Spatial conflict simulator using game engine technology and Bayesian networks for workspace management

(Article begins on next page)

Spatial conflict simulator using game engine technology and Bayesian networks for workspace management

Leonardo Messi[a,b], Borja García de Soto[b], Alessandro Carbonari[a], and Berardo Naticchia[a]

[a] DICEA Department, Construction Division, Faculty of Engineering, Polytechnic University of Marche (UNIVPM), Via Brecce Bianche 12, 60131, Ancona, Italy
[b] S.M.A.R.T. Construction Research Group, Division of Engineering, New York University Abu Dhabi (NYUAD), Experimental Research Building, Saadiyat Island, P.O. Box 129188, Abu Dhabi, United Arab Emirates
E-mail: l.messi@staff.univpm.it, garcia.de.soto@nyu.edu, alessandro.carbonari@staff.univpm.it, b.naticchia@staff.univpm.it

Abstract
Workspace demand changes across space and time, stressing the need to consider space as a limited and renewable resource. Traditional scheduling techniques have not fully handled this issue. This study proposes a workspace management framework using a game engine to address that. The simulator detects spatial interferences by combining geometric computations and physics simulations. The detected conflicts are filtered through Bayesian inference to detect non-critical scenarios and avoid overestimation. The proposed spatial conflict simulator was tested using a real use case and compared to commercial tools. Results showed that the Navisworks approach detected 58 spatial conflicts (of which only 25% were relevant), the Synchro approach detected 1 spatial conflict, and the proposed approach detected 1 “direct” and 4 “indirect” spatial conflicts. Results show its capability to detect more relevant spatial issues than the state-of-the-art tools and avoid overestimations. Construction management teams can adjust or confirm the schedule with that information.

Keywords
Construction Management; Workspace Scheduling; Spatial Conflicts; BIM; Game Engine; 4D tool.

1. Introduction
In the Architecture, Engineering and Construction (AEC) industry, construction sites, which usually involve large numbers of workers, equipment, adjacent buildings, and facilities, and are affected by weather, are very dynamic operating environments. Consequently, safety and constructability issues are usually contextual, as they depend on building and resource displacement, spatial-temporal dependencies, and ever-changing site conditions.

In such a dynamic environment, any activity requires a specific workspace to be executed [1], defined as the suitable space crews and/or equipment occupy execution [2]. As the construction progresses, the space occupied by completed activities will be released and reused by other operations [3]. Consequently, the space required for construction operation continuously changes over time [4], leading to a sequence of workspaces associated with the project’s activities [5]. When the same workspace is occupied simultaneously by two or more activities, a spatial interference occurs, which might lead to significant problems such as construction delay, loss in productivity and labor safety hazards. As suggested by [6], this evidence demonstrates that space in the construction site must be considered as a limited but renewable resource, similar to workers, equipment, and materials [3]. Impacts due to spatial interferences have been measured qualitatively and quantitatively. To cite a few statistics, a study related to masonry works has reported that congested workspaces and restricted access cause efficiency losses of up to 65% [7]. In addition to the productivity impacts, another study conducted in the US private industry sector associated the death of 323 workers over 12 years with poor workspace planning [8].

However, automating the identification of workspaces is a challenging task itself due to several reasons. The first one is that operational workspaces are seldom limited to the volume surrounding the building components interested in ongoing tasks (i.e., the so-called main workspace). Rather, they include additional volumes used for ancillary tasks such as materials storage, passageways, etc. The second reason is that there might occur indirect clashes even between non-overlapping workspaces, hence not detectable using mere geometric intersection checks, because some actions occurring in one space could interfere indirectly with the activity carried out in another detached space (e.g., struck-by hazard from falling objects, electrical hazard). Another reason is that contextual variables often determine the actual occurrence of a risk and its severity. In these cases, expert knowledge can contribute to refining and enhancing the assessment of detected spatial interferences. In other words, two identical clashes detected at different points in time or occurring due to different concurrent activities can result in remarkably different severity levels.

Furthermore, the dynamic nature of construction activities makes the management of workspaces challenging using conventional planning methods. The authors in [9] assert that conventional planning methods do not adequately represent and communicate interferences between construction activities and do not consider space constraints in the planning process. They typically focus on the time and cost aspects [9–12]. In fact, traditional construction scheduling techniques, such as Gantt charts and network diagrams, are inadequate for managing site workspaces, mainly due to the lack of spatial representation [3]. Similarly, traditional safety planning relies on manual observation, which is labor-intensive, time-consuming, and potentially highly inefficient [8]. The resulting safety plans are often error-prone due to subjective judgments of the available decision-makers. As of now, workspace planning has often been performed through judgment or with the aid of 2D sketches [2]. Commercial 4D visual planning software tools (e.g., Autodesk Navisworks, Synchro, etc.) have improved display functionalities that can aid construction managers and field engineers in their tasks but still lack automated assessment capabilities in favor of workspace management [5].

This study will investigate the use of spatial simulation tools with advanced visualization functionalities to detect clashes among workspaces, including looking beyond the case of geometric clashes between overlapping main workspaces. An analysis regarding the advantages that this tool can provide to those in charge of work planning will be performed, and an enhanced workflow will be suggested. In addition, a methodology to develop an expert knowledge system to assess the severity of detected conflicts will be reported and preliminarily tested and compared with current state-of-the-art technologies.

In Section 2, the scientific background about the latest research progresses in workspace management, the application of the serious gaming technology in the AEC industry, and the basics of the Bayesian inference are provided. Section 3 describes the methodology proposed by this study, whereas Section 4 presents the adopted use case. The implementation of the developed prototype, described in Section 5, is followed by the design of the experiments presented in Section 6. Finally, Sections 7 and 8 are devoted to the results of the experiments, the discussion, and the conclusions, respectively.

