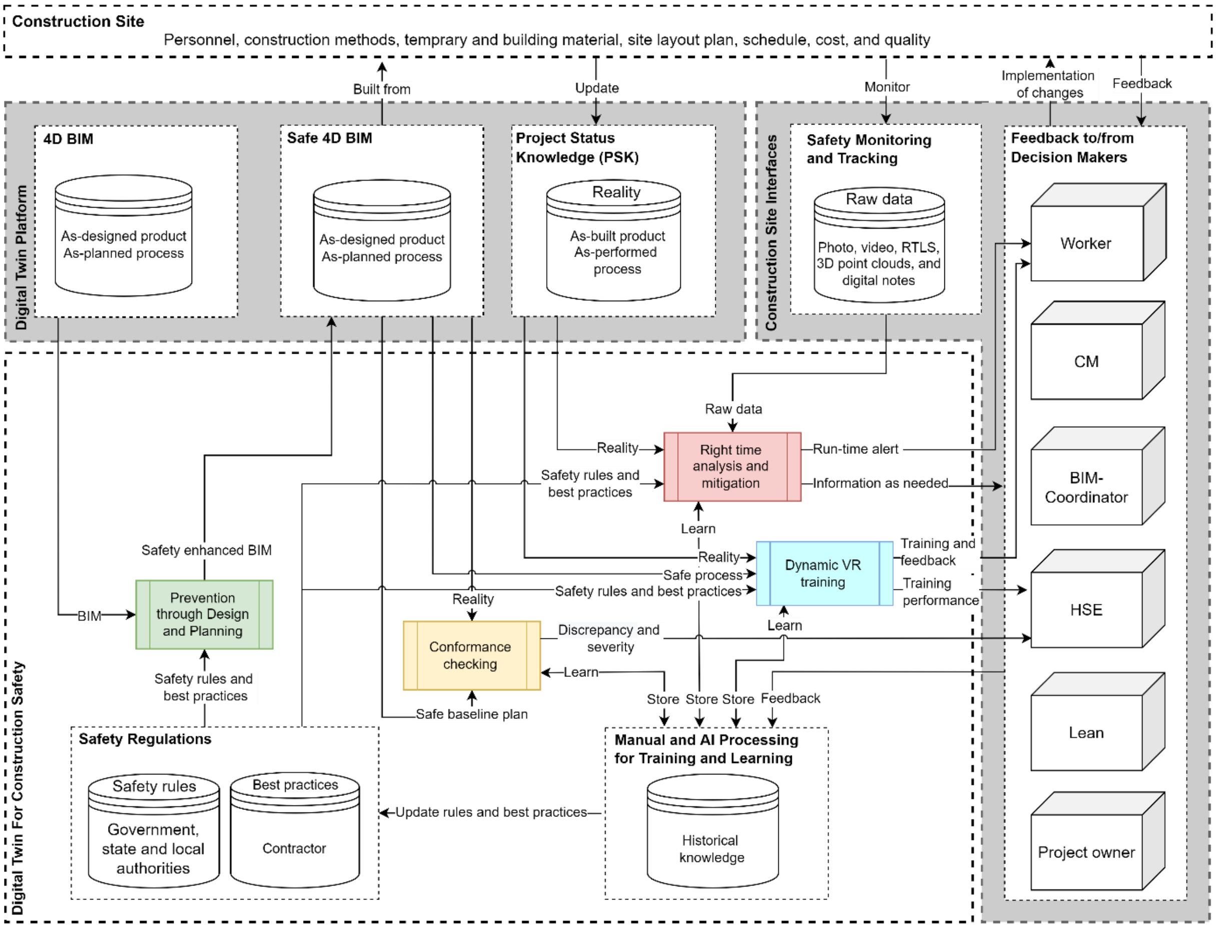


Figure 1 – Overview of the Digital Twin for Construction Safety (DTCS), its relationship and interaction with the other important Digital Twins (e.g., production planning), physical construction site, and construction site interfaces (e.g., monitoring and decision makers).

Construction Site (CS) - The construction site refers to the physical workplace (i.e., the physical twin), which is either being planned, under construction, or constructed. It contains the personnel (e.g., workers, construction management (CM), health and safety expert (HSE), and lean production/planning experts), construction methods (e.g., consideration of equipment alternatives), temporary resources (e.g., scaffolds and safety equipment), building materials (e.g., drywall, concrete slabs, and windows), and construction plan (e.g., site layout plan, schedule, cost, and quality). The personnel (later referred to as decision-makers) has responsibilities, that need to be considered from a broader perspective to facilitate a productive, safe, and high-quality result.

