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Hazard ontology and 4D benchmark model for facilitation of automated construction safety requirement analysis

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Abstract

Over the last two decades, numerous approaches have been developed for automating construction safety assessment, that is, prevention through design and planning (PtD/P), that overcome the limitations of a purely manual safety assessment process. Despite this, such automated approaches are yet to be widely adopted in practice. Barriers include a lack of standardization of construction safety concepts within regulatory frameworks and a lack of confidence in automated approaches on the part of practitioners. This work presents a freely available 4D BIM-based benchmark model (3D Building Information Model and 68 schedules) and construction safety ontology covering the two most frequent and severe construction site accidents: falls from height and struck-by falling object hazards. The benchmark model and ontology enable the construction safety community to test and compare the performance of alternative automated approaches. Moreover, they are utilized in our PtD/P tool SafeConAI, and empirical evaluation results show how the safety situation changes among different construction schedules of the same project.

1 | INTRODUCTION

The construction industry is among the industries with the most hazardous workplaces. According to a report on labor statistics in the United States (BLS, 2020), fatalities in the private construction industry correspond to 21% (1008) of all workplace-related fatalities (4764). The main reasons for fatalities in the construction industry are falls, slips, and trips, which correspond to 37% (368 deaths), and struck-by hazards 15% (170 deaths; Brown et al., 2021); hence, the focus of the activities carried out in this work. Among others, a reason for the high number of hazards is the work environment's unpredictable and dynamic nature, where tasks are generally very similar, but unique from one construction site to another (Pinto et al., 2011).

The current practices of ensuring construction safety start when a project is initiated in the design phase, continue with a more detailed planning phase just before construction begins, and endure with continuous inspections during the project execution phase. Often, the required risk assessment is performed by having 2D drawings in the form of a floor plan available and knowing the schedule that links the activities to a priori known hazards and required measures (Collins et al., 2014).

The continuous inspection and adaptation to a safe work environment have two major consequences: first, the responsible person for health, safety, and environment (HSE) has a great responsibility to ensure a safe workplace before work begins, and second, it is almost impossible to assess the entire construction site once it is started. This also means that this person must rely on every worker's behavior and take responsibility for their own safety planning, which requires safety regulation knowledge and due diligence. While the regulation knowledge can be trained, the latter is affected by many factors. For example, falling behind schedule or running over budget may cut one's obligation to invest in safety.

4D BIM and location-based schedules have existed for some time, but the emergence of the digital twins (DT) paradigm brings further advancements (Sacks et al., 2020; Teizer et al., 2022). DT involves an increased update rate on the current state of the construction site, and recording of discrepancies between the project intent information (PII) and the project status information, which can be used to act and compensate for the remainder of a construction project. The increased insight and synchronization enable detailed safety planning with higher temporal resolution.

For example, DT can discover bottlenecks in schedules, where a subcontractor may decide to pull in another team. This may solve the problem of schedule overruns but may also affect safety, as the team could introduce unforeseen hazards that were not part of the initial safety assessment.

Automated prevention through design (PtD) or construction hazard PtD has been researched for some time (Hardison & Hallowell, 2019; Melzner et al., 2013; Zhang et al., 2015), but only very few approaches perform this in a timely manner and at a level of detail that is sufficient to extract the inter-task hazards that are arising, which will be referred to as prevention through planning (PtP). Additionally, even fewer approaches record changes in the construction plans during a project and incorporate these changes into safety planning. In combination, it becomes PtD and planning (PtD/P). This study will use our previous work on construction safety analysis as a stepping stone (Johansen et al., 2022a), but instead of geometric correctness, this work is concerned with the impact of the temporal component (i.e., the effect of changing the schedule). Consequently, *struck-by falling object hazards* have been introduced, and the previously defined *falls from height hazards* have been adapted to be described in a construction situation that evolves over time.

PtD/P allows the responsible HSE coordinator to automatically assess the safety performance of an initial schedule and investigate how changes to the schedule may affect this performance in terms of the number of applied hazard prevention equipment and hazard exposure of the workers. This automatization enables the safety analysis to happen continually throughout the construction project.

1.1 | Research overview

Figure 1 illustrates the framework of this study. The diagram has been split into two sections. The top illustrates the main objective of the work, and the bottom shows how the results are envisioned to benefit the community and how they are utilized in the case study (Section 6).

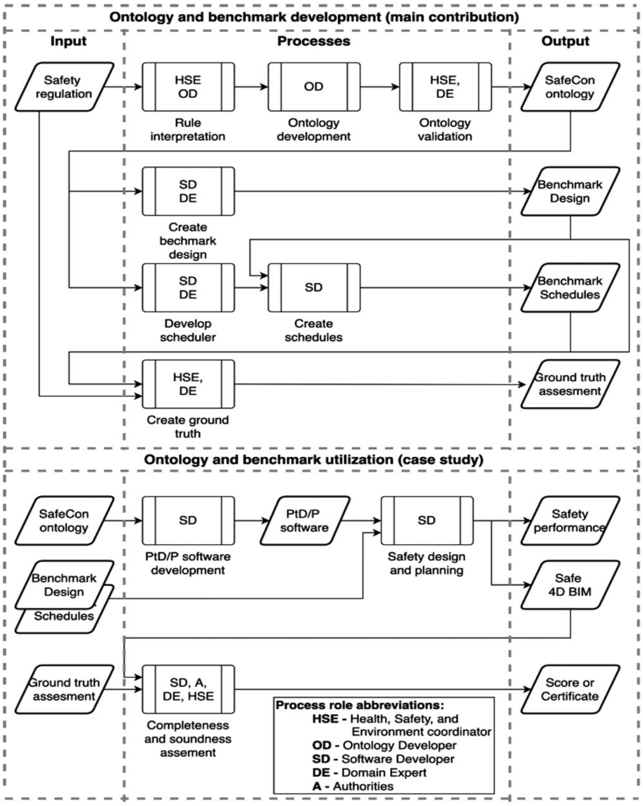


FIGURE 1 Graphical version of research framework.

Based on the selected safety regulations (Section 3.1), the ontology is created and afterward validated with domain experts (Section 4). Based on the ontology, a building design that, at a minimum, includes the hazards covered by our ontology was created (Section 5.1). In collaboration with the domain experts, this work defines the geometric and topological relations between objects in the design, which are subsequently used to generate realistic and constructible construction schedules (Section 5.2).

Based on the design, schedule, and regulation, a ground truth can be created, which can be used for later automated completeness and soundness assessment (not part of this work). The bottom utilizes the outputted results from the upper part, which makes the automated approaches comparable. Additionally, it lowers the barrier to get started in automated safety planning research as a preliminary model and ontology are provided. In the case study, our safety tool called SafeConAI is used to validate that the information in the benchmark model is complete and ready for use in other research projects. Additionally, it documents how the benchmark model is meant to be used.

1.2 | Research questions

RQ 1: Can we formalize *strike from above* hazards, which are dependent on the planned and undertaken tasks, so that they can be used in a spatiotemporal analysis of construction safety performance?

RQ 2: Can we adapt our former presented formalization of *falls from height* to express temporal relationships to a construction schedule?

RQ 3: Can a shared 4D benchmark model and construction safety ontology reduce the gap between developers and domain experts, facilitating comparison of automated approaches?

1.3 | Contributions

C 1: The shared safety ontology lowers the barrier to understanding the domain knowledge, which facilitates the development of automated approaches, possibly widening the scope of possible researchers in the domain.

C 2: The benchmark model with corresponding schedules allows researchers to focus on the algorithms instead of collecting construction projects, which can be challenging.

C 3: The shared benchmark model allows researchers to compare the output of their approach, facilitating continuous improvement in the automated safety domain.

2 | RELATED WORK

This section summarizes research on automated construction safety analysis related to our work. Fargnoli and Lombardi (2020) investigated the emerging trend in research that utilizes BIM to enhance construction safety. The study is based on the last decade and shows an increasing interest from researchers in BIM. It outlines the importance of the application's capabilities to utilize BIM and exchange information. Furthermore, it points out the gap between practitioners and researchers and the need for standardizing joint activities. The following four subsections discuss some related work in the individual activities performed in this study.

2.1 | Knowledge base modeling

To perform safety analysis in an automated or semi-automated fashion, one must capture the kinds of hazards that are of interest, when they emerge, and how to avoid them. One strategy for defining these relations is to generate a database of hazards connected to different subtasks of different construction elements (Mihić et al., 2018). A similar approach is to describe a knowledge library that can identify the risks based on a set of atomic "For, When, With, Having → Then," which suggests mitigation (Hossain et al., 2018). An alternative approach is to create an ontology, which captures the rules of a safety regulation and relations between elements that exist in the building model and their geometrical location (Lu et al., 2015; Zhang et al., 2015; Zhou et al., 2016). Another approach is to rely on the artifact generated by the existence of an element in the building information model (e.g., a slab would create a surface on which a worker can walk; Li et al., 2022). In this work, the ontology is built using the spatial artifact approach, enabling a high geometric accuracy (spatial artifacts are introduced and explained in Section 4.2).

2.2 | Automated identification of construction hazards

Most studies rely on rule-based queries performed on the building model when performing the safety analysis. This way, the building model database returns the elements that fulfill the query (i.e., potential sources of the analyzed hazard) that can then be assessed manually. Other approaches perform similar queries and analyze the elements' geometry to enhance the building model in an automated fashion (Perlman et al., 2014; Qi et al., 2014; Zhang et al., 2015). As query engines often return the building elements as isolated objects that fulfill the query criteria, the enhancement may not consider the nearby elements (e.g., walls on the slab). Creating spatial artifacts in the complete situation facilitates context awareness.

