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AUTOMATED SPATIOTEMPORAL IDENTIFICATION AND DISSEMINATION OF WORK CREWS' EXPOSURE TO STRUCK-BY HAZARDS

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Abstract

The construction industry is among the most hazardous industries, and its continuously changing, and complex environment results in a labour-intensive task to plan and prevent hazards. The current manual safety planning procedures cannot be performed with a temporal resolution that represents all stages of the environment. This leads to unplanned durations and an increased responsibility for the individual workers to analyse and act accordingly to a situation. With this work, we propose an automated approach to identify and measure the amount struck-by falling objects hazard exposure to the construction tasks and their assigned work crews. The automated identification, dissemination, and digitization of hazard identification allows safety professionals to perform safety analysis every time the spatial situation of the construction site changes and introduces temporary safety equipment or suggests changes in the sequence of tasks to lower the exposure of workers to hazards. Additionally, it allows for a comparison between schedules, which is highly relevant with respect to digital twins, where alternative plans are generated based on historical knowledge about construction projects. The approach is described through a graphical and algorithmic approach, which is then validated in two case studies. The case studies reveal the potential and, at the same time, requirements for the scheduling of construction projects if automated approaches should realise their full potential.

Keywords: Automated prevention through design and planning, Digital Twin for construction safety, Hazard exposure identification and dissemination, Spatio-temporal safety analysis

1 INTRODUCTION

Construction is one of the most dangerous industries due to the continuous change in the construction environment. Over time, the previously safest route may have turned into a hazardous one, e.g., tools dropping from crews allocated nearby or above other work areas. Safety planning is currently a manual and labor-intensive task. In particular, the standard planning process only covers the overall site layout in a coarse temporal resolution because it would be impossible to generate a new safety plan for every state change of the construction site. Consequently, the workers are responsible, and must be aware of, consider, and adapt to, new hazardous situations that may not be a part of the safety plan due to the low temporal resolution available when undertaking initial safety planning. Pushing the safety responsibility to the individual worker results in thought-provoking safety statistics in construction. Additionally, some analysis tasks can be too complex for the current manual approaches to solve (e.g., extensive *struck-by-falling object* hazards). This often leads to a hard hat requirement that covers the complete construction site, even in areas where it is not strictly required. Furthermore, having the dangerous areas digitally modelled can allow sensor-based approaches to notify workers about the requirement of safety equipment (e.g., hard hats), and ensure that the workers conform to the requirements.

The complex and dynamic nature and the increasing interest in Digital Twins (DTs) demands an approach that can automatically perform safety assessment and enhancement when the project progresses, and changes on the construction site are recorded. The frequently gathered progress information can be processed and utilized to plan, act, and improve the safety situation for the construction project [1, 2]. This study will represent the DT with a 3D BIM (Building Information Modelling) model and a schedule, which assigns the work crews to the task. The schedule structure is inspired by the structure that is defined in [3].

This work proposes a novel automated algorithm that allows safety management to extract hazardous situations in the construction site based on the (spatial) 3D geometry and the (temporal) construction schedule. The algorithm performs a spatiotemporal analysis (i.e., considering both the geometry and the schedule information simultaneously) using the work crews' exposure to hazards from simultaneously occurring tasks and other work crews. We calculate how one crew exposes other crews to hazards based on an automatically generated workspace (i.e., the zone and location of the task the crew is assigned to in the schedule). The analysis will investigate *struck-by falling object* hazards (aka. overhead work). Most automated safety analysis studies have been performed with respect to *falls from height* hazards, as this is the deadliest hazard in the construction industry [4–11]. Nonetheless, *struck-by* hazards are responsible for the second most fatalities. This work finds inspiration in the approach presented in [12] but describes the hazard source and exposure regions with spatial artefacts that are generated based on the current spatial situation of the construction site.

The spatiotemporal analysis is based on temporarily existing spatial artefacts [13], which are semantically rich empty-space objects describing regions that emerge from a spatial situation. For example, when a crew is assigned to a task on a building object, then the footprint of the object becomes the surface of an extruded workspace spatial artefact. The workspace's impact on other workspaces can be determined through stepwise geometric operations, where the surrounding and related building elements' geometries are considered.