The Digital Twin for Construction Safety (DTCS) consists of three main components, i.e., Prevention through design and planning (PtD/P), Conformance Checking (CC), and Right-time Analysis and Mitigation (RAM) that are described in detail in (Harichandran et al., 2021; Teizer et al., 2022). First, we introduce the overall interaction of these with their surroundings, and subsequently, we describe the contents of these. The construction plan is received from the DTP for safety enhancement and assessment, which means that the protective safety equipment is added to the model. There may exist more than one way to make a safe plan, which will result in an answer set of different solutions. The solutions are created based on the safety regulation, which holds information about safety rules provided by the government, the state, and local authorities, e.g., (BG-Bau, 2021; OSHA, 2019). Another component of the safety regulation instance is best practice, which should hold the decision-makers' preferences (e.g., guardrails over safety net). The safe 4D BIM-model and its related Safety Key Performance Indicators (SKPIs) informs the HSE about the cumbersomeness of, among others, safety equipment installation, protection capabilities and risk analysis. The safety regulation data storage should be updated based on the actual performance of the safe BIM-model and the decision-makers' feedback stored in the historical knowledge database.

2.1 Prevention through design and planning (PtD/P)

Figure 2 illustrates in brief how the alternative plans are generated based on the decision-makers' preferences and the current baseline model. The construction plan is handed to the PtD/P component of the DTCS (right side of Figure 2) and enhanced with safety measures (e.g., guardrails, safety nets, pedestrian walk paths, schedule changes) based on the safety regulation that applies to the construction site. The system analyses the hazard spaces identified in the design, and hazard spaces identified in the process (e.g., work crews working simultaneously on different stories, creating hazard zones in terms of being struck by an object from above). The selected safe alternative plan is returned to the DT Platform.

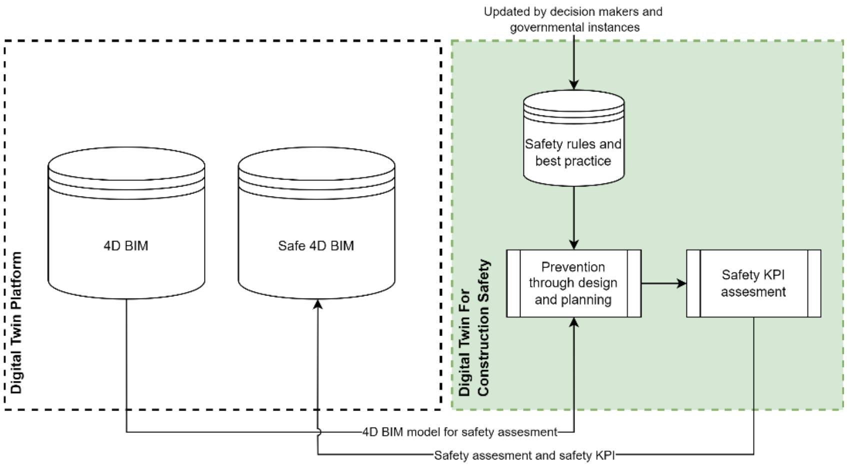


Figure 2 – Internal operation of the prevention through design and planning component. As the in- and output is highly connected to the Digital Twin for production planning it is chosen to include it in the diagram.

3 SafeConDM

By comparing different approaches for the definition of 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.

3.1.1 Organizing and Scoping

The purpose of initiating a formal standardization of a construction safety domain language is twofold: (1) to provide an approach that can be used in our future research and the community; (ii) to streamline the community's efforts on automated construction safety assessment. We initiate the domain language with the most straightforward and predominant spatial artefact (i.e., *movement*, *fall*, and *fall hazard space*) used for fall from heights analysis 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).

3.1.2 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.

3.1.3 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 analysed information is assumed to make our ontology applicable for at least the included countries and continents.

3.1.4 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, we extract the varying factors and define a vocabulary of variables that we extract from the regulation. Subsequently, we define the ontology using spatial artefacts and the vocabulary. Additionally, we propose a strategy to integrate the spatial artefacts into IFC, which exclusively depends on existing IFC-classes, meaning that the ontology is compliant with the IFC4 tools and workflows.

3.1.5 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 refine it during this process. The ontology will be further refined based on other countries and feedback from practitioners in future research studies.

3.2 Ontology development

3.2.1 Safety regulation collection and analysis

In the current version of the prototype we analyse 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 3 shows a graphical representation of the vocabulary variables, which are limited to falls from height, where mitigation approaches include safety guardrails and cover panels. We are not investigating safety nets.