2. Scientific background

Nowadays, the need to consider the spatial dimension to ensure the schedule's feasibility and avoid critical issues, such as safety, productivity, and constructability, is unanimously accepted by field experts. Stemming from this assumption, researchers have spent many efforts on workspace definition, conflicts detection, and severity assessment. As emerged from the literature review, several approaches and technologies, mainly based on geometric intersection tests between workspaces, have been proposed.

The workspace management process refers to three main phases [3,5]. The first one is the generation and allocation of workspaces. The second one is the detection of congestion and spatial-temporal conflicts. Finally, the third phase is the resolution of identified conflicts. Since this study focused on detecting spatial conflicts and severity assessment, these topics will be the subject of the following Subsections 2.1 and 2.2. Afterward, Subsection 2.3 focuses on simulation environments adopted by past studies. Subsection 2.4 provides a literature review of Bayesian inference application in the AEC industry. Finally, Subsection 2.5 formalizes the research questions answered by this study.

Table 1. Overview of workspaces' classification, conflicts taxonomies, and metrics from literature.

	Zhang et al., 2015 [8]	Dawood et al., 2006 [12]	Akinci et al., 2002 [15]	Getuli et al., 2020 [16]	Thabet et al., 1994 [17]
Workspaces	Building component space (BCS)	Product space	Building component space (BCS)	Workers space	*Object-based (Physical surrounding space)*
	Worker space	Workspace	Labor crew space (LCS)	Equipment space	Manpower
	Equipment/temporary structure space	Equipment space	Equipment space (ES)	Safety space (outward hazard)	Equipment
	Space for material handling path	Equipment path	Temporary structure space (TSS)	Hazard space (inward hazard)	Material
	Protective space	Path space	Protected space (PS)		*Space-based*
		Storage space	Hazard space (HS)		Work blocks (Zone + Layer)
		Process space			
		Support space			
		Protected space			
Conflicts	Design clashes	Design conflict	Design conflict (BCS-BCS)		Can share workspace (Class B)
	Congestion	Safety hazard	Safety hazard (HS-LCS)		Cannot share workspace (Class A, C)
	Safety hazard	Congestion	Damage conflict (PS-LCS/ES/HS)		
		Access blockage	Congestion (LCS/ES-LCS/ES/TSS)		
		Damage			
		Space obstruction			
		Work interruption			
Metrics	Conflict Ratio $C_R=V_C/V_R$ where V_C=conflicting volume, V_R=required volume	Space Criticality $S_C=V_R/V_A$ where V_R=required volume, V_A=available volume	Conflict Ratio $C_R=V_C/V_R$ where V_C=conflicting volume, V_R=required volume		Space Capacity Factor $S_{CF}=V_A/V_R$ where V_A=available volume, V_R=required volume
	Space Criticality $S_C=V_R/V_A$ where V_R=required volume, V_A=available volume				

Mirzaei et al., 2018 [1]	Ma et al., 2020 [3]	Kassem et al., 2015 [5]
Product space Labor crew space Equipment space Temporary structure space Material storage space Hazard space	Entity space (ES) Efficient working space (EWS) Safey working space (SWS)	Object space Main space Support space Safety space
Labor congestion (RSD<50%) Constructability issue (RSD>50%)	ES-ES (h=100) ES-SWS (h=50) SWS-SWS (h=20) ES-SWS (h=10) SWS-EWS (h=5) EWS-EWS (h=1)	Temporal/Schedule conflict Spatial/Physical/Workspace conflict Workspace congestion
Required Space Decrease per person *$RSD=1-(A_{AP}/A_{RP})$* where A_{AP}=available workspace per person for activity, A_{RP}=required workspace per person for activity	Severity of the Spatio-Temoporal Conflict *$I_{12}=h(k1*S_{v1}*S_{t1}+ +k_2*S_{v2}*S_{t2})$* where *h*=severity grade (1÷100), k_1,k_2=urgency/danger grades (1÷10), *S_{v1},S_{v2}=ratio of spatial conflict relative to v1,v2,* *S_{t1},S_{t2}=ratio of coincident period relative to t1,t2*	Severity of Conflict $S_C=T_C/T_A$ where T_C=conflict duration, T_A=activity duration Severity of Workspace Conflict $S_{WC}=V_C/V_A$ where V_C=conflicting volume, V_A=available volume Congestion of Severity $C_{gS}=V_R/V_A$ where V_R=required volume, V_A=available volume Workspace Criticality Level $W_{CL}=S_{WC}+C_{gS}$

2.1. Workspace definition and conflicts detection

The hierarchical classification of workspaces, known as Location Breakdown Structure (LBS), can help develop work plans and manage the project's physical size and complexity [13,14]. 2D working areas have been defined irrespective of the activities to be performed. According to [13], an LBS should include the five levels of detail, namely: (1) project, (2) buildings or sections, (3) floors, (4) stage of implementation, and (5) zones. Another application divides the floor into same-size areas (zone-LBS) or considers the position of seismic joints (area-LBS) [14]. However, the limitation of this approach is that it cannot classify non-structured buildings, such as large open spaces lacking demarcating zones or renovation works.