Construction sites change frequently. Even though this is the case, most research activities on automated safety enhancement have been performed on static scenarios, where the construction schedule and its changes to the construction site are not considered. In these cases, some elements have been removed from the building model (to imitate an unfinished building) or only performed at the top level (i.e., the roof). The automated approaches need to incorporate the schedule to determine when an element is built, and thereby the construction scene changes (Heidary et al., 2021; Jin et al., 2019). This work aims to facilitate the temporal analysis of the construction safety situation.

Even though automated approaches have been researched for years, barriers remain before adoption in the construction industry can happen. Beach et al. (2020) have been investigating the counteracting limitations; some limitations are lack of tool support, lack of integration in current workflows, lack of certification, and lack of confidence. The identified hazards and mitigation of the ontology can be injected into the BIM model to accommodate the current workflows of practitioners. In addition, the shared benchmark model supports openness and comparability to facilitate improved confidence.

2.3 | Construction scheduling

Automatic sequencing of construction activities has been researched with four approaches with increasing complexity. The first approach is rule-based, where Borrmann and Rank (2009) sequence construction activities based on rules, and Vries and Harink (2007) sequence activities based on geometric and topological positioning. However, the rules become hard to implement for larger and more complex scheduling tasks.

Another approach is case-based reasoning (CBR), where a knowledge base is gathered from the domain, such as: “if a wall is to be built on the top of the slab; then the slab must be built before the wall” (Wang & Azar, 2019). This approach utilizes the knowledge gained from previous projects. CBR works under the hypothesis that a similar problem should be handled similarly, which means that new solutions are not generated, but existing solutions are revised. Furthermore, this approach is not suitable for generating a set of schedules without changing the input.

The third approach is pattern-based, utilizing templates that generate processes and interdependencies (Sigalov & König, 2017; Wu et al., 2010). It leverages historical sequencing information and machine learning to extract the relationship between future activity planning. The planning of this work is based on the simpler rule-based planning approach because of the low complexity and the ability to create a set of different construction schedules.

The last approach is optimization-based. Karim and Adeli (1999) pioneered the strategy of letting the schedule and its changes be based on the objective of the construction management (CM; e.g., cost or duration). This strategy is still commonly used in commercial scheduling software.

2.4 | Benchmarking

Benchmarking is the procedure of comparing a process and performance measures from one system to another or even between different runs of the same system. Benchmarking has been adapted to many different areas, especially in applications of computer vision and machine learning (Lei et al., 2012; Luo & Paal, 2019). Benchmarking has also been exploited in the construction sector to compare the performance of project executions. Ajelabi and Tang (2010) benchmark project execution on cost, progress, and quality. Castillo and Bonilla (2020) adapt the World Management Survey methodology to streamline benchmarking in construction processes. In both examples, the input is based on historically executed projects, and the output is used to improve the execution of future projects. In general, benchmarking suffers from the lack of the possibility to measure subjective parameters objectively, especially between projects. Automated safety assessment is performed before a construction project is built, making it more challenging to compare different approaches. Inspired by other domains, this study proposes a publicly shared BIM model, where the digital output of automated approaches can be directly compared. Such a direct comparison is currently impossible, as each researcher performs a safety assessment on their own.

3 | METHODOLOGY

This study presents two main topics: (1) modeling the presented ontology and (2) creating a benchmark model with schedules created by our planning software. The methodology of this study is presented for each topic.

3.1 | Ontology

By comparing different approaches to define an extendable domain language for construction safety analysis and assessment, it was possible to select the most relevant, because of its focus on systematization and extendibility. The final choice has been to adapt the methodology called “Methontology” (Fernández-López et al., 1997), which consists of six steps outlining the activities in ontology creation. Our adaptation is described below:

3.1.1 | Step 1: Specification

Our ontology aims to bridge the gap between practitioners interpreting the safety regulation and the software developers producing the tools for construction safety enhancement. The ontology should therefore be formal and precise while describing the content and classes in a language that is understandable and programmable for the developer and at the same time, interpretable, understandable, and extendable from the practitioner’s perspective. The ontology will be extending the already existing work about *fall from height* hazards with *struck-by falling object* hazards, concerning Denmark (BFA, 2020), Germany (BG-Bau, 2021), and the United States (OSHA, 2019) regulations. Additionally, the ontology will be extended to describe temporal relations of hazards.

3.1.2 | Step 2: Knowledge acquisition

To bridge the gap between practitioner and developer, it is necessary to understand the safety regulations regarding *struck-by* hazards, which involves the construction safety regulations from the countries above (BG-Bau, 2021; European Standards, 2018; OSHA, 2019). These regulations and dialogues with domain experts in the construction safety field facilitated a definition of the glossary, varying factors, and classes necessary to describe the *struck-by falling* object hazards. The interaction with the domain experts has consisted of informal discussions with two responsible safety regulation enforcers in construction companies and one specialist from an organization responsible for defining the safety regulation. Besides acquiring knowledge from safety regulations and domain experts, this work has been inspired by the ontologies presented by Zhang et al. (2015) and later advanced by Li et al. (2022).

3.1.3 | Step 3: Conceptualization

Based on the knowledge acquired, a glossary of terms is created to capture those concepts, instances, verbs, and their properties. The glossary was assessed for mutual exclusivity and collective exhaustion within the scope.

3.1.4 | Step 4: Integration

The resulting ontology integrates the ontology presented in Johansen et al. (2022a). Therefore, it can integrate with Industry Foundation Classes (IFC). IFC is an open BIM standard that can be imported and exported from the majority of BIM modeling software used by practitioners in the industry. Integrating with IFC benefits from the already defined interface to BIM models in a non-proprietary fashion, which enables a wider variety of development tools. This work proposes a strategy to integrate the proposed ontology classes, mitigation resources, and safety tasks into IFC, which exclusively depends on existing IFC classes, meaning that the ontology complies with the IFC4x tools and workflows. Compliance means that the output of the proposed ontology can be parsed, shown, and analyzed in, for example, Revit or FreeCAD. Additionally, the IFC data structure is similar to the graph databases used in DTs.

3.1.5 | Step 5: Implementation

The new construction safety ontology has been implemented in Protégé following (Noy & Mcguinness, 2001), which describes this activity step-by-step. Protégé, as an editor, allows for both lexical and syntactical analysis. Furthermore, it facilitates portability and documentation.

3.1.6 | Step 6: Evaluation

The ontology is verified for correctness and validated for completeness within the aforementioned scope as suggested in Gómez-Pérez (1996). A twofold procedure is performed: (1) an ongoing collaboration with the domain experts and (2) simultaneous software development of SafeConAI that utilizes the ontology. To assess the applicability, a benchmark IFC model (https://github.com/kakke14/BIM-Based4DBenchmark/blob/master/4DBenchmarkBim.ifc) has been created and used together with the ontology in the case study. The outputs have been discussed with domain experts.

3.2 | Benchmark BIM model

The benchmark BIM model serves multiple purposes. First, it aims to assess the completeness of the ontology (i.e., to determine whether the ontology can capture the scenarios described in the regulations). With the benchmark model, which is a BIM model, the completeness can be assessed by domain experts in their regular workflows. Second, it contributes to the community and the testing of algorithms for automated safety or human-assisted assessment. The benchmark model has been modeled in Revit and later exported to IFC, an open and non-proprietary file format. Most BIM tools support the IFC schema, which makes the model useable, editable, and interactable for most users. The IFC community provides freely available libraries that have been created to interact with the schema.

3.2.1 | Schedule

The schedules are captured in an Excel spreadsheet consisting of multiple tabs, each capturing an individual schedule. The reason for choosing a spreadsheet is that it is easily accessible and readable for the practitioner and the developer. Many libraries have been developed to interpret excel files, and for Python, an example is Pandas (McKinney, 2010; Reback et al., 2022).

The schedule and planner are tightly coupled to the IFC file, which means that each line in the schedule is connected to individual elements in the BIM model. The connection is made through the IFC Global Unique Identifier (GUID), extracted through the levels (native part of the IFC schema), and a zone manually added as a comment in the BIM tool. The working principle of the developed scheduler is rule-based, as it schedules an intuitive sequence of tasks that depend on geometric and topological relations.

3.2.2 | Design

The design of the benchmark model has a relatively low geometric complexity because this is not the objective of this work. The goal is that it should be straightforward to understand where the guard railing is needed based on the ontology and the actual state of the planned activities. This allows both the practitioner and the developer to follow the development of the construction process over time and look for discrepancies between the expected and actual output. The BIM model itself is stored in the IFC format, enabling others to use their BIM modeling tool of choice. The high-rise scenario was chosen because it involves different work area sizes and shapes, for example, slabs and columns. Additionally, it contains walls that create a task that is performed close to the edges, which means that there is a struck-by hazard source, but also that the wall replaces the guard railing when the task is initiated. This information should be reflected in the analysis output.