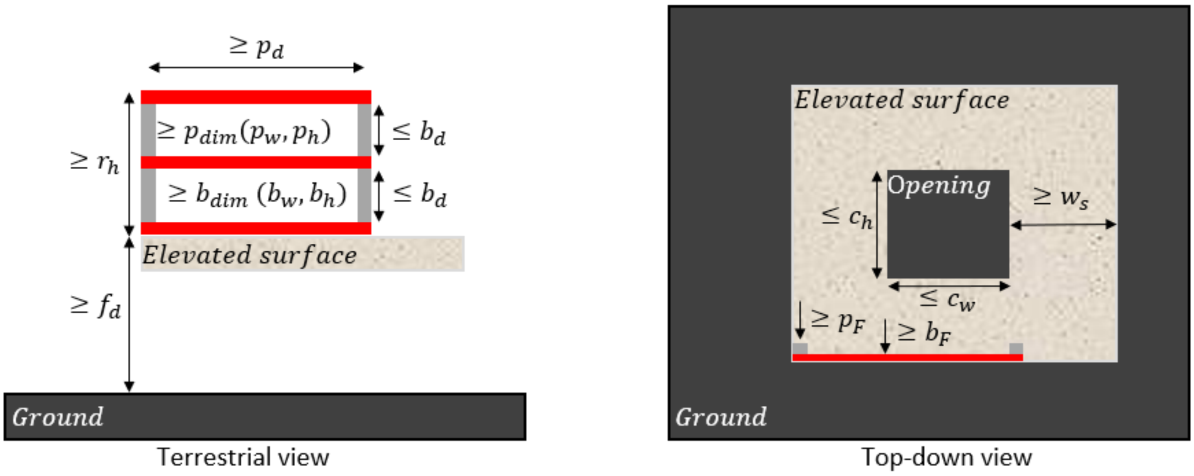


Figure 3 – Illustration of values in Table 1 (horizontal boards coloured in red and vertical poles in grey)

3.2.2 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.

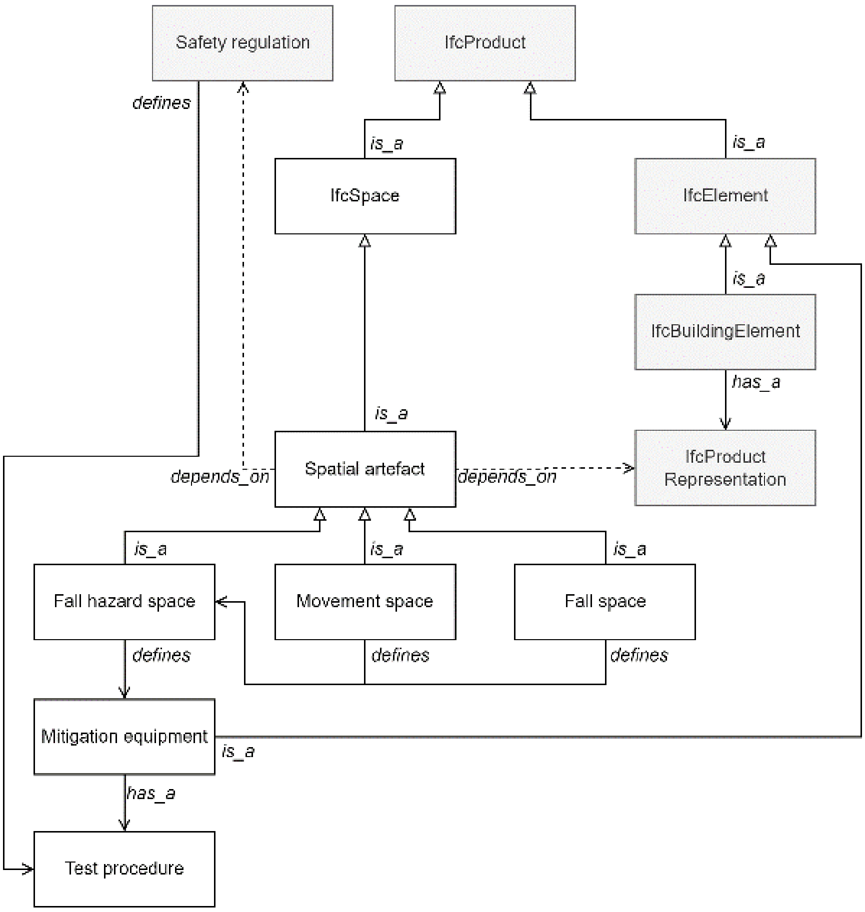


Figure 4 – Diagram of our BIM-based ontology of construction hazards and mitigation interventions.

Our ontology shown in Figure 4 is based on spatial artefacts, which capture 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 artefacts 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 artefacts 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.