Due to the wide variability of scenarios, other works have suggested several classifications, which adopt different approaches, including object-, activity-, space- and process-based classifications. The object-based classification uses a 3D visualization of workspaces and requires allocating volumes adjacent to the building element under construction for specific functions [5,12,15]. An example can be provided by the micro-level discretization defined in [15], which includes the following workspaces: building component space, labor crew space, equipment space, hazard space, protected space, and, finally, temporary structure space (Table 1). Complementarily, the concepts of macro-level (e.g., storage areas) and paths (e.g., equipment's and crews' paths) discretization have been introduced [12]. An activity-based classification focused on Health and Safety (H&S) management has been defined in [15,16], where safety and hazard spaces correspond respectively to outward and inward hazards (Table 1). Another unique classification for the three discretization categories was proposed (Table 1) [12]. Also, a macro- and micro-level discretization can help differentiate labor crew workspaces into static and dynamic ones [1]. In the first case, the entire workspace is required throughout the activity duration; in the second case, the labor crew occupies a specific portion of the space during each time interval. Four execution patterns have been defined to simulate labor movement through the subspaces. In [8], a micro-level discretization and the material handling path space have been introduced. In the research presented in [3], the workspaces defined by the studies mentioned above have been grouped into two main categories: entity and working spaces. The first includes the space occupied by laborers, mechanical equipment, and building components, whereas the second corresponds to the spaces required to ensure smooth operation and tasks. In [17], the authors compare an object-based and a space-based workspace definition to quantify workspace demand and availability. The authors include some of the space categories seen in previous works in the object-based workspace definition, such as manpower, equipment, and material spaces. In the space-based workspace definition, a work block is the combination of a zone (i.e., the portion of the architectural layout of the floor) and a layer (i.e., the status of construction work progress in a zone within a specific time). In order to include the effects of dynamicity, a novel method for look-ahead equipment workspace during earthworks was developed in [18]. For this purpose, Dynamic Equipment Workspaces (DEWs) and Look-Ahead Equipment Workspaces (LAEWs) have been defined. The two types of workspaces differ in that while DEWs are generated based on the equipment pose, state, geometry, and speed in real-time (to form a safety buffer around the equipment that can help to prevent collisions), LAEWs are built based on the predicted future motion of equipment and operator visibility in near-real-time (to help finding a collision-free path for equipment). This method enables different pieces of equipment to ensure that their initially planned paths are collision-free, or it adjusts their path planning to avoid potential collisions.

Inspired by the manufacturing industry, a shift from object-based to process-based workspace definition has been proposed in [5]. In addition to the workspaces occupied by building elements and reserved as safety distance, the working area is discretized considering the value added by the activities (Table 1). For example, building a wall requires a “main workspace” since it adds tangible value to the project; on the contrary, transferring materials requires a “support workspace”, a preparatory activity supporting the first one.

Another challenge relies on the estimation of the shape and size of workspaces. A first approach is to represent workspaces as user input rectangular prisms [15], whereas in other applications, they are represented as user-inputted bounding boxes [2,3,5,16]. In the studies mentioned above, workspace occupation is either estimated based on the authors' background or experience or estimated by the user as input values during simulation. On the contrary, the authors in [8] implement an occupancy model to define distance offsets from the building components under construction; in this way, they infer the workspace allocation based on historical workforce location data densities.

For the sake of a realistic estimation of clashes and temporal dependences, once workspaces have been defined, they must be associated with specific time slots in which each correspondent activity is scheduled. In other words, the 3D model is extended towards the fourth dimension, i.e., time [1–3,5,8,12,15].

Running 4D simulations can lead to the identification of potential interferences within the project schedule and their visualization. This approach assumes that time-space conflicts may occur only between concurrent activities [15]. In addition to the temporal detection, some authors report other approaches available in the literature to identify spatial issues. For example, the approximation detection compares the length of the line connecting center points for every pair of adjacent workspaces against the combined lengths of workspaces’ radii [2]. In the topographical detection, each workspace is assigned a spatial matrix, and the entry-wise product of matrices would mark the collisions [2]. Finally, geometrical intersection tests check each workspace against all other ones (pairwise comparison) for detecting eventual overlaps, called Spatial/Physical/Workspace conflicts [2,5], as reported in Table 1.

Lately, several studies have attempted to classify spatial interferences between tasks that share the same workspace. One of the first time-space conflict taxonomy in construction differentiates design conflicts, safety hazards, damage conflicts, and congestions [15] (Table 1). The first category occurs when a conflict between two building components’ geometries occurs. Since existing commercially available applications (e.g., clash detection and coordination) already solve this issue [8], design clashes are outside the scope of this research. According to [15], a safety hazard occurs when the space required by a hazardous activity (e.g., hazard space) conflicts with the space allocated to a labor crew. Indeed, sharing a space, which should be left free to protect a building component, with a labor crew, a piece of equipment, or a hazardous space may cause damage conflicts. The mutual sharing of space between labor crews, equipment and temporary structures identifies a more or less severe congestion [5,15]. On the contrary, the authors in [17] differentiate the activities that can share the workspace and those that cannot share it to define a work schedule. The taxonomy presented in [15] has been adopted by the authors in [8,12] and extended in [12], with path-related conflicts (e.g., access blockage and space obstruction). Other authors consider two types of spatial interferences, namely labor congestion and constructability issue [1], corresponding respectively to Acceptable (ASI) and Unacceptable Spatial Interferences (USI) [19]. Finally, a time-space conflict taxonomy, including the three available combinations between the Entity Spaces (ES) and Working Spaces (WS), is presented in [3]. As long as two different entity spaces (ES-ES) overlap, a breakage in the building element is caused [15]. In case an entity crashes into a working space (ES-WS), delays of construction and, in some cases, accidents occur. Finally, an interference between working spaces (WS-WS) occurring between parallel activities, corresponds to a particular scenario of congestion [2,15].

As mentioned earlier in this text, spatial conflicts are detected in existing studies by simply carrying out geometric intersection tests between defined workspaces. Although being able to provide early valuable results and enabled process automation, this approach overestimates the results and misses to detect those clashes that are not purely geometric.

In addition, most existing studies consider object-based workspace taxonomies that allocate static workspaces around building elements under construction for very specific purposes. Due to this strong assumption, these studies look for spatial conflicts between static object-based workspaces. The possibility of crews and equipment moving and eventually getting into conflicts within the construction site has been sporadically considered [1,4,8,18]. This gap must be addressed by considering more realistic simulations.