2 RELATED WORK

Safety planning is a complex labor-intensive task and can, therefore, not be carried out every time the construction site's spatial situation changes. The safety planning procedure is often referred to as Prevention through Design and Planning (PtD/P) and tries to remove the hazards with changes to the design (e.g., inserting temporary protective equipment like guardrails and safety nets), or changes to the schedule (e.g., reordering the scheduled tasks or crane lift paths). An alternative solution to the manual PtD/P is to automate the efforts, which can be divided into two categories, based on semantic or spatial analysis. In the first category, the safety engineers are, often based on patterns in a hazard database, guided through a safety evaluation sequence, where hazards can be identified [14], [15]. The other category is based directly on the geometry of the objects and safety regulations which enables the identify the hazards and their geometry. This approach allows the solution to inject safety protective equipment directly into the BIM model, which therefore becomes a part of the digital design [5, 7, 8, 10]. The second approach, which is based directly on the BIM model geometry and injection of protective equipment, demands less manual handling from the safety engineer, which is important, especially in the DT setting.

When the safety analysis is performed in a (semi) automated way, the software needs a way to represent the scoped rule of the safety regulation. Spatial artefacts [13, 16] can be used for this purpose as they represent empty-space regions that emerge and change based on the existence of BIM elements or situations in the 3D space. The spatial artefact approach was initially investigated for construction safety in [7, 17], allowing one to express the situation in greater detail, as they can be modelled with the inclusion of more than one BIM element. For example, in a situation where the operation space (i.e., the region where a crew will be situated to perform a task) can be modelled as the overlapping region of an enlarged version of the element footprint that the work is performed on and the surface, which the crew is standing on to perform the work. The details allow the analysis to be performed in a more realistic and detailed situation, as it also, dependent on the implementation, can model the fact that the crew cannot levitate (i.e., that the operation space should only be extended towards already existing surfaces).

There have been research activities in the *struck-by falling object* hazard type. As the *struck-by falling objects* hazard emerges from competing work crews, the approaches involve information about the active work crews and their workspaces. This information often comes from the schedule, but when the geometry of the workspaces must be determined, the approaches differ. [14] has a semantic approach, where a set of rules are checked based on the user's selection of analyzed hazards. In this approach, the exposed BIM elements light up if their spatial representation is exposed by a task that is performed simultaneously. Work crews may not only be situated inside the geometry of the BIM element that they are working on, but they would also often be placed in the surroundings of the element; thus, the geometry of the BIM element itself can be a help but is not enough to identify when and where workers are exposed to struck-by falling object hazards. In [12], zones are defined to represent the spatial representation of the workspaces, and those are activated or deactivated by the schedule. This way, the exposure is related to a zone that may contain the surroundings of the BIM elements as well. In [18], the approach relies on a rule-checking engine that identifies areas that are exposed by other work crews, but in do also offer a way to represent the worker´s trajectory paths, which enables the tool to identify hazards that are not just within the geometry of an exposed BIM element. It is important that the information that is utilized in automated hazard analysis tools stem directly from information that is readily available from the existing 3D BIM model and belonging schedule. as the additional modelling of zones, and worker trajectories may not be available at the time of analysis. Modelling this information can be a time-consuming procedure, that must be performed repeatedly due to the constant change of the construction sites' spatial situation. Additionally, too much manual handling does not conform with the vision of DTs, which will act and improve automatically based on the situation and gathered knowledge.

Together with automatization, open standards, and non-proprietary formats are key for the DT to exist. As the vision for the DT is that all the stakeholders can utilize the information and knowledge that is gathered in it, it must be able to exchange information with many different workflows. Likewise, it must be able to take information from as many workflows. Additionally, [19] investigated why the automated BIM-based safety enhancement tools remain in research and are still not widely used in practitioners' workflows. Lack of confidence, standardization, and fit to current workflows impede the widespread adaption. Industry Foundation Classes (IFC) is an initiative for open standard, platform-neutral Computer-Aided Design (CAD) data exchange in an object-oriented fashion. IFC is supported by most CAD and BIM tools and facilitates data exchange between different stakeholders with different workflows in a construction project. IFC has also been welcomed in the open-source community, where contributors have collaborated on IFC interfacing software that can read, write, and modify the IFC file format (e.g., the JavaScript-based plugin [20] and C++ and python-based [21]).