3.2.3 | Safety key performance indicator (S-KPI)

Based on our interaction with the domain experts, three values are proposed that compare the different construction approaches; these values have previously been inaccessible to the CM team but would enable the CM to select a construction approach in terms of safety. These S-KPIs facilitate informing the CM about how different approaches and changes to those may affect a construction project's safety situation. The first is the amount of hazard mitigation equipment (i.e., the amount of guard railing), which allows the CM to select a schedule that fits equipment availability. The value is captured for each time step in which the geometric representation of the construction site changes (i.e., when an activity has been performed). Through a detailed spatiotemporal analysis investigation, the exact location of the guard railing is captured from which the installation can be performed, and the amount can be computed. Additionally, the overall minimum, average, and maximum values are computed for the assessment, which enables the HSE-responsible person to quickly get an overview (for further information, see Section 6.1). The second value captures the spatiotemporal exposure of workers concerning struck-by falling objects from work crews competing for the same work space. The exposure is computed as a percentage of the subject work space that is exposed to struck-by hazard. This value is captured similarly (i.e., at each time step and overall minimum, average, and maximum). See Section 6.1 for more information.

Additionally, the exposure is captured cumulatively, an approach inspired by Rozenfeld et al. (2009), which captures spatial and temporal overlap. This assessment, combined with the maximum equipment demand, serves as two numbers that assess the overall feasibility of a plan compared to others. The values for each time step can determine when certain changes occur.

4 | ONTOLOGY DEVELOPMENT

This section describes how each step of the ontology development was performed. Many actions and activities can be a source of falling objects in a construction situation, for example, working at height, crane lifting, and heavy winds. In general, events can be divided into static and dynamic sources. *Static-origin dropped items* occur when, for example, a building part falls from height due to corrosion, that is, the item is dropped from a static position. The other scenario, which is more relevant for safety during the construction process, can be referred to as *dynamic-origin dropped items* that are highly dependent on the construction workers, the spatiotemporal relation of their tasks, and the equipment in use. Common mitigation strategies are to train workers to look for overhead work crews, wear a hard hat, plan the path of a construction crane to avoid work crews below loads, application of safety nets, keep the work area clean, and tie handheld tools to workers (CPWR, 2021; OSHA, 1996).

4.1 | Ontology components

To capture the situation that can potentially lead to falling object scenarios and *struck-by falling object* hazards, it is first necessary to extract a glossary to describe (1) where workers may be present while performing a task on a construction element, (2) the behavior of a falling item, (3) danger source and endangered subject, (4) exposures, and (5) temporal variables. Table 1 shows an overview of the glossary needed to capture *struck-by falling object* situations during a planning process. It makes it possible to define and describe the additional spatial artifacts necessary to formalize *struck-by falling object* hazards in the ontology.

Spatial artifacts are empty space objects that emerge, or are generated, from the existence of a building element or a scheduled task that requires a crew consisting of workers. The collection of spatial artifacts, shown in Tables 2 and 3, where *functional space* and *range space* in the context of construction safety were first introduced in Li et al. (2022, 2020) but extended in this work. *Functional space* is extended with three subclasses for construction safety, *operational space, reachability space*, and *work space*. The *reachability space* was first introduced in (Madova, 2022), which in this work has been adapted to construction safety. For *range space*, this work introduces an artifact, namely, *Item drop space*.

The *reachability space* is a region that a piece of equipment or worker can reach and therefore operate in. For the crane, the reachability distance is similar (but not equal) to the length of the boom, and for a worker, similar to the

TABLE 1 Glossary for struck-by falling objects hazards

Term	Description
Reachability distance	The distance from the agent to the device or object that is worked on; for a pedestrian worker, this distance is similar (but not equal) to an arm's length, where for a crane the distance would be similar (but not equal) to the boom. The operatable distance is illustrated in Figure 2
Fall angle	The angle at which the cone formed space will expand due to items that can fall non-vertically or be kicked off a surface, for example, an item kicked off a scaffold by accident
Subject	The subject location, the subject task, the subject crew: the task, crew, or region that is exposed to the source. The subject can be associated with a distance, which has the symbol Z_{sub}
Source	The source location, the source task, the source crew: the task, crew or region that exposes the subject. The source can be associated with a distance, which has the symbol Z_{sor}
Spatial exposure	The part of the subject location/work zone that is exposed to the region of the source at that height
Temporal exposure	The fraction of the time overlaps between the source task and the subject task

arms' length. The distance is referred to as the *reachable distance* (d_r). The *reachability space* can also be described as a region where the agent can perform an action on an object. The counterpart to the *reachability space* is the *functional space* of an object, which is the region in which an agent's *reachability space* must overlap to perform an action on the object. For example, the footprint of the *functional space* for a wall is found to be the footprint of the wall extended in the directions where an agent can walk (i.e., the *movement space*). This means that the *functional space* is limited by access to the work area and that a wall that is planned to be built at the edge of a slab (see Figure 4 (t3)) only extends into the slab; otherwise, there must be a scaffold, which the work can be performed from.

The other additional subclass of *functional space*, called *work space*, is the region created when a *reachability* and *functional space* overlap. This action is conceptually like an activation of the space and represents the temporal component, where a work crew is scheduled to be present in an area to perform work on an object. Therefore, *reachability* and *functional spaces* may exist without being active, which allows for other analyses, for example, studying access or egress. The *work space* is defined as the region that the agent or piece of equipment occupies to undertake their task, either emerging by necessity based on the assigned tasks (e.g., the worker moves between work spaces), or as specified in the construction plan (i.e., work zoning).

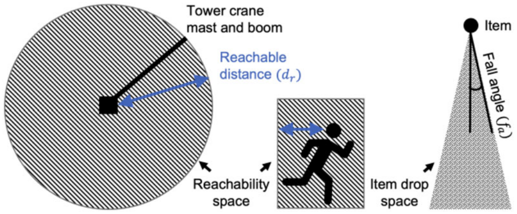


FIGURE 2 Examples of reachability distance for a crane (left image, plan view) and a worker (middle, section view) and the item fall angle forming a cone-shaped item drop space (right, section view).

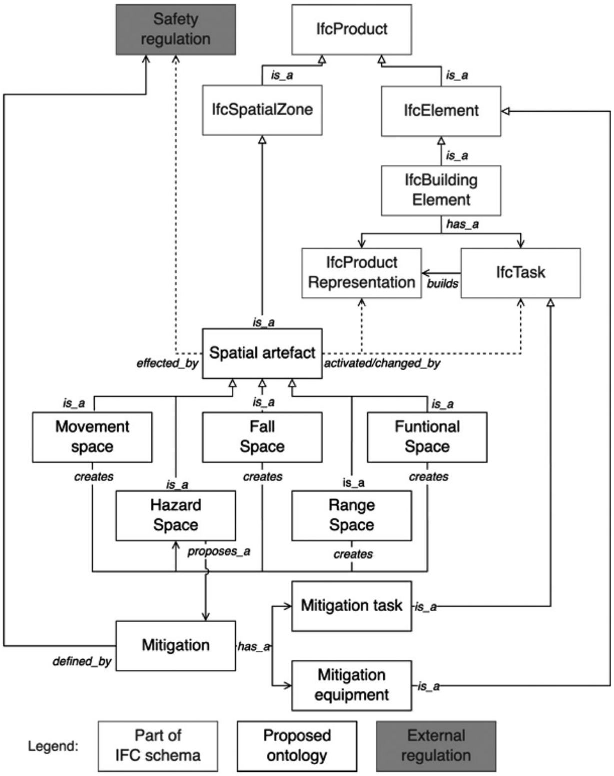


FIGURE 3 Ontology and its eventual utilization of Industry Foundation Class (IFC) schema and external safety regulation.

4.2 | Ontology relations

Figure 3 shows the ontology, illustrated from *Spatial artifacts*, and downward in the inheritance tree. A spatial artifact is not a material element that can be inserted into a building (like walls and doors) and is instead an empty-space object that emerges, or is generated, from the existence of other building elements (Bhatt et al., 2009, 2012). In this illustration, it has been chosen to include the IFC classes representing the elements from a BIM model. The usage of the IFC classes does not have any relevance for the ontology and could be other representations as well.

All the spatial artifacts are *activated_by* or *changed_by* an element and a construction task from the BIM model. The combination of an element and its construction task should create a physical object in the real world.