Finally, a workflow that integrates currently available construction planning methods and the most advanced simulation systems (e.g., based on physics simulations, expert knowledge, etc.) for detecting spatial conflicts must be defined. This would improve existing construction planning approaches by covering their gaps and ease the assessment of the added values provided by novel spatial conflict simulators.

2.2. Conflict's severity assessment

In order to rank lists of conflicts generated as a result of an automated conflict detection, the activities' conflicting status must be evaluated by adopting metrics that concisely describe the severity of conflicts and their overall trend. For this purpose, several metrics for evaluating the magnitude of the collisions are available in the literature. Some can assess the conflicting status between workspaces by computing ratios between volumes and/or setting arbitrary thresholds for different congestion severity levels [5,8,12,15,17] (Table 1). More sophisticated metrics also consider temporal, severity, urgency and danger parameters [3] (Table 1). Other metrics assess the conflict severity based on the decrease of workspace per person for a given activity [1] (Table 1). The main limitation of this assumption is that some spatial conflicts may occur even if workspaces are not reduced or do not intersect each other (e.g., struck-by risk from falling objects, electrical risk, etc.).

2.3. Simulation environments of spatial conflicts

Past studies address spatial conflict challenges by adopting different technological approaches. Low-tech workspace management applies LBS and spreadsheet applications (e.g., Microsoft Excel) [13,14]. The familiar and easy-to-use interface of such applications represents the strength of this approach. In contrast, the approximate 2D-modelling of space and the too rigid and arbitrary workspace discretization provided by LBS affect the results.

These issues are overcome by high-tech workspace management approaches that apply BIM for a continuous 3D modeling of space and the definition of the 4D model by linking tasks and building elements. In this context, serious game engines are promising tools to integrate semantically rich models (e.g., BIM models) and simulation engines. The first application of gaming technology can be found in the aircraft industry, using Microsoft Flight Simulator for educational purposes [20].

Later, serious game engines also became widespread in the AEC industry, demonstrating that mere entertainment is not the only feasible nor the only promising application. The success of this approach is due to the difficulty in carrying out real field experiments in some research areas, such as construction management, which usually requires quite a huge budget and time efforts to set up an experimental study. The use of game engines facilitates the deployment of virtual testbeds and test execution.

In the construction industry, game engine usage was first limited to construction safety training purposes. In 2009, Torque 3D game engine was applied to develop a tool aiming to enhance electrical safety awareness within the construction industry [21]. Virtual safety learning platforms have been developed using Unity3D™ and head-mounted display (HMD) technologies [22]. A similar technological stack can be applied to develop a virtual learning environment for multiplayer lean training [23], with the possibility of collecting run-time feedback [24].

Several studies applied serious game engines to improve collaboration and communication in construction. A tool based on the Java-based jMonkeyEngine 3.0 game enabled clients to navigate in first-person design-in-progress environments [25]. Another example is the Database-supported VR/BIM-based Communication and Simulation (DVBCS), a middleware and communication system between the design team and stakeholders, developed in [26] using the Unreal game engine and tested in healthcare design. Similar-purpose systems have been developed using Unity3D™ too [27,28] and adopting openBIM principles (i.e., IFC format rather than a vendor-specific one) [29]. The integration in Unity3D™ of BIM models and as-built images, processed via various computer vision techniques, enables the definition of a 3D virtual environment of the construction site that can be updated automatically according to work progress [30]. Another tool, developed in Unity3D™ and tested for modular-based construction projects, integrates four main project teams (i.e., design, production, transportation, and construction teams) and supports them by providing a virtual environment to visualize their process to make better-informed decisions [31].

The application of serious game engines recently embraces simulations of physical building dynamics and behaviors of virtual building users, such as in the framework called Design-Play and based on the Microsoft XNA game engine, for design validation [32]. An open-source gaming engine, namely Blender, has been applied to develop parallel and loosely coupled simulation-driven visualizations of industrial construction operations [33]. An Industry Foundation Class (IFC) compliant 4D tool has been developed using the Microsoft XNA game engine as a holistic solution for workspace management, including workspace allocation, conflicts detection and real-time resolution [5]. A holonic emergency management system, based on Unity3D™, can compute the most effective way out by pathfinding algorithms (i.e., A*) and enhance the contribution given by standard emergency plans [35]. Unity3D™ has been applied to simulate activities and analyze the productivity difference between conventional and robotics-based modular construction [34]. Other Unity3D™ game engine applications have resulted in a digital twin mock-up that implements a BN for the real-time assessment of runover hazards by drilling machines [35] and fall hazards [36]. Unity3D™ spatial simulators aim to detect conflicts, among main and support workspaces, to address COVID-19 threats [37] and struck-by hazards [38,39].

Previous studies prove the possibility of importing Building Information Models by an open file format, namely IFC, into a serious gaming environment [26,28,29]. The 4D BIM model has been recreated within the gaming environment [28] and specifically for workspace management [5]. A proof-of-concept of a reasoner, implemented using a BN within a serious game engine, has been presented [35]. Some authors have demonstrated the possibility of integrating simulation functionalities with game engines [40]. This can carry out dynamics and physics simulations directly within a BIM-based construction site environment recreated in Unity3D™ [36]. Unity3D™ game engine, being widely adopted by past studies and supporting C# scripting for endless functionalities implementation, represents the candidate tool for this study.

2.4. Bayesian inference and its applications in AEC

A system that assesses the severity of spatial-temporal conflicts must reproduce how humans perform cognitive tasks. This implies developing applications that can perform both steps of inference reasoning conditioned upon contextual evidence and knowledge elicitation from experts. The core claim of Bayesian reasoning, called conditionalization, is that it can adjust prior beliefs given new evidence [54]. This is suitable for those scenarios in which a model describing a set of events can be defined in advance. However, the severity of the outcomes is conditioned upon a set of pieces of evidence that change over time. In this context, the advantages of Bayesian networks (BNs) are largely in simplifying conditionalization, planning decisions under uncertainty, and explaining the outcome of stochastic processes [55]. Basically, BNs are graphical models for reasoning under uncertainty, where the nodes represent variables and arcs represent the quantitative strength of those direct connections, allowing probabilistic beliefs to be updated automatically as new information becomes available [54].