The usage of IFC can also be a way to tackle the issues of lack of standardization and fit to current workflows. The lack of confidence in automated approaches has also been addressed by researchers, for example, by this work´s authors [22], where an application can assess the automated safety analysis tool´s performance can be assessed in terms of soundness, completeness, and spatial correctness. The assessment is based on benchmark models and corresponding ground truth assessments. This approach can facilitate goal-oriented improvement of the algorithms for the developer. Furthermore, it helps to convince construction industry practitioners to adopt automated safety analysis approaches.

3 METHODOLOGY

This study is split into three different activities. The first activity is initiated by importing the construction situation and processing the geometries and schedule information to build a spatial representation of the construction situation for the time stamps described in the schedule (i.e., spatiotemporal representation). In the second activity the workspaces are defined and extracted from the spatiotemporal representations of the construction project. Additionally, this stage defines and extracts the *item drop space*, which in conjunction with the workspaces, creates the *struck-by falling object* hazard spaces. Finally, the third activity consists of exporting the identified hazard spaces in a way that is useful for construction practitioners but also useful in a DT setting. The three activities are visualised in Fig. 1 and are further elaborated in Sections 3.1, 3.2, and 3.3, respectively.

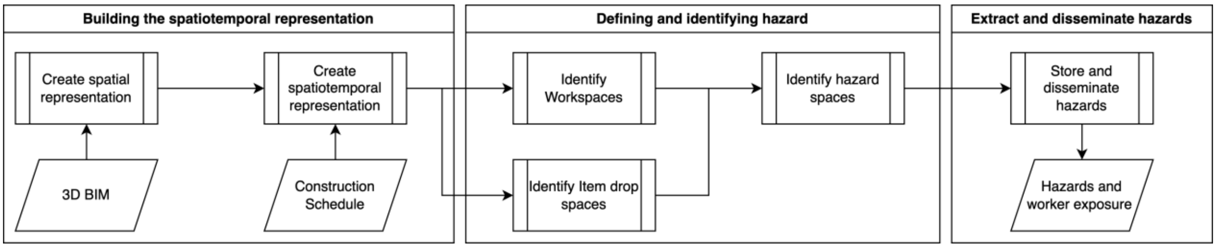


Fig. 1 Visualization of research approach, showing the three performed activities.

3.1 Building of the spatiotemporal representation

To create a spatiotemporal representation, it has been chosen to work with the open standard file format IFC, and the open-source python library IfcOpenShell to parse the geometries of the BIM elements. Each element is stored with its upwards-pointing surfaces, i.e., surfaces that can be walked on by humans, and on to which items or humans can fall onto. Additionally, the downwards-pointing surfaces are extracted, as these define regions that must be subtracted, e.g., when a wall is placed on a slab, it is the downwards-pointing surfaces that should be subtracted from the walkable space.

Once the spatial situation of the construction site has been extracted from the IFC, the temporal component is then added. In this work, it has been chosen to select a human interactable format for the schedule, namely Excel. The excel format is widely used in construction, and it is straightforward to export Comma Separated Values (CSV) from it, which can be interfaced with most applications and software development tools. The schedule pairs the BIM object with tasks, which individually have start and end dates. After parsing the schedule this information is added to the python object that also captures the geometry of the object.

The 4D BIM (3D geometry and schedule) representation in python now holds a list of BIM objects, and their planned start date and completion date, also referred to as the As-planned BIM. Based on analysis date (T_a) the 4D BIM allows the program to query the As-planned, As-Built, and Ongoing tasks shown and described in Tab. 1. These queries are used to build a spatial representation of the construction site at different dates, such that the analysis can be performed for the complete schedule duration in discrete steps.