TABLE 2 Overview and description of spatial artifacts for fall hazard identification and analysis

Spatial artifact	Specialized subclasses	Description (Regions . . .)	Illustration	Constraints
Movement space		In which an agent (e.g., construction worker, manager, and visitor) can travel		
	Crawlable space	In which an agent can travel crawling	(Johansen et al., 2022a)	$h_c \leq height < h_w$ $and\ width \geq w_s$
	Walkable space	In which an agent can travel upright	(Johansen et al., 2022a)	$height\ = h_w\ and\ width \geq w_s$
Fall space		In which an object or agent will fall by f_d	(Johansen et al., 2022a)	$F_{z_{lower}} = M_{Z_{lower}} + f_d$
Functional Space		Empty space that the worker must be positioned in order to work on, or control, the construction element, item, or device		Only extends toward accessible regions such as movement spaces
	Operational space	That the agent or piece of equipment needs to be empty to perform a particular action		
	Reachability space	That an agent of a piece of equipmet can reach	Figure 2	Constrained by reachability distance d_r
	Work space	That the agent or piece of equipment occupies to undertake their task, either emerging by necessity based on the assigned tasks or as specified in the construction	Figure 4	
Range Space		That carry information about whether, and how, an object can be detected by an agent	(Li et al., 2022)	
	Visibility space	In which an observer (agent) has visual access to the target object (i.e., the visibility space is derived from the observed object)	(Li et al., 2022)	Should be constrained by some meaningful maximum distance
	Blind spot space	In which an agent has no visual access (i.e., derived from the observer, e.g., blind spots of a driver operating an excavator)	(Li et al., 2022)	Should be constrained by some meaningful maximum distance
	Item drop space	In which an object can be expected to be present, when dropped from a source activity	Figure 4	$Z_{sub} < z_{sor}$

TABLE 3 Overview of hazardous spatial artifacts

Hazard type	Specialized subclasses	Description (Regions . . .)	Illustration	Constraints
Fall from height	Leading edge space	Where th e movement space at its full height intersects with a fall space	(Johansen et al., 2022a)	$M_{z_{lower}} \geq F_{z_{lower}} \wedge M_{z_{upper}} \leq F_{Z_{upper}}$
	Offset leading-edge space	Where a portion of the movement space intersects with a fall space	(Johansen et al., 2022a)	$M_{z_{lower}} + offset_{lower} < M_{z_{lower}} + r_h$
	Offset top leading-edge space	Where a portion of the movement space intersects with a fall space	(Johansen et al., 2022a)	$M_{z_{upper}} - offset_{upper} < M_{z_{lower}} + h_c$
	Tumbling space	In which an agent can tumble over fall prevention equipment on lower surface	(Johansen et al., 2022a)	$z_{upper} - z_{lower} < f_d \Lambda width_{lower} < w_s$
Struck-by	Falling object space	In which agent is subject to struck by an object falling from above hazard	Figure 4	$Z_{sub} < z_{sor}$

The spatial artifacts from Table 2 are shown below the spatial artifact class and consist of movement-, fall-, functional-, and range-spaces. Additionally, the hazard spaces from Table 3 are also shown as subclasses of spatial artifacts. The artifacts from Table 3 are extracted from the geometries of the building design and completion of construction tasks, whereas the hazard spaces from Table 3 are created from combinations of artifacts in Table 2.

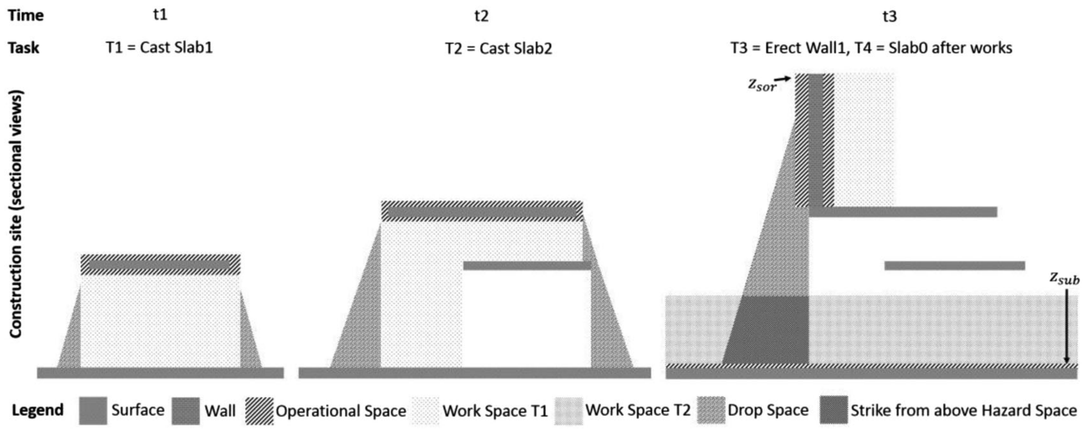


FIGURE 4 Cross-sectional views of construction progressing over time and task-dependent spatial artifacts at t1, t2, and t3 (denote time steps) and tasks T1, T2, T3, and T4 (being carried out in the corresponding timestep/s).

For example (shown in Figure 4), when a slab is built, it creates a movement space (i.e., the spatial artifact is *activated_by* the building element and the scheduled task), in which the workers can move around (safely or unsafely), for example, t2 in Figure 4. After building the slab, the schedule may include building a wall, which changes the previous movement space (i.e., the spatial artifact is *changed_by* the building element and scheduled task), for example, t3 in Figure 4. The spatial artifacts that are initiated are all *affected_by* the *safety regulation*. An example is that a movement space should only be created if the width of the surface is wider than the minimum width, which a worker is allowed to be present on, referred to as w_s (Europe: 0.56 m, the United States: 0.6 m). Similar dependencies exist for the other spatial artifacts in Tables 2 and 3, which explains the connection between the spatial artifact class to the safety regulation.

Example (illustrated in Figure 4 (t3)): When a wall is planned to be built and *activated_by* the scheduled task, its *work space* gets activated by the overlap of a crew's *reachability space* and the element's *functional space* for a given task. The *work space* can also be referred to as the potential source of a struck-by hazard. At the same time, another crew is located on a lower-level floor and has their *work space* activated by being present in the *functional space*. This *work space* can be referred to as the potential subject to the struck-by hazard. The source *work space* will create a gradually expanding space (expanding by the fall angle f_a), referred to as the item drop space, a subclass of *range space*. The *item drop space* will follow the nature of an item that is dropped and will be subtracted by physical object surfaces that can stop an object from falling further. The *struck-by falling object hazard space* will be *created* as the intersection of the *item drop space* created by the potential source and the *work space* of the potential subject.

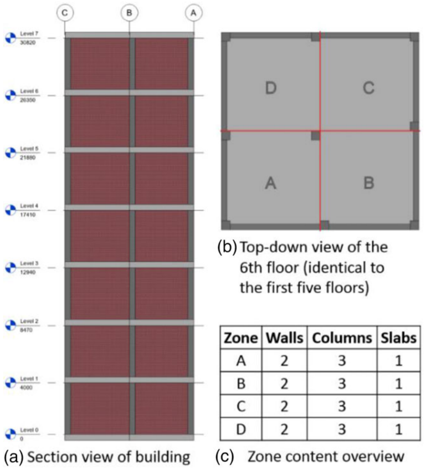
The different options of mitigation are *defined_by* the safety regulation, and the individual hazards *proposes_a* mitigation accordingly. Mitigation is composed of two initiated classes, namely, the *mitigation task* and *mitigation equipment*. The first class captures the tasks related to the mitigation equipment, such as installation, inspection, and removal of temporarily installed equipment. The *mitigation task* is shown in this example as a subclass of IfcTask. The tasks should be injected into the construction schedule to get an overview of the safety activities on equal terms as regular construction-related tasks. The *mitigation equipment* is exemplified as a subclass of IfcElement and can therefore be incorporated into the incoming BIM model and coupled with the *mitigation tasks*. It is, as mentioned earlier, not demanded to utilize IFC but solely included for illustration of connecting the ontology to the BIM.

5 | BENCHMARK MODEL DEVELOPMENT

The reason for creating a benchmark model is primarily to bridge the gap between PtD/P software developers and practitioners in the construction industry. The model and planning software has been developed in collaboration with construction engineering domain experts focusing on simplicity so that the resulting safety enhancement and assessment can be manually inspected for correctness. In previous work (Johansen et al., 2022a), our focus was on geometric correctness and edge cases. In contrast, the benchmark model presented in this study is created to test the temporal capabilities of our approach.

5.1 | The design of the benchmark BIM model

The benchmark BIM model is a high-rise building consisting of seven stories as shown in Figure 5a. It represents the reinforced concrete shell of the structure only. The first six



(a) Section view of building (b) Top-down view of the 6th floor (identical to the first five floors) (c) Zone content overview

Zone	Walls	Columns	Slabs
A	2	3	1
B	2	3	1
C	2	3	1
D	2	3	1

FIGURE 5 Benchmark model and visual presentation.

stories are identical and divided into four work zones, A, B, C, and D shown in Figure 5b. Each zone consists of a concrete slab, two masonry or prefabricated concrete walls, and two to three concrete columns as shown in Figure 5c. The top story consists of the slab, serving as a roof, and a leading edge that will remain throughout the work phase.

5.2 | Planning in the benchmark BIM model

Construction scheduling is a cumbersome process that takes time and effort. In the construction project that is captured in the proposed benchmark model, a scenario, which can be modeled with a few logic rules has been chosen. It should be noted that the planning tool is not the main contribution but rather the results captured in the publicly shared construction schedules. Nevertheless, the scheduler is briefly described to explain how the schedules have been produced. The logic rule approach enables us to write a piece of software, that can plan realistic sequences based on parameters such as individual tasks that must be performed for the element types and the available crews. The developed planning software generates plans that differ in the sequence of the locations, resulting in different spatiotemporal exposure between work crews. While this work considers safety analysis as a process that happens after the scheduling, the outputted schedules will, at this point, not involve any safety considerations. Mahdavian et al. (2022) use an alternative approach where safety is considered during the scheduling procedure.

5.2.1 | Scheduling rules

To produce realistic and constructible schedules, it is necessary to define a set of rules that must be satisfied in the result. Therefore, simple and intuitive rules that consider geometric and topological dependencies have been used in the scheduler. The rules are stated below:

1. Construction of slabs at level $L + 1$ cannot be initiated before the columns are finished in level L.
2. Construction of columns in level L cannot be initiated before the slab is finished in level L.
3. Construction of walls in level L cannot be initiated before the slab is finished in level L.
4. A work crew can be assigned to one task at a time.