Several studies applying BNs to manage construction-related issues have been published in the last 20 years. A literature review mapped articles selected within the last two decades against the 12 construction management functional areas defined by [41] to identify the major areas of Bayesian application [42]. Bayesian approaches are most frequently applied in safety management, followed by risk management, contract management and process control, demonstrating the merits of Bayesian approaches to deal with uncertainties and the interdependencies of multiple factors. Most of the selected studies apply BN for predictive reasoning, whereas the Bayesian diagnostic function is relatively underutilized compared to prediction.

2.4.1. Application to safety management

As reported in [42], the application of Bayesian approaches to safety management is mainly related to safety performance [43–46], the selection of effective safety management strategies [46–48], and safety supervision [49–53].

The full potential of Bayesian approaches to analyze the interdependencies of a wide range of physical and psychosocial hazards is yet to be exploited [42]. Existing Bayesian research on safety performance has mainly adopted a static approach, whereas the potential to use dynamic BNs to capture the changes in safety performance over time (e.g., before and after implementation of safety interventions or in different project phases) is underutilized.

2.4.2. Application to risk management

Risk assessment is the most popular application field of Bayesian approaches in risk management [42]. BNs have the advantages of showing the propagation influence of risks in a network and updating the interdependency among risks when new information is available, overcoming the limitation of structural equation modeling, artificial neural networks and other simulation techniques in analyzing risks [54].

As reported in [55], risk assessment includes two main processes: estimating the occurrence probability [56–60] and impacts [60–62] of certain events to calculate risk. Although Bayesian approaches are widely applied to manage risks in construction-related research, the interaction and propagation of risks throughout the whole lifecycle of construction projects is relatively understudied [63]. To solve this, [63] proposes a modified BN to consider risk propagation in different stages.

Bayesian approaches for risk management are applied to various types of projects, such as excavation projects [57,60,64], deep foundation pit construction [65], buried infrastructure [66] and high-speed rail projects [67]. For these projects, the historical data are limited and difficult to obtain. Bayesian approaches are able to combine both objective data from field observation and subjective data from expert knowledge, which can improve the quality of input data and achieve a relatively high assessment precision even with a small number of samples [56,65].

Generally, applying Bayesian approaches to risk management still has room for improvement in dynamic risk management (i.e., covering all stages of the project), whole process risk management (i.e., covering all steps of risk management) and comprehensive consideration of the risk occurrence probability and impact degree.

2.4.3. Application to contract management

Bayesian approaches are used in the contract management field to analyze construction contractual risks [68,69], deal with disputes [70–77], improve the effectiveness of bidding decisions [78–81] and the efficiency of required contractual text extraction [82].

Further studies are needed to explore the application of Bayesian approaches in contract management, such as expanding the influence of a single contractual risk to a set of contractual risks in a construction project and applying the established model to more scenarios (e.g., different types of construction projects and market conditions) [42].

2.4.4. Application to process control

Process control includes various activities, such as management of project schedule [59,83,84], productivity and resource allocation [85–90] for achieving project success.

Although Bayesian approaches have been adopted in the above areas of process control, the application in each area still needs to be further investigated in different contexts [42]. There is limited application of Bayesian approaches for efficient allocation of resources and the workforce in specific construction projects, which concerns process control.

2.5. The research questions answered by this study

This study shows that by combining physics simulations with geometric computations, even those spatial-temporal conflicts that are not caused by direct overlapping of main workspaces can be detected. Then, an implementation of this tool in a serious gaming environment has been reported, along with the development of an interface between the simulation environment and the BIM model of the building under construction. In addition, a methodology and a demonstrator concerning the integration of a Bayesian reasoner in the form of a BN are developed. The combined simulator embedding the BN is showcased to automatically update the severity assessment of detected spatial-temporal conflicts due to workspace displacement and the scheduled work plan. This is applied in the specific case of crews that may be struck by falling objects. Finally, a comparison between the performance of this novel system and the state-of-the-art commercial software tools is provided.

3. Methodology

3.1. System architecture

In order to cover these research gaps, this study presents a novel methodology that integrates the work planning phase with a spatial conflict simulator and a Bayesian reasoner. The resulting system architecture is depicted in Figure 1. The BIM authoring and the project management software provide the BIM model and the work schedule to the spatial conflicts simulator. The latter embeds mechanical physics and carries out physics simulations and geometric computations. Simulation results are transferred as a list of spatial conflicts to the Bayesian reasoner fed by expert knowledge and sent back to the expert for further consideration. At this point, the expert can resolve detected spatial conflicts by carrying out the required action, such as updating the BIM model, the work schedule, or workspace size. In Figure 1, solid arcs represent the interfaces implemented in this study.