Tab. 1 overview of 4D BIM queries inspired by [1], [2], where the analysis date refers to the time stamp that the analysis is performed for and BO is a set of all Building Objects.

Query	**Description**	**Definition**
As-built(T_a)	Elements whose tasks' end-dates (T_e) are before the analysis date (T_a)	$bo \in BO: end\_date(bo) < T_a$
Ongoing(T_a)	Elements whose tasks' start-dates (T_s) are before, and end-dates (T_e) are after the analysis date (T_a)	$bo \in BO: start\_date(bo) \leq T_a \leq end\_date(bo)$
As-planned(T_a)	Elements whose tasks' start-dates (T_s) are after the analysis date (T_a)	$bo \in BO: T_a < start\_date(bo)$

3.2 Definition and identification of hazards

Performing the analysis directly in the geometry of the BIM elements has certain drawbacks, where it cannot be expected that workers are only present within the object geometry, e.g., that workers are only located on the specified construction site slabs. Likewise, predefined zones lead to additional manual handling, as described in the related work (Sec. 2). Therefore, this work uses an approach where the analysis spaces emerge from the existence of BIM elements, but where the surrounding is also considered. These analysis spaces will, from now on be referred to as *spatial artefacts*, which is a way to express semantically rich regions of empty spaces that emerge from a spatial situation in the construction site [7, 13]. This work uses spatial artefacts to represent three kinds of regions, which is *workspaces*, *item drop spaces,* and *struck-by falling object hazard spaces.* The spatial artefacts will be defined and described based on Fig. 2, which illustrates a construction scenario consisting of four slabs and one wall. The sequence in which the building object is constructed is shown with the annotation on the building objects (i.e., T_s and T_e, capturing the start and end times of the construction task, respectively).

Workspaces

While the geometry of a workspace may differ based on the performed task, this work describes a definition of a workspace that is related to the cast-in-place structural work of building elements. Nevertheless, other workspace definitions can be added as specialized child classes that inherit the general parent space properties and relation to the analysis. For the cast-in-place workspace, referred to as just the workspace in the following, it is necessary to describe the nature of its emergence. Fig. 2 shows the spatial representation of these spaces in the fourth time step of the analysis. In this representation, one of the active workspaces emerges from the slab, and one emerges from the wall that are both under construction at T_a=4. Common for both workspaces is that they result from an enlargement of the upwards-pointing surface(s) in combination with the intersection of a lower existing building object. The intersection is reasoned with the fact that the work crew needs something to stand on to build the building object, and that it is natural to assume that it would be based on a surface that exists directly below.

Alg. 1 formalises the described procedure, where variables are shown in *italic* and inputted lists in **bold**. The dilate()-function in line 3 refers to the standard Minkowski sum operator, which extends the polygon region, and the intersection()-function in line 6 returns the overlapping portion of the polygons. The subtract()-function in line 7 returns the difference, and ^-operator represents a concatenation of two lists. Line 6 consequently appends the new workspace to the resulting list S.

Alg. 1 Algorithm for workspace extraction

```
Input: OBO (a sorted list of ongoing building objects, based on z-offset),
       EBO (a sorted list of as-built building objects, based on z-offset)
Output: S (a list of workspaces)
S = []
for each BO in OBO:
    WS_Polygon := BO.Top_polygon.dilate(Work_distance)
    for each EBO in EBO:
        S := S^[ WS_polygon.intersection(EBO.Top_polygon)]
        WS_polygon := WS_polygon.subract(EBO.Top_polygon)
return S
```

The workspaces can, in this way, also be limited in height, which could be used for access analysis, for example, to investigate if and how much scaffolding would be needed. In this study this aspect is not included, and the workspaces are not limited by a maximum height, and it is therefore assumed that the work crews can reach with ladders or mobile scaffolding. Additionally, these workspaces can be used in automated reasoning and analysis of activity and progress, such as [23, 24].