The above rules ensure that the scheduler produces schedules that, for example, progress from bottom to top, that one crew is not assigned to different tasks simultaneously and that a building element is not installed without a supporting element in place. Additionally, the number of different crews available is an input that affects the scheduler. The scheduler does not prefer solutions that finish all elements of a type for each floor (e.g., completing all walls) before moving to the next level because it is irrelevant to our study. That is, the schedules' main purpose is to represent different construction approaches, and not completing all tasks of a particular type on a floor before moving on to the next floor is also a construction approach.

5.2.2 | Scheduler implementation

The scheduler program has been implemented using a combination of Python 3.8 and Answer Set Programming (ASP; Gebser et al., 2007; Marek & Truszczyński, 1999). To make the planning tool compatible with other BIM files beyond our benchmark file, it has been chosen to rely on the comment that can be added to the elements in a BIM tool (e.g., Revit). In the comment field, the user will select the zone to which the element belongs and export the IFC with properties. From the Python application, the comment can be extracted through IfcOpenshell, and the levels and zones of the elements are revealed. The level is extracted from the already existing *IfcContainedInStructure*-relation. For each task that has been selected for the element, a task is added to the instance file that is later used to create the schedule. After completing the instance file, the planning software can run, which generates a set of plans that comply with the planning constraints. ASP's working principle is that it will assign the tasks to time steps that comply with the predefined durations and check if the constraints are satisfied. If that is the case, the answer becomes a part of the answer set (i.e., the set of possible solutions to the problem). For a problem of this size, the answer set is very large, and having several hundreds of schedules would not serve any purpose for a benchmarking model. Therefore, it has been chosen to only let the schedule run for some time in the different configurations (i.e., changing maximum duration and available crews), which resulted in the 68 schedules.

The output from ASP is formatted as text, which is parsed into Excel for human readability and storage. Each solution has a worksheet placed in the repository (Johansen et al., 2022b). Every plan has a row per task and element. The nine columns describe the *ID, task name, Contractor, Level, Zone, IFC GUID, Planned start, Planned end*, and *assigned crew*.

The planner assigns different crews for the defined tasks (e.g., column crews 1 and 2), and the crews do not necessarily have to have the same safety performance in the subsequent analysis. The naming convention of the plans available at the repository is *Plan_X_Y*, where "X" is either D (dual) or S (single), describing if the planner was able to assign two crews for a task or only a single crew for each task type. "Y" is an integer for plan identification.

5.2.3 | Example schedules

Each of the generated plans is accompanied by two visualizations. top in Figure 6a,b illustrates the utilization of the individual crews throughout the construction schedule.

The bottom visualization shown in Figure 6a,b illustrates in which location (y-axis) and dates the individual crews are active. The identification of the crews is based on the corresponding colors and hatched in the top plot.

The benchmark model has 68 plans, from which a plan involving two of each crew was just described. Figure 6b illustrates how an alternative construction schedule could look if it were decided only to have one of each crew active (top of Figure 6b has only one of each crew present throughout the construction duration; the x-axis now shows a significant increase from 99 to 186 days).

The information revealed in these figures can be used to further analyze the safety situations that may occur if the construction project is carried out according to the plans. The schedules and their visualizations are publicly available in Johansen et al. (2022b) for others to use in their applications without generating the schedules themselves.

6 | CASE STUDY

This section describes the case study of our PtD/P software SafeConAI. SafeConAI utilizes the ontology developed and described in this work, such that this part of the work serves as a part of the ontology validation. The case study is additionally performed on the benchmark model that has been modeled, planned, and described as part of this work. This section describes how the model and combination of spatial artifacts in the ontology allow us to extract the potential safety hazards and the model performance of individual schedules in discrete time steps. Subsequently, the discrete performance is accumulated to estimate the overall safety performance of the individual schedule. The case study is inspired by our research project (BIM2TWIN Consortium, 2020), in which a baseline plan exists and several alternative plans (APs), each representing small changes to the schedule and crew assignments.

The APs are analyzed to enable the CM team to choose the AP that accommodates their goals in the best possible way. The baseline plan (i.e., meant for construction execution) is updated when the CM team has selected the desired AP.

SafeConAI analyzes *falls from heights* and *struck-by falling object* hazards. It investigates those two hazard types based on the geometry and the scheduled tasks. The number of leading edges can, first and foremost, be used to measure how much the workers are exposed to falling from heights and calculate the demand for mitigation equipment. In the extraction of leading edges (also the demand for safety railing equipment), the intersections between movement spaces and fall spaces are found in the model.

Each time a new element is introduced in the schedule, it automatically creates these spatial artifacts and additional hazardous regions that must be mitigated. This means that if a slab is installed at a height greater than the maximum allowable fall distance, it also introduces the safety task of installing the demanded preventive equipment. Additionally, temporarily installed equipment needs continuous inspection and removal before installation of the construction element that removes the hazard (e.g., a wall, façade, window, or balcony) can be installed.

For example (see Figure 7), let the installation of a slab requiring mitigation equipment be denoted, Ta. Then let the following task (Td) install a wall on the slab, which removes the fall hazard and, thereby, the demand for the mitigation equipment. In between, there might exist tasks Tb and Tc, which demand the mitigation equipment in place to perform the work safely.

This example would result in a mitigation equipment *placement* after Ta has been performed, *inspection* tasks before Tb and Tc, and finally *removal* before Td. Likewise, installing a building element can result in safety equipment changes (e.g., when placing a column). This action can conceptually be interpreted as a combination of remove and install, in which case, the remove happens before the task and the installation after. Alternatively, it is suggested to be modeled as a task happening in parallel to the original task.

6.1 | Analyzing the schedules

SafeConAI extracts the spatial artifacts described in our ontology from the incoming 3D BIM and schedules, to

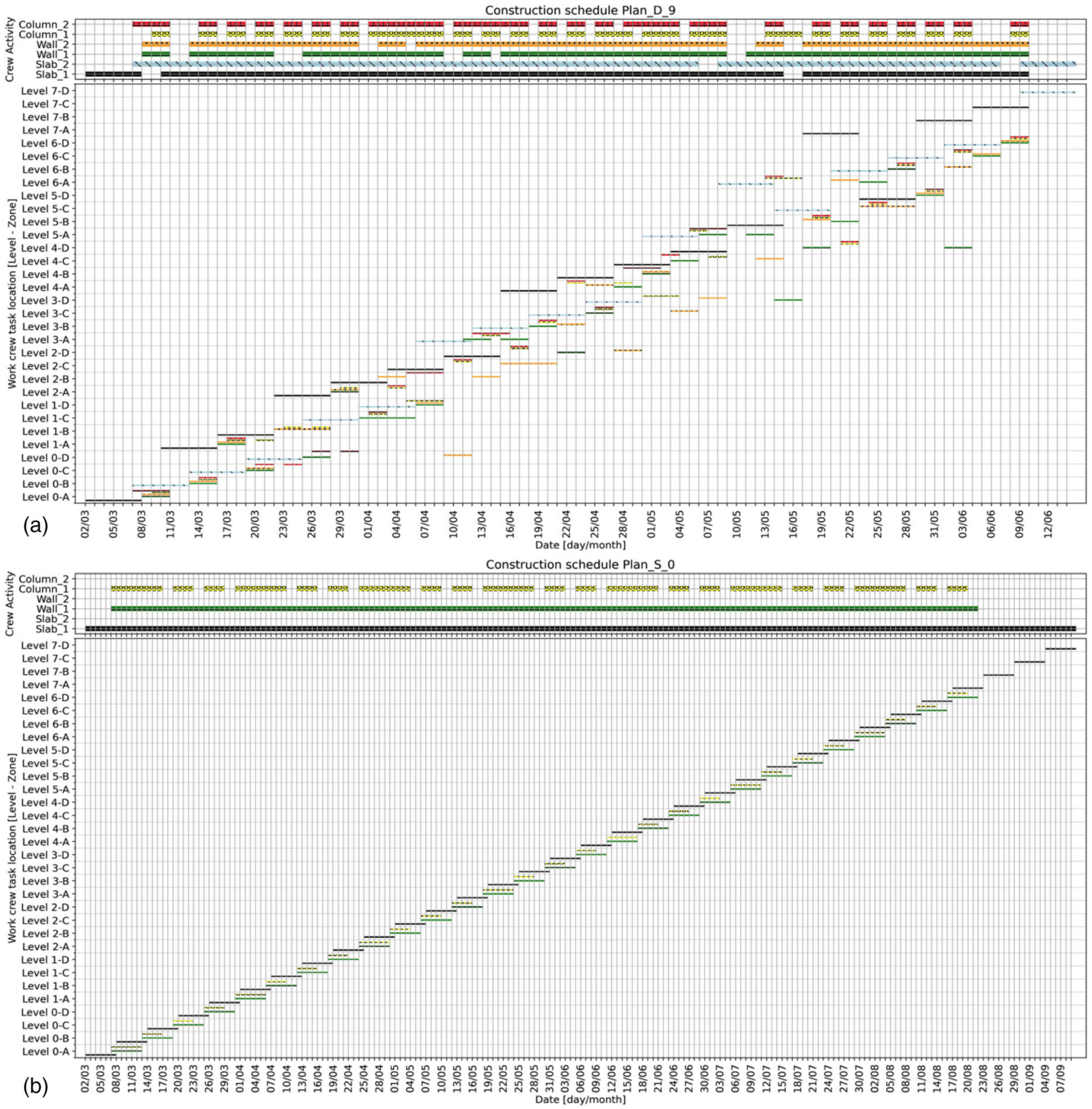


FIGURE 6 Work crew utilization (top), and work crew activity in a location (bottom): (a) Plan_D_9 and (b) Plan_S_0 (Johansen et al., 2022b)—in this schedule, some of the work crews are not active (i.e., column_2, wall_2, and slab_2).