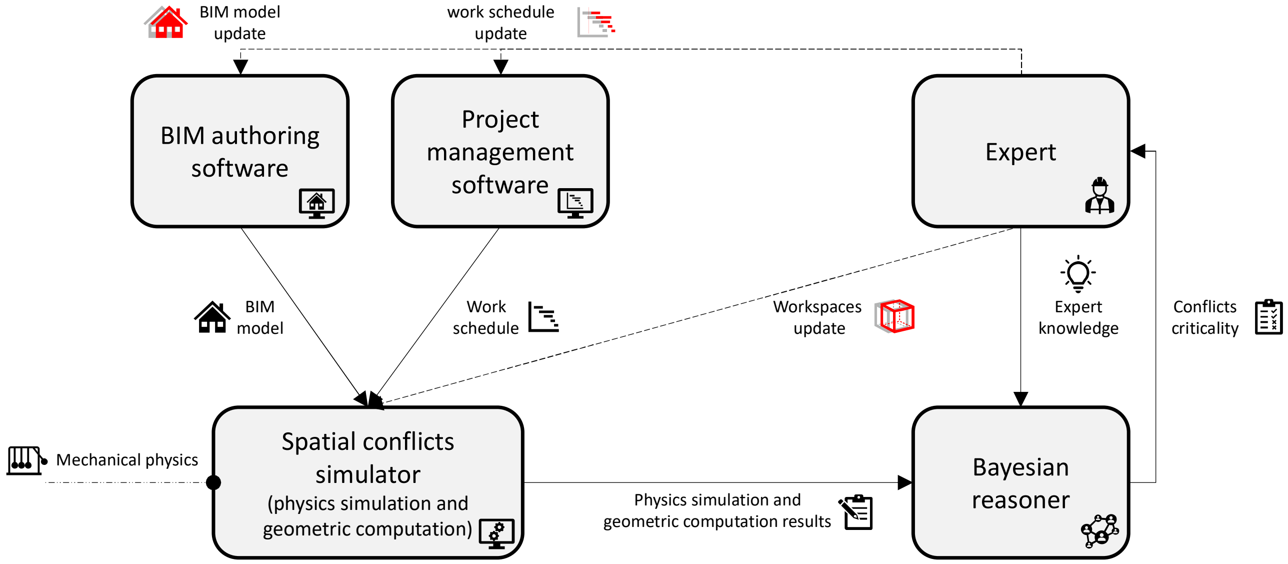


Figure 1. System architecture.

3.2. Workspace management framework

The implementation of the proposed system architecture leads to the definition of a novel workspace management framework, described by the Business Process Model (BPM), reported in Figure 2. The top lane of the BPM includes the tasks executed by the project management team during the construction planning phase, whereas the bottom lanes depict the functioning of the proposed spatial conflict simulator and the Bayesian reasoner.

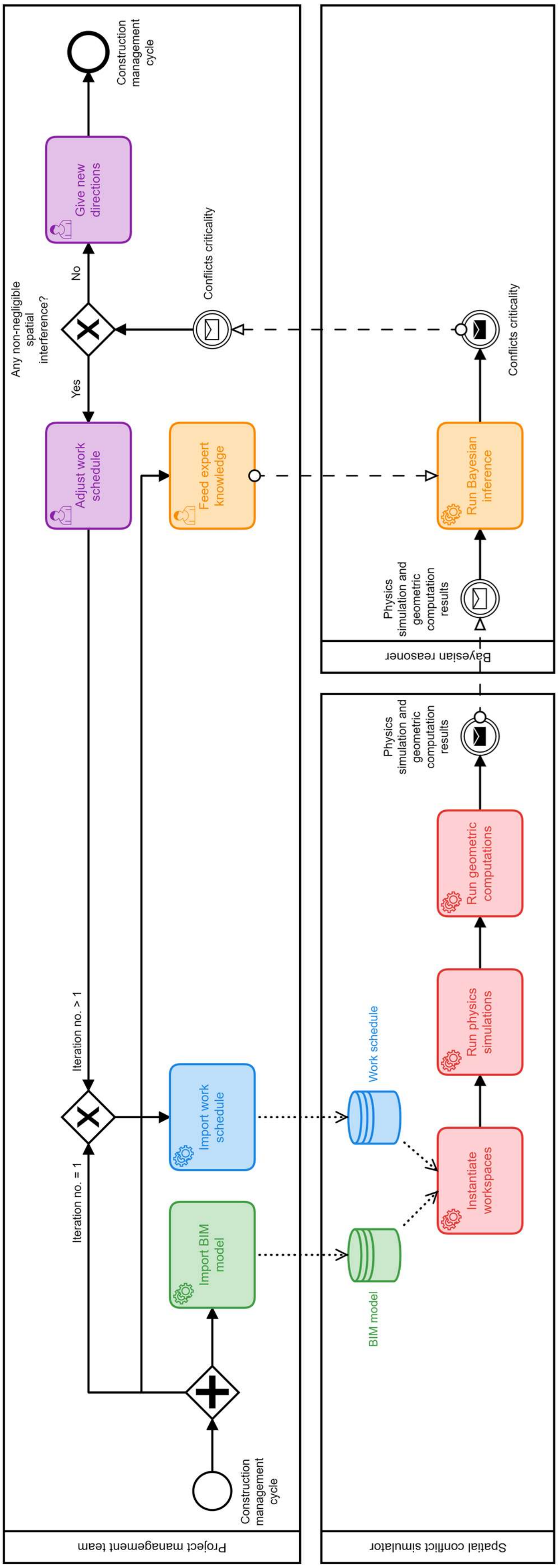


Figure 2. Overview of the proposed workspace management framework with the implementation of the proposed system architecture (please use color in print).

As indicated by the parallel gateway reported at the beginning of the BPM, the construction manager executes three main tasks in parallel. Green nodes describe the process of loading the BIM model within the serious gaming environment (i.e., "Load BIM model" task). Blue nodes describe the process of importing the work schedule in the spatial conflict simulator (i.e., "Import work schedule" task). Orange nodes summarize the milestones involving expert knowledge formalized in Bayesian networks (BNs). Basically, this expert knowledge is applied to define the BNs' structure (i.e., cause-effect relationships between node variables) and then the conditional probability tables (CPTs) (i.e., "Feed Bayesian network" task).