Item drop spaces

The purpose of the *item drop space* is to determine where an item or object that originates from a workspace would be able to drop. Fig. 2 illustrates an *item drop space* in analyzing the fourth time step of the construction example. The illustrated *item drop space* emerges from the active *workspace* that emerges from the task of building the wall element at the top. The space gradually grows with an angle, which means that the size of the *item drop space* will increase with the distance from the workspace that it originates from (i.e., creating the cone-formed shape).

Alg. 2 show how the item drop spaces are extracted. The angular_dilation()-function returns a dilated version of the polygon, where the dilation amount equals $\tan\,(\theta_{drop\ angle} * distance)$. If the elements are already built, the algorithm will subtract its geometry (i.e., the dropping item cannot go through existing elements). On the other hand, if the building object is in progress, the algorithm appends the dilated version to the list of item drop spaces.

Alg. 2 Algorithm for item drop space extraction

```
Input: AWS (a sorted list of active workspaces, based on z-offset),
       BO (a sorted list of all building objects, based on z-offset),
       EBO (a sorted list of as-built building objects, based on z-offset)
Output: S (a list of item drop spaces)
S = []
for each WS in AWS:
    IDS_Polygon:= WS.Top_polygon
    Z_WS:=WS.top_Z
    for each BO in BO:
        IDS_Polygon:= angular_dilation(Z_WS - BO.top_Z)
        if BO in EBO
            IDS_Polygon:= IDS_Polygon.subtract(BO)
        else if BO not in EBO
            S:=S^[IDS_Polygon]
return S
```

The recursive analysis allows the item drop space artefact to describe its impact on other workspaces all the way down to the bottom of the construction model if it is not removed by existing elements. In the end, it reaches the ground, which always exists, and the subtraction will consequently return an empty polygon, that cannot generate further artefacts. Nonetheless, until it is removed, it can impact workspaces that were not identifiable by the human eye, especially in more complex BIM models.

Struck-by falling object hazard space

After the automated extraction of both workspaces and item drop spaces, it is possible to extract the potential struck-by falling object hazard space artefacts. The way that it is extracted is to loop through the item drop spaces and find their overlapping regions with the active workspace artefacts. The illustration of the result of this procedure is shown in Fig. 2, which shows that the work crew, who are working on the slab, is exposed to items that are accidentally dropped by the work crew working on the wall task.

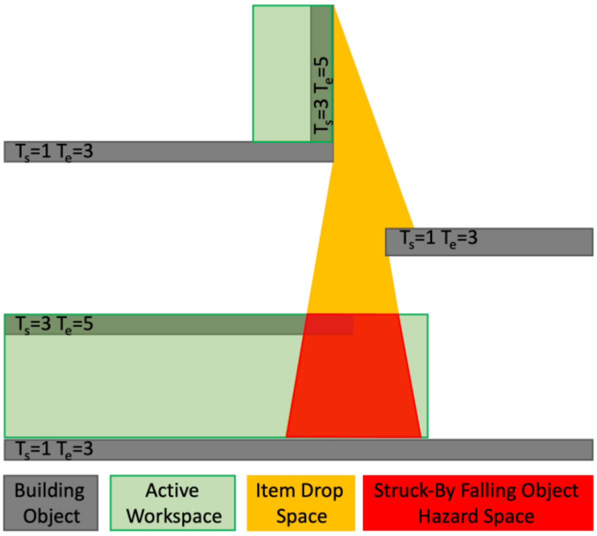


Fig. 2 visualization of the proposed struck-by falling object hazard analysis in a simplified building scenario showing the emerging spatial artefacts.

3.3 Extraction and dissemination of identified hazards

Automated safety analysis for construction is not currently being widely adopted in the industry, as mentioned previously. Some of the reasons for this are that there is a lack of confidence, but also a lack of a fit with, and support for, the current workflows of construction practitioners. Therefore, this work bases its output on IFC, which can be used in almost any CAD tool. This strategy consequently enhances the incoming BIM model with spatial artefacts, which are captured with the IfcSpatialZone class. This enables the practitioner to investigate when and why the hazard zones appear and potentially mitigate these hazards using safety nets and guardrails that are equipped with nets.