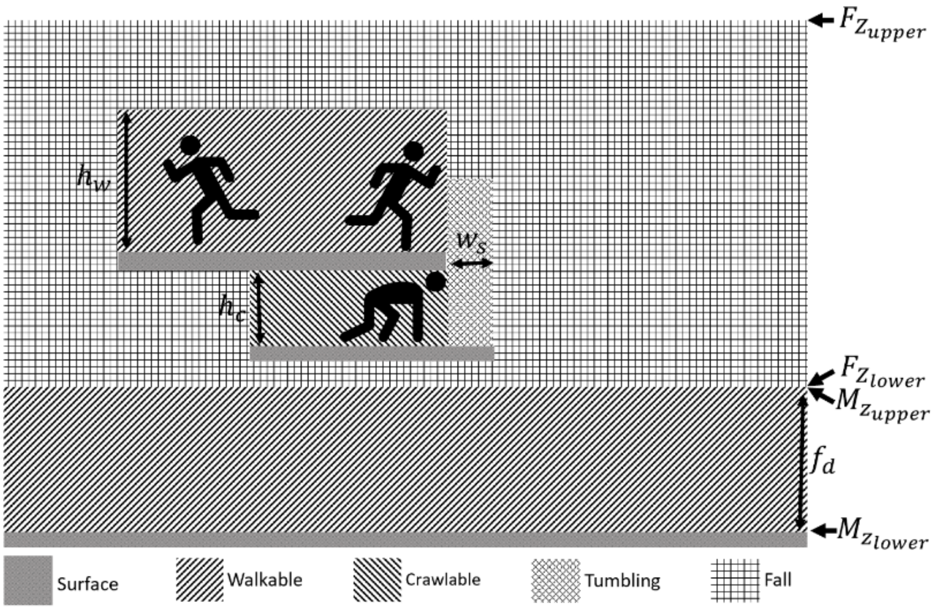


Figure 5 – Illustration of spatial artefacts extracted from IfcElements.

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

Natural language formulations	Attribute	Symbol	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	1m	1m	1m
The minimum width of a surface, which an agent is allowed to be present on	Surface width	w_s	60cm	60 cm	60cm
The minimum Height of a space, which is considered walkable	Walk height	h_w	NA	NA	NA
Minimum height of a space considered crawlable	Crawl height	h_c	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	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	NA	NA	NA
Minimum height of guardrail (aka., Safety railing, safety barrier)	Railing height	r_h	1m	1m	1m
Maximum distance between vertical poles of guardrail installation	Pole distance	p_d	NA	2m	2,25m
Maximum distance between horizontal boards in guardrail installation	Board distance	b_d	0,47m	0,47m	0,47m
Best practice width of applied vertical poles in guardrail installation	Pole width	p_w	NA	3cm	4,5cm
Best practice height of applied vertical poles in guardrail installation	Pole height	p_h	NA	15cm	7cm
Best practice width of applied horizontal boards/rails in guardrail installation	Board width	b_w	NA	3cm	3,2cm
Best practice height of applied horizontal boards/rails in guardrail installation	Board height	b_h	NA	15cm	15cm
Minimum continues force that vertical poles in guardrail installation should withstand	Pole force	p_f	300N	300N	300N
Minimum continues force that horizontal boards in guardrail installation should withstand	Board force	b_f	300N	300N	300N

Table 2 – Overview and description of spatial artefacts for fall hazard identification and analysis.

Spatial Artefact	Specialized subclasses	Description	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.	$h_c \leq height < h_w \text{ and } width \geq w_s$
	Walkable space	Regions in which an agent can travel upright	$height = h_w \text{ and } width \geq w_s$
Fall space		Regions in which an object or agent will fall by f_d.	$F_{z_{lower}} = M_{z_{lower}} + f_d$
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	$M_{z_{lower}} \geq F_{z_{lower}} \wedge M_{z_{upper}} \leq F_{z_{upper}}$
	Offset leading-edge space	Regions where a portion of the movement space intersects with a fall space	$M_{z_{lower}} + offset_{lower} < M_{z_{lower}} + r_h$
	Offset top leading-edge space	Regions where a portion of the movement space intersects with a fall space	$M_{z_{upper}} - offset_{upper} < M_{z_{lower}} + h_c$
	Tumbling space	Regions in which an agent can tumble over fall prevention equipment on lower surface	$z_{upperSurface} - z_{lowerSurface} < f_d \wedge width_{lowerSurface} < w_s$

3.3 Integration into IFC

Figure 6 presents our latest version of IFC integration, which is based on the work presented in (Li et al., 2021). 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 artefact. This version is fully compliant with IFC4 and can be processed by all IFC4 compliant tools. Each spatial artefact is implemented as an instance of the IfcSpatialZone class. The spatial artefact type is expressed as an instance of IfcProperty that selects an enumerated value.

The enumeration of spatial artefact 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.