At this point, the spatial conflict simulator can be considered as initialized. Red nodes are related to the workspaces' generation and related physics simulations and geometric computation. First, the workspaces are generated within the serious gaming environment (i.e., "Instantiate workspaces" task), given as inputs both the BIM model and the work schedule. The instantiated workspaces are the input of the physics simulations (i.e., "Run physics simulation" task) and geometric computations (i.e., "Run geometric computation" task). Geometric intersection tests between main workspaces are carried out, considering them in their static position and then falling down under the law of gravity. As a result, spatial conflicts are detected and labeled as either "direct" in the first case or "indirect" in the second one. Their criticality level is computed by the Bayesian reasoner (i.e., "Run Bayesian inference" task) in order to support the project management team in refining the work schedule. The decision-making process is represented by purple nodes and the exclusive gateway. The project management team adjusts the work schedule if any non-negligible spatial interference is detected; otherwise, they can give instructions on the field.

3.3. Integration with existing technologies

One of the key features of the proposed methodology is the integration with existing technologies (Figure 2). In fact, a BIM model can be generated by using any of the BIM authoring software tools available in the market (e.g., Autodesk Revit in our implementation) and then exported as an IFC file. Similarly, the work schedule can be generated by using one of the commercial project management software tools (e.g., Microsoft Project in our implementation). A resource-constrained schedule is generated by defining first the baseline and allocating available resources. Then, the resulting work schedule can be exported into the CSV or XML format. The information in machine-readable file formats, like IFC, CSV and XML, is used to define the 4D model required to generate workspaces within the proposed spatial conflicts simulator. In Section 4, this kind of integration is done in a real use case. A BIM model and a work schedule related to the execution of construction works will be presented.

3.4. Development of the spatial conflicts simulator

The first added value of the proposed approach is the integration of 4D BIM data, provided by commercial tools, into an environment carrying out physics simulations and geometric computation. The literature review reported in Section 2.3 indicates serious game engines as a proper technical solution. In fact, game engines embed mechanical physics and enable the execution of physics simulations and can enhance the range of spatial conflicts detected by existing commercial tools. Contrarily to the rule-based approach usually adopted by currently available 4D software, serious game engines enable the adoption of an agent-based approach to effectively simulate the interaction among involved agents.

In this study, the Unity3D™ game engine was chosen to develop the proposed spatial conflicts simulator. Unity3D™ has been widely adopted by past studies (Section 2.3) and industries beyond video gaming, such as film, automotive, architecture, engineering, construction, and the United States Armed Forces [91]. This game engine, supporting C# scripting, ensures the implementation of endless functionalities. The integration of multiple spatial conflict simulator's C# scripts with the overall workspace management framework is depicted in Figure 3. Every task of the Business Process Model, labeled by a squared brackets' caption, represents a component of the serious gaming tool. In addition, for each task, input and output are represented, respectively, by an ingoing and an outgoing arrow.

The “File Chooser” C# script (Figure 3), developed in-house by the authors based on the IFC Engine DLL library [92], enables importing the Building Information Model in IFC format into the gaming environment. The advantage of importing the IFC model is that topological information, materials properties, and semantic information are directly applied to the building model in the serious gaming environment. This IFC Loader models the environment using one of the most powerful techniques in solid modeling: boundary representation (B-REP). B-REP represents a solid as a collection of connected surface elements, which are the boundary between solid and non-solid.

The “Model Input” C# script imports the works schedule in CSV format to define, along with the building model, the 4D BIM model. The latter is received as an input by the “Instantiate main workspace from IFC” C# script to generate main workspaces linked to the work schedule tasks. At this point, the “Intersection test” C# script uses workspaces-related information to run physics simulations and geometric computations. This script includes several methods. The “FindSpatialConflict()” (Figure 4 (a)) method carries out a geometric intersection test between main workspaces in their initial static position and provides a list of so-called “direct” spatial conflicts. The “FindAllOverlaps()” (Figure 4 (b)) method, instead, carries out a geometric intersection test during physics simulations in a gravitational environment. The “OnTriggerEnter(Collider other)” (Figure 4 (c)) method, attached to each main workspace, detects spatial conflicts between the main workspaces while the physics simulation is running.

An application example of the presented spatial conflicts simulator is provided in Section 5.1.