Besides capturing the analysis result in the BIM file, it also provides a selection of overall Safety Key Performance Indicators (SKPI), which enable the construction management to rapidly assess whether a construction plan´s amount of struck-by hazard exposure exceeds the expected or even to compare two different construction approaches. The latter is especially relevant in a DT setup, where different construction approaches are captured in what is referred to as alternative plans in [1] and [2]. To provide the overview, the SKPI for *struck-by falling object* hazards are captured for each individual time step of the construction schedule (i.e., when the geometry of the environment changes), and as an accumulation of the overall exposure. Both numbers are based on the normalization of the exposed area compared to the total amount of active workspaces.

4 CASE STUDIES

This section describes how the proposed *struck-by falling object* hazards analysis has been used in two case studies. The case studies have been used to validate the approach and to propose requirements for the schedule and construction scenario. The two case studies are based on two different models with corresponding schedules and are further described in the following two subsections.

4.1 Case study high-rise

The first case study consists of a low-complexity BIM model illustrated in Fig. 3. The construction schedule consists of two crews per element type, i.e., two crews building slabs, two crews building columns, and two crews building walls. The schedule follows topological rules, which ensure that a slab on level L is not built before the columns are built on Level L-1. The building comprises seven stories, each consisting of nine columns, four slabs, and eight walls. The construction process is planned to take around 100 days.

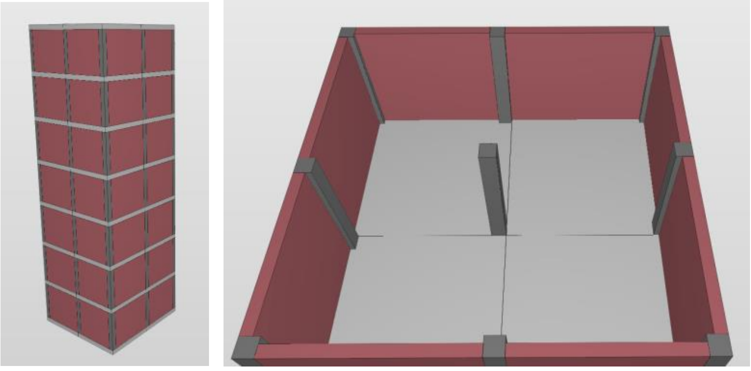


Fig. 3 Visualization of construction scenario in the high-rise case study

The analysis results consist of the two plots shown in Fig. 4, where the upper plot captures the normalized spatiotemporal *struck-by falling objects* hazard exposure for the construction scenario in each time step of the schedule. The normalization is captured based on the exposed hazardous area over the total area of the active workspace, multiplied by the hazard-exposure time over the total duration of the hazard-exposed task. The second plot captures the cumulative hazard exposure, such that an overall degree of hazard exposure in the construction project and schedule can be compared to other schedules or even other projects.

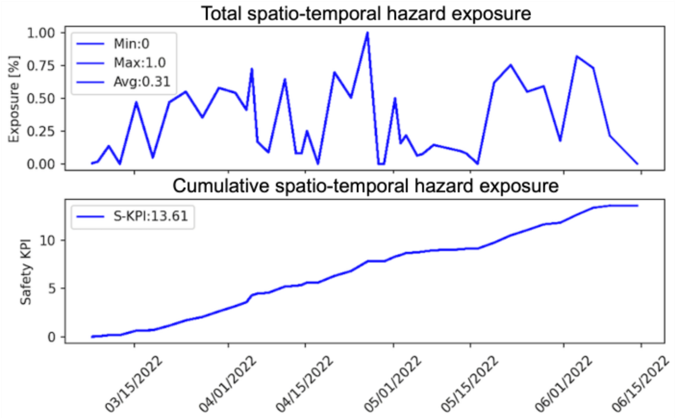


Fig. 4 Resulting spatiotemporal struck-by falling object exposure for the high-rise case study.

4.2 Case study school building

The second case study is based on a structural model of the Autodesk school model shown in Fig. 5, and a schedule that has been created for the EU-funded research project COGITO. The schedule is based on construction zones, which means that elements within the individual zones are constructed simultaneously. The zones are split by stories, which means that there is no work performed on different building stories at the same time. Below each slab, there are columns and concrete beams that are scheduled to be constructed in the same period as the slab they support.