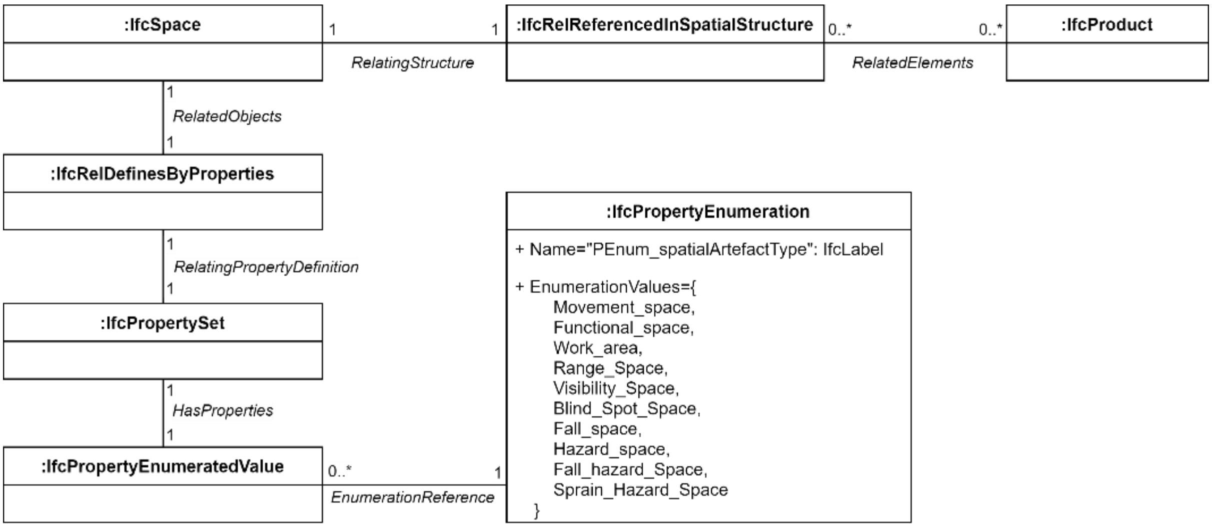


Figure 6 – UML class diagram depicting how instances of spatial artefacts for safety analysis are expressed in standard IFC4.

3.3.1 Future extension of ontology

The application will as shown earlier connect to the Digital Twin platform, from which it gathers the 4D BIM-model that has to be enhanced. Through analysis of the covered safety regulation, and construction codes the engine extracts the areas, where there has been a violation of the aforementioned. The output of this process is referred to as hazard zones that are captured in IfcSpatialZones. Subsequent to the identification of hazard areas, we enhance the model with the required safety mitigation equipment to counter measure the hazard. We enrich the resulting file with both the spatial zones for future computations, but also the mitigation measures. For future extension of the ontology, we envision to populate the following elements in the shown categories:

Legend: *Extension to IFC (italic),* Part of IFC (normal)

- IfcElement
  - *WorkerHazardMitigationElement*
    - *Safety guard rail*
    - *Cover panels*
    - *Safety net*
    - *Fence*
    - *Harness tie-off point*

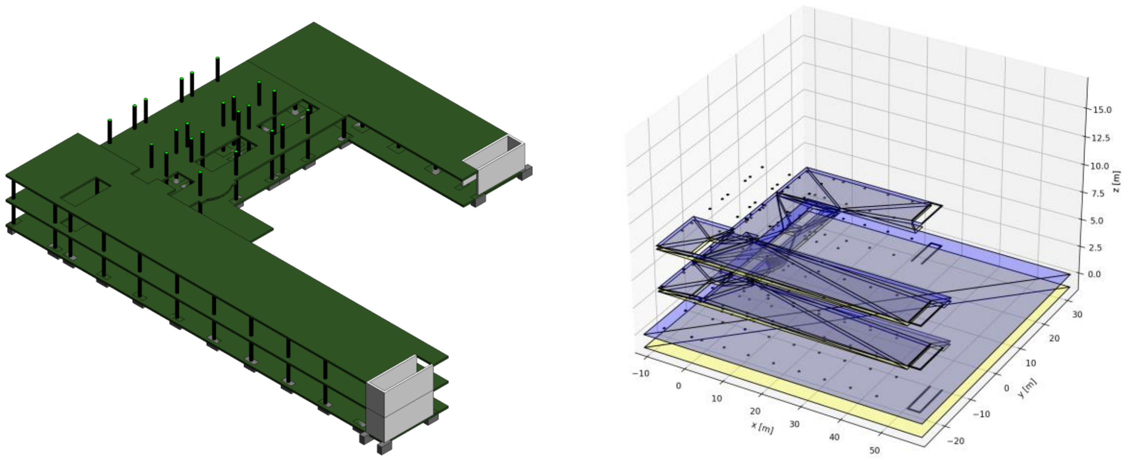
            - *Cone*
            - *Ribbons*
- IfcSpatialZone
    - *Spatial artefact (human behavior and experience)*
        - *Range*
            - *Visibility*
            - *Blind spot*
            - *Sensor range (e.g., location tracking sensor)*
        - *Operational*
        - *Functional*
            - *Movement*
            - *Fall*
        - *Hazard*
            - *Fall hazard*
            - *Strike by vehicle hazard*
            - *Strike from above hazard*
            - *Slip trip fall hazard*

3.4 Generating objects in safe BIM

In this section we describe how the SafeConDM objects are extracted from an incoming model, and afterwards injected to the BIM model, resulting in a safe BIM. The algorithms are created based on the definitions of the spatial artefact presented earlier and are in most cases approximations of the complete mathematical definition based on assumptions about the BIM model. These approximations are used in order to develop more simple algorithms and to keep computational runtime low. In the next stage of development, we will develop more comprehensive algorithms that are closer to the actual mathematical definition rather than approximations. Handling a BIM model and its elements does involve rounding errors and numerical instabilities, which in this current version is handled by rounding all incoming to the nearest millimetre.