FIGURE 7 Illustration of injected safety-related tasks.

assess the safety of the model at each incremental time step. The results are captured visually in a graphics interchange format (GIF) and are replayable.

In Figure 8, three subsequent frames of Plan_D_9 are shown of the resulting safety analysis performed by SafeConAI. The remaining frames and plans are shared in the GitHub repository (Johansen et al., 2022b). The first column of Figure 8 captures the number of days since the project was initiated. Notice, the analysis is only performed on dates when tasks are completed and elements are created. The reason is that intermediate dates do not change the geometric representation of the construction site.

The second column, *Construction Site*, shows the geometric representation of the construction site, where green elements are associated with completed tasks and blue with ongoing tasks at a specific date. The third column, *Movement Space*, illustrates the bottom surface of the spaces where the workers can move. The reason for not plotting all the spaces' boundaries, but only the bottom surface, is that the plot's readability would decrease. For movement spaces, Table 2 defined the top surfaces are offset 2 m in walkable spaces and 1 m for crawlable spaces.

The fourth column, *Fall Space*, shows the bottom surfaces of the spaces where an object or a worker would

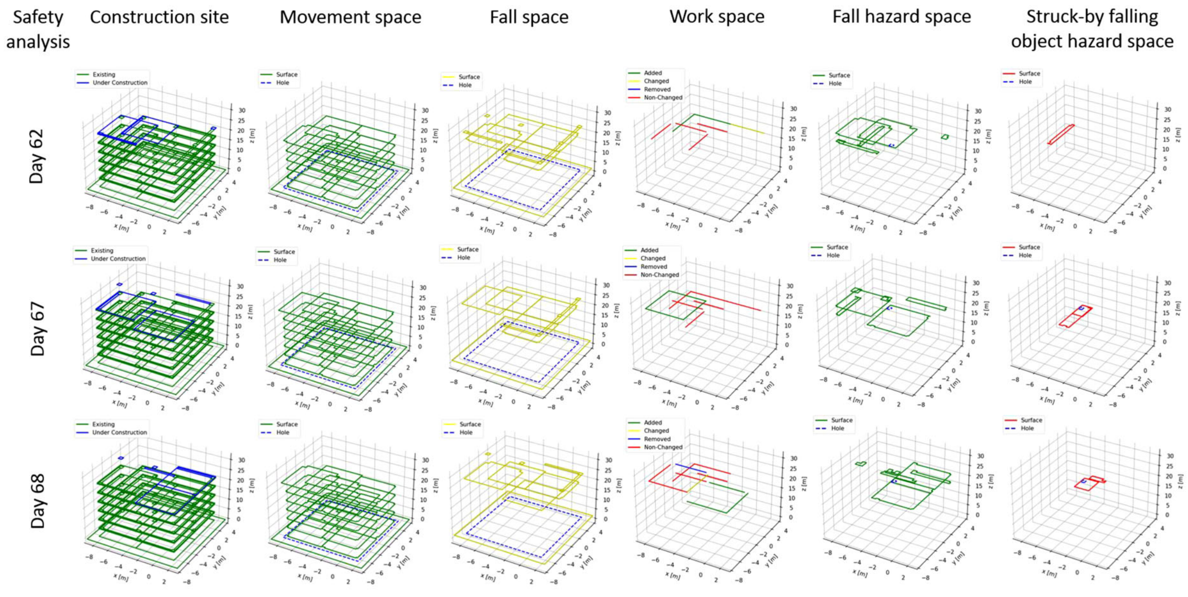


FIGURE 8 Visualization of three subsequent states at day 62, 67, and 68 of resulting safety analysis of Plan_D_9 (https://github.com/kakke14/BIM-Based4DBenchmark/blob/master/Plan%20Visualizations/Dual/Plan_D_9/Analysis.gif).

fall more than the maximum allowable fall distance (for this study, set to 1.8 m as described in OSHA, 2019). The fifth column, *Fall Hazard Lines*, shows the intersections of movement spaces and fall spaces, which is conceptually the plane where a worker can access a fall hazard. The fall hazard lines are essentially where the protective equipment must be installed to mitigate the fall hazard. As shown in the legend, this plot also captures the safety-related tasks, as the fall hazard lines are colored corresponding to *added, changed, removed, and not changed*. The sixth column *Work Space* shows where the work crews are currently located to perform the tasks according to the schedule. The seventh column, *Struck-by Falling Object Hazard Space*, shows the parts of the work spaces subject to a falling object from competing work crews in other operational spaces above as described earlier.

In Figure 9, *Guardrail demand* captures the summed length of the railing at each time step and holds the minimum, average, and maximum values in the legend. *Spatiotemporal (ST) exposure* captures the summed percentage of exposed area relative to the summed size of all active areas and holds the same values in the legend. Finally, *Safety KPI* (key performance indicator) captures the summed temporal percentage of exposure and holds the value in the S-KPI in the legend, for easy model comparison.

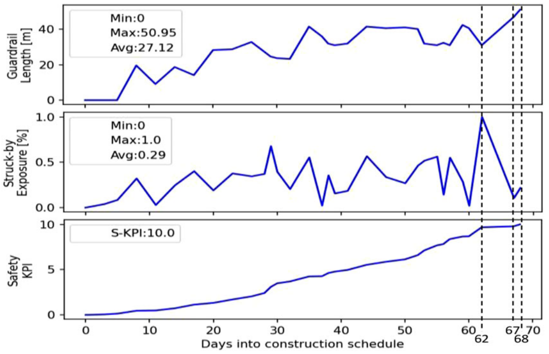


FIGURE 9 Visualization of three subsequent states at day 62, 67, and 68 of resulting safety analysis of Plan_D_9 (https://github.com/kakke14/BIM-Based4DBenchmark/blob/master/Plan%20Visualizations/Dual/Plan_D_9/Analysis.gif).

6.2 | Validation of output

The output of our PtD/P software has been validated by our three domain experts through a sample-based approach, where the construction design has been visualized in the time steps of the construction schedule. The corresponding safety analysis graphical result has been compared to the expectations of the domain experts and discussed. The *falls from heights* analysis was easier to assess as the geometric complexity of the building is relatively low. On the other hand, it became more difficult to assess the *struck-by falling object* cases, as this is not part of the current practices and the resulting hazards zones are of higher geometrical complexity due to the expansion that varies over distance (i.e., the item drop space is expanding with the fall angle, which together with the distance from source to subject impacts the hazard area).

The three subsequent frames shown in the three rows of the figure are based on the schedule called Plan_D_9, but Figure 10 summarizes the values that can give an overview of all the individual schedules' safety performance. The summarization can then be used to select a model for

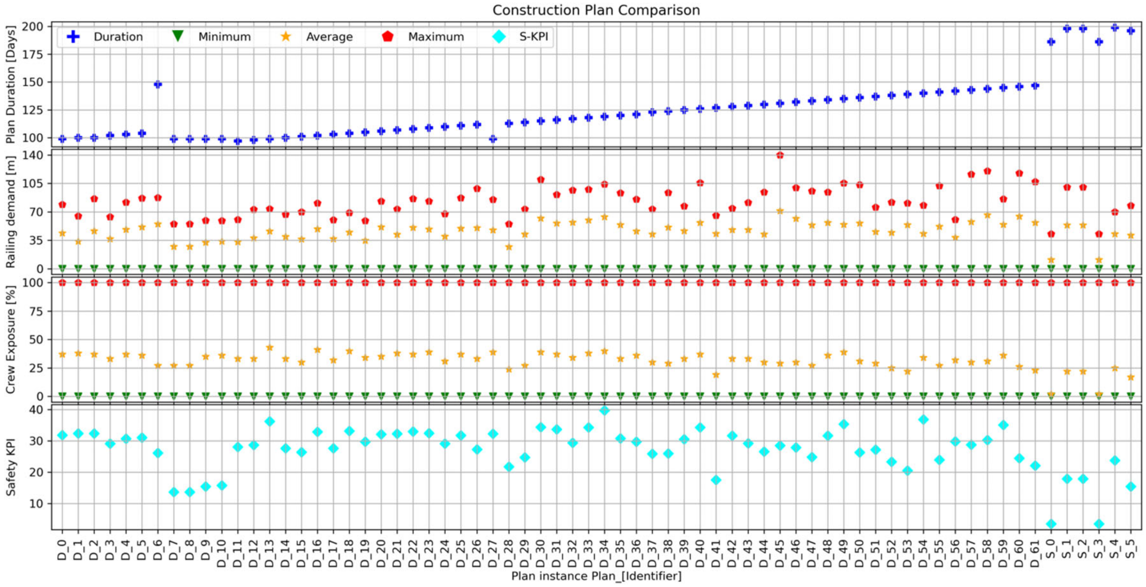


FIGURE 10 Graphical comparison of the safety analysis results for each construction schedule. From the top, the first plot shows the total construction duration. The second plot shows the minimum, average, and maximum demand for guard railing. The third plot shows the minimum, average, and maximum worker crew exposure. The fourth plot shows the overall safety key performance indicator (S-KPI).

further inspection, that is, investigate the detailed analysis captured in the GIF or even select the schedule for performing the construction process.