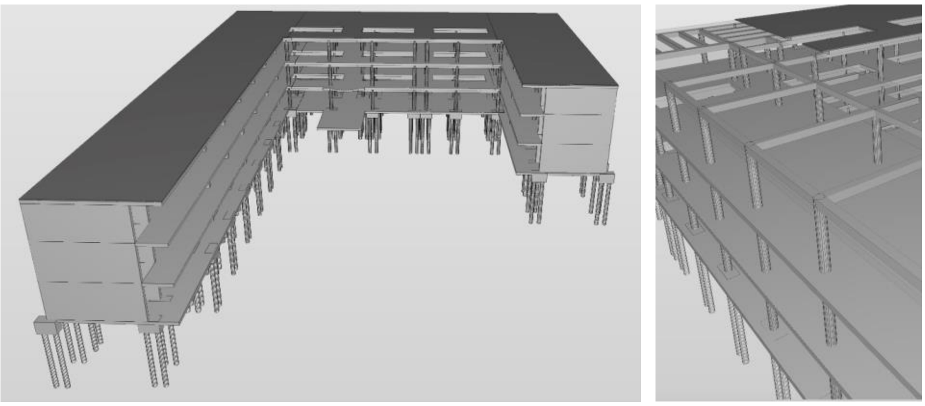
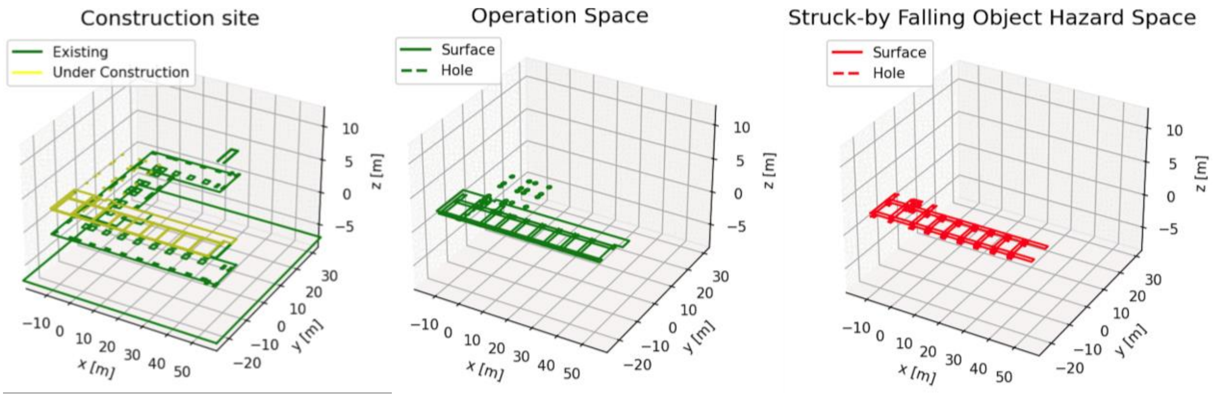


Fig. 5 Visualization of construction scenario in the school case study



a) Spatiotemporal situation b) Active operation zones c) Struck-by hazard zones

Fig. 6 Illustration of spatial artefacts for T=23/12/2009

Fig. 6 illustrates the resulting spatial artefacts that are used to compute the work crew's inter-exposure. The algorithm produces the visualized results for each time stamp, and this is produced for the time stamp representing 23/12/2009, where the yellow elements in Fig. 6 (a) are under construction, which results in the active operating zones in Fig. 6 (b). As the slab, accordingly to the schedule, is being built simultaneously with the supporting beams below it, it introduces a hazard for the work crew below. The overlap can represent that the formworks are planned to be removed from the beams, while the formwork is installed for the slab. Based on the revealed information, it is possible to investigate whether the slab task should be postponed until the beam task has been completed, or if this is a mistake in the schedule. In both cases, the revealed information can be used to prevent hazards or identify mistakes in the schedule, potentially creating problems in the construction process.