3.4.1 BIM surface extraction

After receiving the BIM from the Digital Twin platform, the SafeConAI application initiates its rule-based analysis by extracting the horizontal surfaces of it. For this operation we utilize the ifcopenshell, which returns the triangles of each element. In Figure 7 we show the model, that we are analysing in the BIM tool for reference. Figure 7a shows the resulting triangles that are extracted from the BIM. Blue is representing upwards pointing surfaces, and yellow, downwards pointing surfaces.



a. b.

Figure 7 – Visualization of (a.) the BIM in BIM-tool (Revit) and, (b.) the horizontal triangles extracted from BIM.

The triangles shown in Figure 7b are the ones that we use for our further analysis, but before the analysis the triangles are turned into polygons. This is done by finding all the triangles that belong to the same surface and those that have an overlapping edge are merged. This procedure results in the polygons, shown in Figure 8, where blue is representing upwards pointing surfaces, and yellow, downwards pointing surfaces.

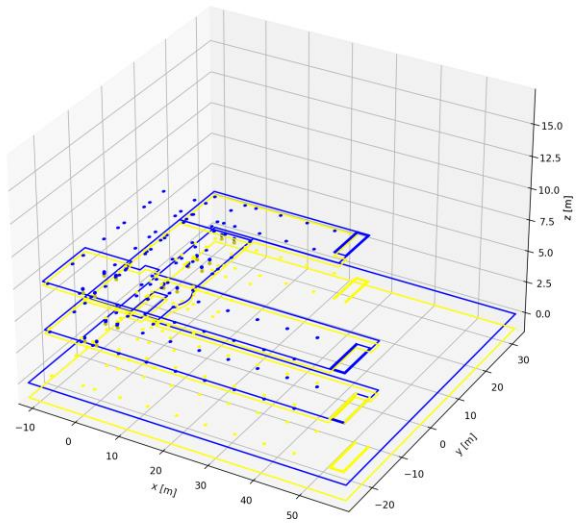
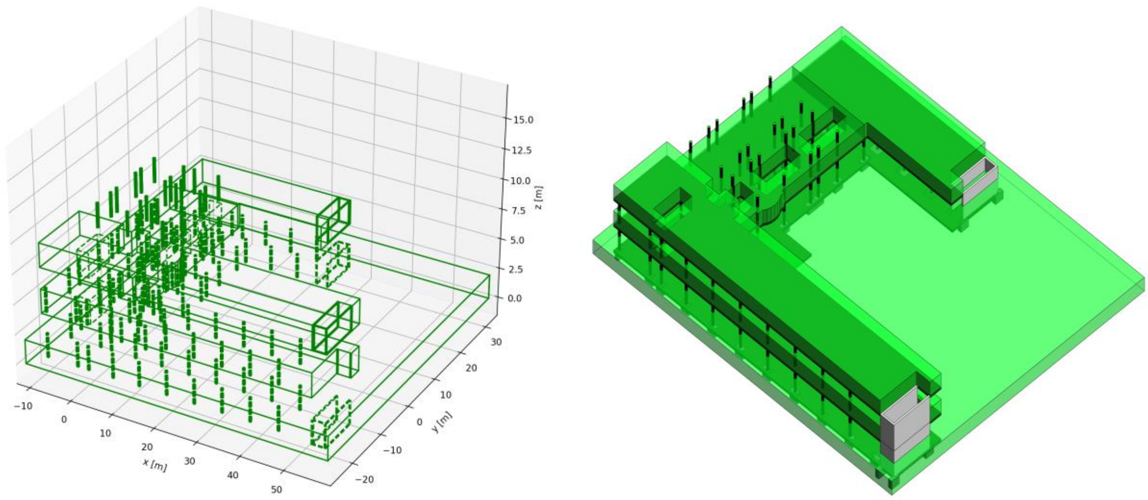


Figure 8 – Visualization of polygons representing horizontal surfaces, obtained from processing the triangles in Figure 7b.

3.4.2 Movement space extraction

Based on our definition of movement spaces from Table 2: *Regions in which an agent (e.g., construction worker, manager, and visitor) can travel,* the application extracts the movement spaces as being the upwards facing surfaces, minus the downwards pointing surfaces within the height of the movement space.

Figure 9a and b shows a visualization of the extracted movement spaces that are afterwards injected to the resulting safe BIM file and afterwards visualized in the BIM-tool.