The first plot of Figure 10 shows a trend of increasing construction time in the plans where two of each crew are assigned. This is because the planner was limited in terms of the completion date and that the upper bound was changed to ensure the creation of differing construction plans. Outliers are also observable, especially, when the planner is limited to one crew per task. In the second plot, it is possible to see that the different plans differ in the amount of needed guard railing, for example, between plan_D_45 and Plan_S_0, there is a difference of 100 m. The third plot shows that the average exposure is, in most cases, between 20% and 40%, but that Plan_S_0 has a relatively low (less than 10%) work crew exposure. Additionally, the plot shows that all the plans have at least one time step, which results in the subject work space (i.e., a work space performed at a lower elevation than a competing task) being 100% exposed to struck-by hazards. It should be kept in mind that this percentage is computed from the portion that is exposed in relation to the total area of the subject work space. The last plot shows an overview of the S-KPIs, where outliers also exist. For example, Plan_D_7-10, but especially Plan_S_0 and Plan_S_3, has low S-KPIs, representing accumulated exposure. With this plot, it is possible to isolate the plans that do well in terms of the selected parameters. If time is the most essential component, one may consider Plan_D_7, and the safest is Plan_S_0. In both cases, the HSE coordinator could investigate when the increased exposure is introduced and mitigate those scenarios with additional personal protective equipment (PPE), such as safety nets or lanyards. Alternatively, the rise of exposure could be handled in the automated safety assessment tool, which would introduce additional mitigation equipment automatically, for example, by replacing the injected regular guard railing with a model that has smaller or even no gaps.

7 | DISCUSSION

7.1 | Ontology

We developed an ontology that relies on the concept of spatial artifacts that allow for extracting *fall from height* hazards and *struck-by falling object* hazards. Using spatial artifacts allows adding an abstraction such that the hazard spaces are not generated directly based on the geometry of a single object but allows us to process the relation of nearby elements before further analysis (e.g., subtracting walls/columns from the movement space of a slab). The spatial artifacts facilitate a higher geometric precision that is more realistic, which benefits the safety analysis and exploits other purposes in a DT.

The ontology has been created such that it can capture the dynamic nature of the construction site, which enables analysis that has so far not been possible to investigate with the current practices of safety planning. Even though the ontology has a limited scope, we envision that a similar approach using spatial artifacts that are activated or deactivated by the existence of building elements can be extended to cope with other hazard types. Our ontology is based on our BIM2TWIN and COGITO research projects, which involve industry practitioners in the consortium. This and their involvement in ontology development raise our confidence in its correctness and applicability.

7.2 | Benchmark BIM model and schedule

Inspired by the approach of other domains, we developed a benchmark BIM model with associated schedules that can be used by other researchers and developers to design and test their own approach without having to create a model and schedules. Another major benefit of using a benchmark model is that the community can easily compare the output of future research using the model and schedules, to clearly determine the contributions of new approaches beyond state-of-the-art approaches in the safety analysis.

Our benchmark BIM model is a high-rise model that includes zones, tasks, and elements to incorporate many of the hazards that exist in the industry. As part of our ongoing research, we are extending this benchmark model to other construction scenarios. We encourage the community to collaborate on extending or creating and sharing benchmark models to represent different scenarios using diverse construction methods to more comprehensively represent many safety-critical activities in the industry.

7.3 | Planner

The planner that has been created and utilized is not the main contribution but serves as an enabler for creating schedules that are applicable in the automated safety analysis. It was possible to create constructible plans, going from the bottom to the top, where none of the elements were unsupported during the construction. There are many improvements that can be implemented in the scheduler, for example, different subtasks for the elements. It could also be extended to incorporate a learning curve and account for material storage to make it more realistic.

7.4 | Case study

The case study showed how the benchmark model can be utilized and validated that our ontology was able to capture the *falls from height* and struck*-by falling object* hazards in a 4D BIM. We illustrated in detail some of the information that can be extracted from the construction design and schedule but also how different APs can be compared. As a part of a research project (BIM2TWIN Consortium, 2020), it is envisioned to validate the approach more in terms of processing time, usability, and generality. With the analysis, we acquire information that has, so far, not been accessible to safety management, thus the possibility of creating a ground truth is still limited.

Making this information available can lead to a safer work environment and remove hazards already from before the work started and assess how changes in the construction sequence will affect the situation. The insight makes decisions on a more informed basis, which hopefully reduces the accident numbers that prevail in construction. Overall, the feedback from the domain expert was positive, especially for the fall-from-height hazards. However, there is a need to advance the illustration of the struck-by hazard spaces. The reason is that, although the illustration of struck-by hazard spaces is appropriately comprehensible when individual frames are displayed, the illustration becomes overly complicated when the construction evolves over time. Another reason that the struck-by hazards are hard to perceive is that this type of analysis is currently not performed in such detail, where the actual work area is analyzed individually. Both the illustration of the construction site states and the hazard spaces must improve to facilitate the creation of a ground truth that is needed for automated assessment of soundness, completeness, and correctness. Additional domain experts need to be involved in future studies.

8 | CONCLUSION AND OUTLOOK

Throughout this work, a construction safety ontology for *falls from heights* and *struck-by falling* object hazards has been created. The ontology has been made to bring the researchers creating automated safety analysis approaches closer to the construction practitioners and their domain knowledge. Additionally, this study proposes a publicly shared benchmark model, consisting of a 3D BIM model and 68 different schedules for the construction of the building. Ontology, benchmark model, and our safety analysis results are available in Johansen et al. (2022b). The purpose of making them freely available is to lower the barrier to start researching automated safety approaches and facilitate comparison of the output of those. Even though the scope of the ontology is still relatively limited, it captures the two most fatal hazards in construction and does this in a spatiotemporal environment. The ontology has been created based on spatial artifacts and their spatial relationships, which are activated by the occurrence of construction tasks. The benchmark model has been created to represent a simple construction scenario, in which complexity is kept low on purpose. The low complexity is a limitation in terms of assessing some forms of performance (e.g., processing time, special geometries, and precision). For this purpose, we have been working on the special geometries in previous work (Johansen et al., 2022a) and envision addressing other performance criteria in future studies. For this study focusing on the schedule component, the simple scenario ensures that the researchers and domain experts can look at the resulting hazardous zones and follow the reasoning behind them. Additionally, the low complexity allows the users to manually compare analysis results to others until a proper automated comparison approach has been developed.

A case study is performed to validate that the information in the benchmark model is complete and meaningful for automated safety analysis. In this study, the benchmark model is utilized in SafeConAI, our tool for automated safety enhancement and assessment. Throughout this study, it is explained how the ontology and benchmark model can be utilized to analyze the 68 different schedules and compare their safety performance. The performed validation of the ontology and contents of the benchmark model is insufficient to validate the completeness and meaningfulness properly, but hopefully this will happen over time when other researchers start using the content.

In the future, more depth in the selected hazards will be incorporated into our ontology and benchmark model, for example, struck-by vehicle, caught in between and additionally scaling up the empirical validation through an extended series of structured exercises with domain experts to formalize ground truth assessments that can be utilized in automated correctness, soundness, and completeness assessments.

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REFERENCES

Ajelabi, I., & Tang, Y. (2010). The adoption of benchmarking principles for project management performance improvement. *International Journal of Managing Public Sector Information and Communication Technologies*, *1*(2), 1–8.

Beach, T. H., Hippolyte, J. -L., & Rezgui, Y. (2020). Towards the adoption of automated regulatory compliance checking in the built environment. *Automation in Construction*, *118*, 103285. https://doi.org/10.1016/j.autcon.2020.103285

BFA, B. (2020). *Håndbogen—Arbejdsmiljø i bygge og anlæg*. Branchearbejdsmiljørådet for Bygge & Anlæg.

BG-Bau. (2021). *Absturzsicherungen auf Baustellen Seitenschutz/Absperrungen*. Berufsgenossenschaft der Bauwirtschaft. https://www.bgbau.de

Bhatt, M., Dylla, F., & Hois, J. (2009). Spatio-terminological inference for the design of ambient environments. In K. S. Hornsby, C. Claramunt, M. Denis, & G. Ligozat (Eds.), *International Conference on Spatial Information Theory* (pp. 371–391). https://doi.org/10.1007/978-3-642-03832-7_23

Bhatt, M., Schultz, C., & Huang, M. (2012). The shape of empty space: Human-centred cognitive foundations in computing for spatial design. *IEEE Symposium on Visual Languages and Human-Centric Computing, Innsbruck, Austria* (pp. 33–40). https://doi.org/10.1109/VLHCC.2012.6344477

BIM2TWIN Consortium. (2020). https://bim2twin.eu/

BLS, B. of labour statistics (2020). *Fatal occupational injuries by industry and event or exposure*. https://www.bls.gov/iif/oshwc/cfoi/cftb0340

Borrmann, A., & Rank, E. (2009). Topological analysis of 3D building models using a spatial query language. *Advanced Engineering Informatics*, *23*, 370–385. https://doi.org/10.1016/j.aei.2009.06.001

Brown, S., Harris, W., Brooks, R. D., & Dong, X. S. (2021). *Fatal injury trends in the construction industry*. https://stacks.cdc.gov/view/cdc/115527

Castillo, T., & Bonilla, M. (2020). Benchmarking the construction industry: An adaptation of the world management survey methodology. 28th Annual Conference of the International Group for Lean Construction (IGLC), Berkeley, CA. https://doi.org/10.24928/2020/0057

Collins, R., Zhang, S., Kim, K., & Teizer, J. (2014). *Integration of safety risk factors in BIM for scaffolding construction 307–314*. https://doi.org/10.1061/9780784413616.039

CPWR. (2021). *Struck-by hazards*. https://www.cpwr.com/research/research-to-practice-r2p/r2p-library/other-resources-for-stakeholders/struck-by-hazards/

European Standards. (2018). *Temporary edge protection systems - DS_EN 13374_2013+A1_2018*.