Fig. 7 shows the same information as described in the high-rise case study, but this figure also shows that the amount of exposure is low compared to the other results. The decreased exposure is first a sign of the increased project footprint, which means the increased size of work areas and, consequently, a decreased normalized exposure. Secondly, the decreased exposure is a result of the decision to disallow work to be undertaken on two different stories simultaneously. Thus, the exposure that is shown here is a result of the beams being planned to be constructed within the same task as their supporting slabs. This work is not about assessing whether a schedule is realistic, complete, and correct, but about identifying and measuring the hazard exposure that is created by competing work crews in an automated approach and informing the construction management about it. This way, they can investigate and change the schedule if the schedule is incorrectly modeled, or alternatively test an alternative construction approach.

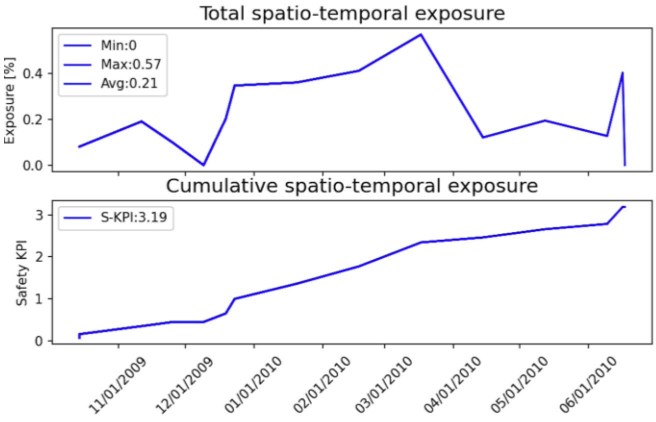


Fig. 7 Resulting spatiotemporal struck-by falling object exposure for the school building case study.

Tab. 2 Processing time for each case study using Apple M1 Max CPU with 32 GB memory.

Case study	**Number of BIM Objects**	**Processing time**
High-rise	153	39 seconds
School	896	65 seconds

The *struck-by falling object* analysis is performed on a laptop equipped with the Apple M1 Max processor and 32 GB of memory. The processing time for both case studies is presented in Tab. 2, and includes creating a spatiotemporal representation of the construction project, extracting the spatial artefacts, and disseminating identified hazards. The table presents the processing time that has been produced for this study, which does not include any runtime optimization; thus, the numbers can be improved.

5 CONCLUSION AND FUTURE WORK

This work proposes a novel automated approach to identify and measure the struck-by falling object exposure of work crews in a Digital twin-inspired 4D BIM-based construction situation. The approach is based on spatial artefacts capturing spatial regions that stem from the construction elements and their planned activities. Throughout this work we define new spatial artefacts for modelling *struck-by falling object* hazards and provide a detailed description of their extraction from the spatiotemporal construction situation.

Even though this study is based on 4D BIM models, it is highly motivated and inspired by the increasing interest and maturity of digital twins, where autonomous approaches are demanded to keep up with the update rate and flow of information. In the digital twin vision, is it also proposed that the planning component will propose alternative schedules based on the progress of current and previous projects. These alternative plans would need to be assessed and compared in terms of safety as well as cost and time. While the case study results in this work yields different numbers based on the different project and thereby get more difficult to compare, it is straightforward to compare two different plans for the same project. Besides being able to compare different schedules, the proposed work also enables the construction management to identify, if work crews are scheduled to work on different tasks in close vicinity, which is not desirable for progress, but especially in terms of safety.

Currently, the proposed analysis does not include the areas which are traversed when the work crew is not actively working within their designated workspace, for example, when entering the area in the morning or gathering material. Modeling these areas would mean that information about the location of onsite storage and construction crew trailers needs to be included in the analysis. It is envisioned to extract this kind of information from the construction site layout and incorporate it in the hazard analysis. Additionally, an onsite tower crane would also be a potential source of dropping items, which could also be the proposed analysis. Including the crane would, although, demand information about where and when the crane is operated. Generally, including more information in the hazard analysis consequently increases the demand for the input information.

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