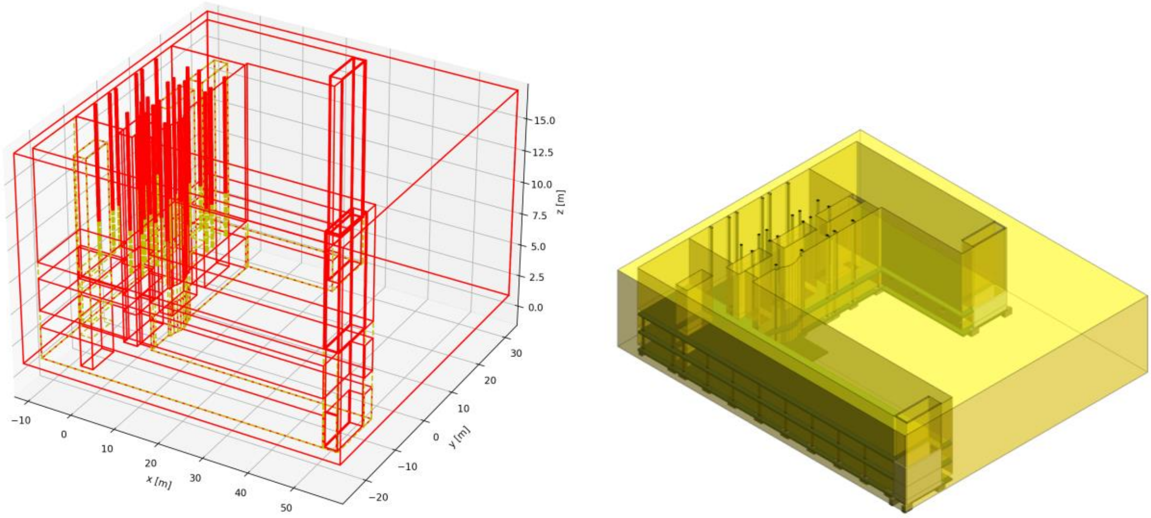


a. b.

Figure 9 – Visualization of (a.) movement spaces, where solid lines are the actual space, and stamped lines are holes and, (b.) the injected movement space in BIM-tool

3.4.3 Fall space extraction

Based on our definition of a fall space from Table 2, we extract the fall spaces. Conceptually those are extracted by iterating over the upwards pointing surfaces and subtract all the downwards pointing surfaces that are within the fall distance f_d. This is done until the top of the bounding box containing all construction elements has been reached, or the surface is empty. Every time a surface is subtracted it creates a new fall space. Figure 10 show the fall spaces in the BIM-tool, whereas Figure 11 shows a cross section view, from which it can be seen that the fall space is offset f_d from the surface.



a. b.

Figure 10 – Visualizations of (a.) fall spaces, where solid red represents space, and stamped yellow stamped line represents holes and, (b.) of the injected fall spaces in BIM-tool

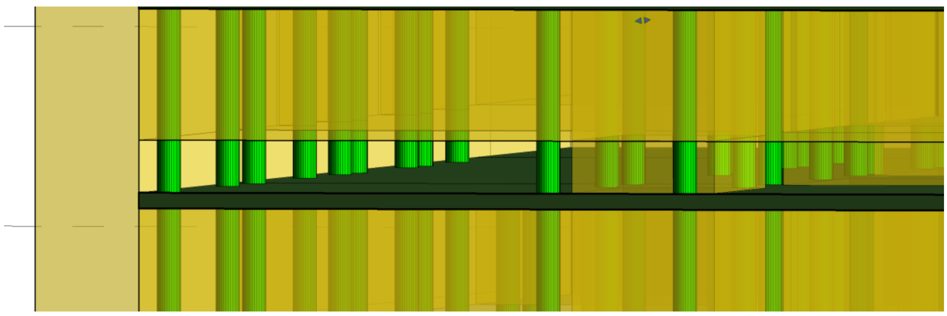
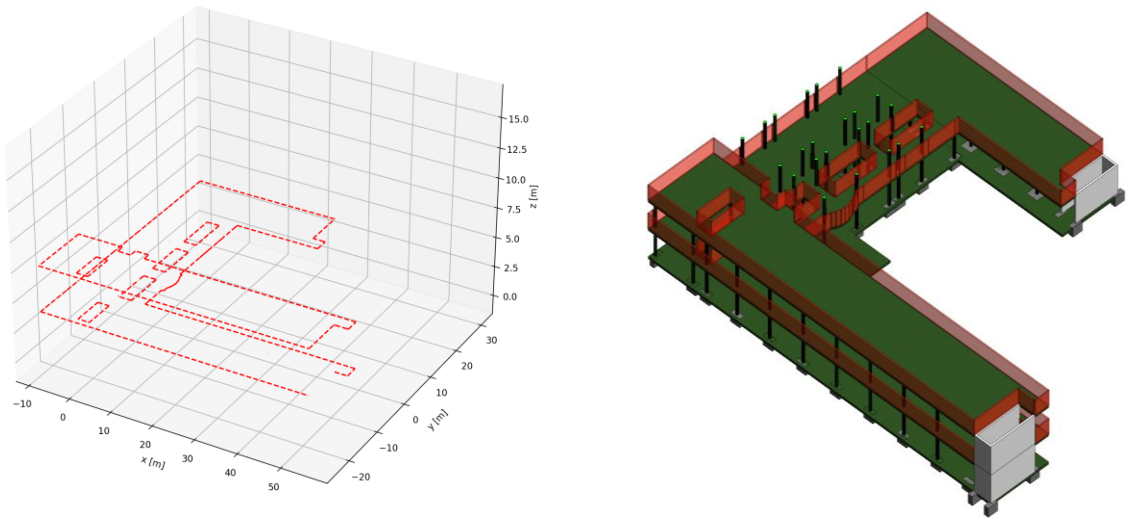