Fargnoli, M., & Lombardi, M. (2020). Building information modelling to enhance occupational safety in construction activities: Research trends emerging from one decade of studies. *Buildings*, *10*, 98. https://doi.org/10.3390/buildings10060098

Fernández-López, M., Gómez-Pérez, A., & Juristo, N. (1997). Methontology: From ontological art towards ontological engineering. *AAAI-97 Spring Symposium*, Stanford, EEUU, Stanford, CA.

Gebser, M., Kaufmann, B., Neumann, A., & Schaub, T. (2007). Clasp: A conflict-driven answer set solver, logic programming and nonmonotonic reasoning. In C. Baral, G. Brewka, & J. Schlipf (Eds.), *Logic Programming and Nonmonotonic Reasoning. LPNMR 2007*, Lecture Notes in Computer Science (pp. 260–265). Springer. https://doi.org/10.1007/978-3-540-72200-7_23

Gómez-Pérez, A. (1996). Towards a framework to verify knowledge sharing technology. *Expert Systems with Applications*, *11*, 519–529. https://doi.org/10.1016/S0957-4174(96)00067-X

Hardison, D., & Hallowell, M. (2019). Construction hazard prevention through design: Review of perspectives, evidence, and future objective research agenda. *Safety Science*, *120*, 517–526. https://doi.org/10.1016/j.ssci.2019.08.001

Heidary, M. S., Mousavi, M., Alvanchi, A., Barati, K., & Karimi, H. (2021). Semi-automatic construction hazard identification method using 4D BIM. ISARC Proceedings, Dubai, UAE (pp. 590–597).

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

Jin, Z., Gambatese, J., Liu, D., & Dharmapalan, V. (2019). Using 4D BIM to assess construction risks during the design phase. *Engineering, Construction and Architectural Management*, *26*, 2637–2654. https://doi.org/10.1108/ECAM-09-2018-0379

Johansen, K. W., Schultz, C., & Teizer, J. (2022a). BIM-based fall hazard ontology and benchmark model for comparison of automated prevention through design approaches in construction safety. *International Workshop on Intelligent Computing in Engineering*, Aarhus, Denmark. https://doi.org/10.7146/aul.455.c231

Johansen, K. W., Schultz, C., & Teizer, J. (2022b). *kakke14/BIM-Based4DBenchmark: BIM-based 4D benchmark model for sound-*

ness and completeness assessment of automated approaches in construction safety. GitHub: https://github.com/kakke14/BIM-Based4DBenchmark

Karim, A., & Adeli, H. (1999). CONSCOM: An OO construction scheduling and change management system. *Journal of Construction Engineering and Management*, *125*(5), 368–376.

Lei, Y., Wu, D. T., & Lin, Y. (2012). A decentralized control algorithm for large-scale building structures. *Computer-Aided Civil and Infrastructure Engineering*, *27*, 2–13. https://doi.org/10.1111/j.1467-8667.2010.00707.x

Li, B., Schultz, C., Teizer, J., Golovina, O., & Melzner, J. (2022). Towards a unifying domain model of construction safety, health and well-being: SafeConDM. *Advanced Engineering Informatics*, *51*, 101487. https://doi.org/10.1016/j.aei.2021.101487

Li, B., Teizer, J., & Schultz, C. (2020). Non-monotonic spatial reasoning for safety analysis in construction. *22nd International Symposium on Principles and Practice of Declarative Programming*, Bologna, Italy (pp. 1–12). https://doi.org/10.1145/3414080.3414096

Lu, Y., Li, Q., Zhou, Z., & Deng, Y. (2015). Ontology-based knowledge modeling for automated construction safety checking. *Safety Science*, *79*, 11–18. https://doi.org/10.1016/j.ssci.2015.05.008

Luo, H., & Paal, S. G. (2019). A locally weighted machine learning model for generalized prediction of drift capacity in seismic vulnerability assessments. *Computer-Aided Civil and Infrastructure Engineering*, *34*, 935–950. https://doi.org/10.1111/mice.12456

Mahdavian, S., Lu, M., & Pereia, E. (2022). Application framework for safety-centric construction acceleration planning. Engineering, Construction and Architectural Management. Advance online publication. https://doi.org/10.1108/ECAM-03-2021-0195

Madova, T. (2022). *Human-centred architectural design - visualisation of occupants' experience and behaviour in BIM models*. Aarhus University, Electrical and Computer Engineering, Denmark, (Thesis).

Marek, V. W., & Truszczyński, M. (1999). Stable models and an alternative logic programming paradigm. In K. R. Apt, V. W. Marek, M. Truszczynski, & D. S. Warren (Eds.), *Logic Programming Paradigm: A 25-Year Perspective, Artificial Intelligence* (pp. 375–398). Springer. https://doi.org/10.1007/978-3-642-60085-2_17

McKinney, W. (2010). Data structures for statistical computing in Python. *Python in Science Conference*, Austin, TX (pp. 56–61). https://doi.org/10.25080/Majora-92bf1922-00a

Melzner, J., Zhang, S., Teizer, J., & Bargstädt, H. -J. (2013). A case study on automated safety compliance checking to assist fall protection design and planning in building information models. *Construction Management and Economics*, *31*, 661–674. https://doi.org/10.1080/01446193.2013.780662

Mihić, M., Cerić, A., & Završki, I. (2018). Developing construction hazard database for automated hazard identification process. *Tehnicki Vjesnik*, *25*, 1761–1769. https://doi.org/10.17559/TV-20180417105624

Noy, N. F., & McGuinness, D. L. (2001). Ontology development 101: A guide to creating your firstontology. Stanford knowledge systems laboratory technical reportKSL-01-05.

OSHA. (2019). 1910.29—*Fall protection systems and falling object protection-criteria and practices*. Occupational Safety and Health Administration. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.29

OSHA. (1996). *1926.451(h)—Falling object protection*. Occupational Safety and Health Administration. https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.451

Perlman, A., Sacks, R., & Barak, R. (2014). Hazard recognition and risk perception in construction. *Safety Science*, *64*, 22–31. https://doi.org/10.1016/j.ssci.2013.11.019

Pinto, A., Nunes, I. L., & Ribeiro, R. A. (2011). Occupational risk assessment in construction industry—Overview and reflection. *Safety Science*, *49*, 616–624. https://doi.org/10.1016/j.ssci.2011.01.003

Qi, J., Issa, R. R. A., Olbina, S., & Hinze, J. (2014). Use of building information modeling in design to prevent construction worker falls. *Journal of Computing in Civil Engineering*, *28*, A4014008. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000365

Reback, J., jbrockmendel, McKinney, W., Van den Bossche, J., Roeschke, M., Augspurger, T., Hawkins, S., Cloud, P., gfyoung, Sinhrks, Hoefler, P., Klein, A., Petersen, T., Tratner, J., She, C., Ayd, W., Naveh, S., Darbyshire, J. H. M., Shadrach, R., … Li, T. (2022). *Pandas-dev/pandas: Pandas 1.4.3*. https://doi.org/10.5281/zenodo.6702671

Rozenfeld, O., Sacks, R., & Rosenfeld, Y. (2009). "CHASTE": Construction hazard assessment with spatial and temporal exposure. *Construction Management and Economics*, *27*, 625–638. https://doi.org/10.1080/01446190903002771

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*, e14. https://doi.org/10.1017/dce.2020.16

Sigalov, K., & König, M. (2017). Recognition of process patterns for BIM-based construction schedules. *Advanced Engineering Informatics*, *33*, 456–472. https://doi.org/10.1016/j.aei.2016.12.003

Teizer, J., Johansen, K. W., & Schultz, C. (2022). The concept of digital twin for construction safety. *Construction Research Congress*, Arlington, VA (pp. 1156–1165). https://doi.org/10.1061/9780784483961.121

de Vries, B., & Harink, J. M. J. (2007). Generation of a construction planning from a 3D CAD model. *Automation in Construction*, *16*, 13–18. https://doi.org/10.1016/j.autcon.2005.10.010

Wang, Z., & Azar, E. (2019). BIM-based draft schedule generation in reinforced concrete-framed buildings. *Construction Innovation*, *19*(2), 1471–4175. https://doi.org/10.1108/CI-11-2018-0094

Wu, I. -C., Borrmann, A., Beißert, U., König, M., & Rank, E. (2010). Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation. *Advanced Engineering Informatics*, *24*, 379–388. https://doi.org/10.1016/j.aei.2010.07.002

Zhang, S., Boukamp, F., & Teizer, J. (2015). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, *52*, 29–41. https://doi.org/10.1016/j.autcon.2015.02.005

Zhou, Z., Goh, Y. M., & Shen, L. (2016). Overview and analysis of ontology studies supporting development of the construction industry. *Journal of Computing in Civil Engineering*, *30*, 04016026. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000594

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