Figure 11 – Section view of fall spaces in BIM-tool

3.4.4 Fall Hazard space identification

Based on our definition of a fall space from Table 2, the fall hazards spaces are identified as spaces, where the movement space intersects with the fall space. Figure 12 illustrates the fall hazard lines, which are the lines that follow the intersection of the spaces along the surface that created the movement space. Subsequently those lines are dilated into polygons, and afterwards extruded with the height of the safety guardrail shown in Table 1 as r_h. Figure 12b shows the injected fall hazard spaces in the Safe BIM shown in the BIM-tool. Finally, all the identified fall hazard spaces are replaced by actual fall protection equipment, in this case safety guardrails. Those elements are injected to the safe BIM and shown in the BIM-tool in Figure 13. The injected safety guardrails follow the rules identified in Table 1.



a. b.

Figure 12 – Visualization of (a.) fall hazard spaces, where stamped red line represents the space and, (b.) of the injected fall hazard spaces in BIM-tool.

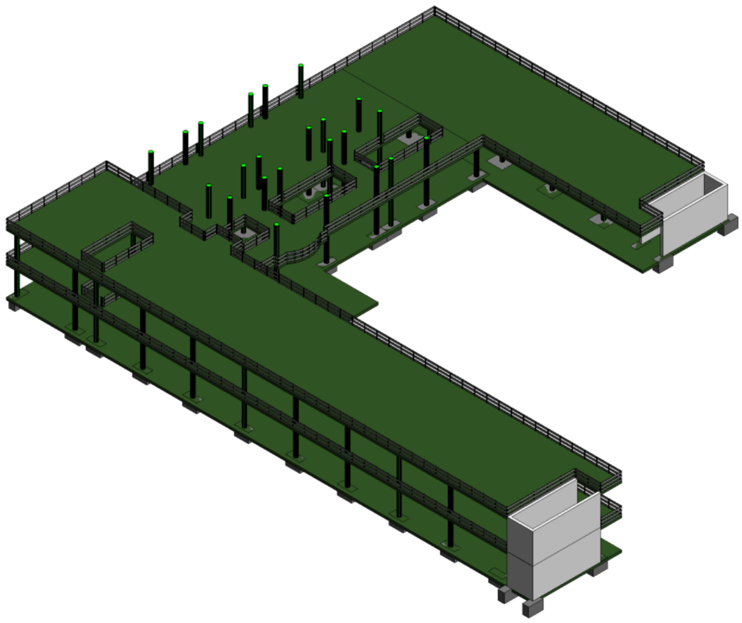


Figure 13 – Visualization of the safe BIM in BIM-tool, after replacing fall hazard zones with mitigation measures.

3.5 Licensing

The SafeConAI application is offered in the form of an open-source software component.

3.6 Installation Instructions

The SafeConAI application is offered to the COGITO platform as a web service; as such, no file download, installation, maintenance or other related operation is to be performed by entities other than its creators.

3.7 Development and integration status

As already explained in the previous sections the Preventive Health and Safety Application consists of the data model, namely the SafeConDM and, the SafeConAI application. The current IFC utilizes the IfcProperty class and the IfcRelReferencedInSpatialStructure class to capture information about which products in the BIM model directly generate a given spatial artefact. This version is fully compliant with IFC4 and can be processed by all IFC4 compliant tools. The IFC structure is similar to graph databases used in the emerging DTs, which facilitates the future integration of the currently developed Preventive Health and Safety Application into the COGITO Digital Twin Platform.

4 Conclusions

This deliverable presents our work on developing the Preventive Health and Safety Application, called SafeConAI and its domain model (SafeConDM) that contribute to the automated assessment of building models from the perspective of construction safety. The developed algorithms approximate the environment features of the models and identify the spatial artefact (e.g., walkable spaces, fall hazard spaces). The SafeConAI application enhances the resulting model in two ways. First, by injecting the identified environment features and hazardous spaces to the BIM model, and second, by integrating the mitigation measures of the identified hazards. We have developed the SafeConAI application to currently interact with IFC but it will further developed to interact with the COGITO DT Platform data structure.

References

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COGITO

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