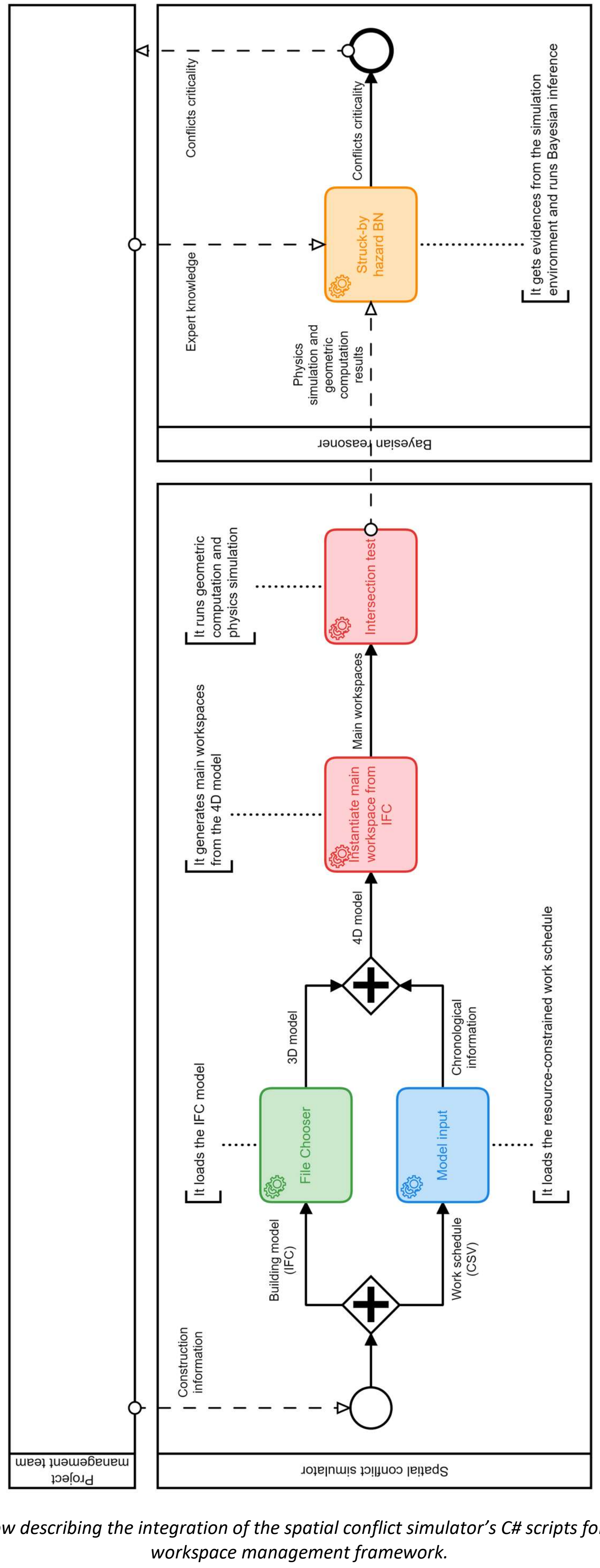


Figure 3. Simulation workflow describing the integration of the spatial conflict simulator's C# scripts for Unity3D™ with the overall workspace management framework.

```
FindSpatialConflict()
CREATE empty workspaces array(gameobject)
GET gameobjects having tag equal to "Workspace"
ADD gameobjects having tag equal to "Workspace" to workspaces array
CREATE conflicts dictionary(integer, gameobject array)
GET display conflicts material
FOREACH i-th gameobject in workspaces array
        FOREACH J-th gameobject in workspaces array
                COMPUTE hash sum of i-th gameobject and j-th
                gameobject
                        GET i-th crew string
                        GET j-th crew string
                        IF i-th gameobject is different from j-th
                        gameobject AND conflicts dictionary does
                        not contain hash sum AND i-th crew string
                        is different from j-th crew string AND i-th
                        gameobject intersect j-th gameobject
                                ADD conflict(hash sum, (i,j)) to conflicts
                                dictionary
                                SET i-th gameobject material equal to display
                                conflicts material
                                SET j-th gameobject material equal to display
                                conflicts material
                        END IF
        END FOREACH
END FOREACH
END
```

(a)

```
FindAllOverlaps()
CREATE empty workspaces array(gameobject)
GET gameobjects having tag equal to "Workspace"
ADD gameobjects having tag equal to "Workspace" to workspaces array
CREATE overlaps dictionary(integer, gameobject array)
GET display conflicts material
GET simulation duration
        START COROUTINE PhysicsSimulation()
                FOREACH i-th gameobject in workspaces array
                        GET i-th gameobject initial position
                        SET Rigidbody useGravity as true
                        WAIT for seconds (simulation duration)
                        SET Rigidbody useGravity as false
                        SET Rigidbody constraints as freezeAll
                        SET i-th position equals to initial
                        position
                END FOREACH
END COROUTINE
```

(b)

```
OnTriggerEnter(Collider other)
IF other has tag equals to "Workspace" AND game object crew string
is different from other crew string THEN
        COMPUTE hash sum overlaps of gameobject and other
        CREATE overlaps array(collider) containing gameobjects and
        other colliders
        IF overlaps dictionary does not contain hash sum overlaps
        THEN
                ADD (hash sum overlaps, overlaps array (collider))
        END IF
END IF
END
```

(c)

Figure 4. Pseudo-codes of the methods defining the "Intersection test" C# script for Unity3D™.

3.5. Development of the Bayesian reasoner

Bayesian networks (BNs) represent a powerful knowledge representation and reasoning tool to visually model conditional probabilistic relationships among a set of variables [93]. As already mentioned in Subsection 2.4, they are made of connected nodes and can perform both diagnostics and predictive reasoning. In this study, the second type of reasoning has been applied. It flows along the path pointing from new information about causes, that is, evidence included in the network through the instantiation of the set of query nodes associated with the variables representing causes, towards new beliefs about query nodes, i.e., the severity of a detected conflict. In fact, as soon as variables are instantiated with new evidence, the corresponding variables are set at a particular value. For BNs' basics and examples of computing posterior probability, given conditional probability tables (CPTs), the authors refer to [56,57,93].

BNs have many advantages, such as suitability for small and incomplete data sets, the combination of different sources of knowledge, the ability to model causal relationships among variables, and the explicit handling of uncertainty for decision analysis [93].

In this study, a BN for assessing struck-by hazards of objects that may fall and constitute a threat for laborers at a lower level is developed. The results of the simulations represent the input of the Bayesian inference (i.e., "Run Bayesian inference" node). Its role is to estimate the severity of each detected spatial conflict. Each spatial conflict will be assessed by running Bayesian inference and estimating its criticality level as "low", "medium", or "high". This approach has the potential to label any detected spatial conflicts in the simulator that are not critical.

The approach adopted here for developing the BN comes from the basic concept presented in [93]. An accident due to struck-by hazards can be described as originated from a combination of triggering conditions and acts. An act can be defined as the possibility that whatever element falls to a lower level. The triggering condition can be defined as the vulnerability of laborers to be hit by elements that may potentially fall down. This general model is based on a risk factors classification into four levels: external (e.g., factors related to political or external issues), policy (e.g., factors related to contracting strategy, ownership and control, and construction company culture), organizational (e.g., factors related to site organization and local management), and direct ones (e.g., factors related to site technicians).

The BN depicted in Figure 5 originates from both the basic cause-effect relationship between the event and triggering acts/conditions and the general BN model introduced by [93]. For simplicity, three out of four risk factor levels defined in [93] have been considered in this first implementation.

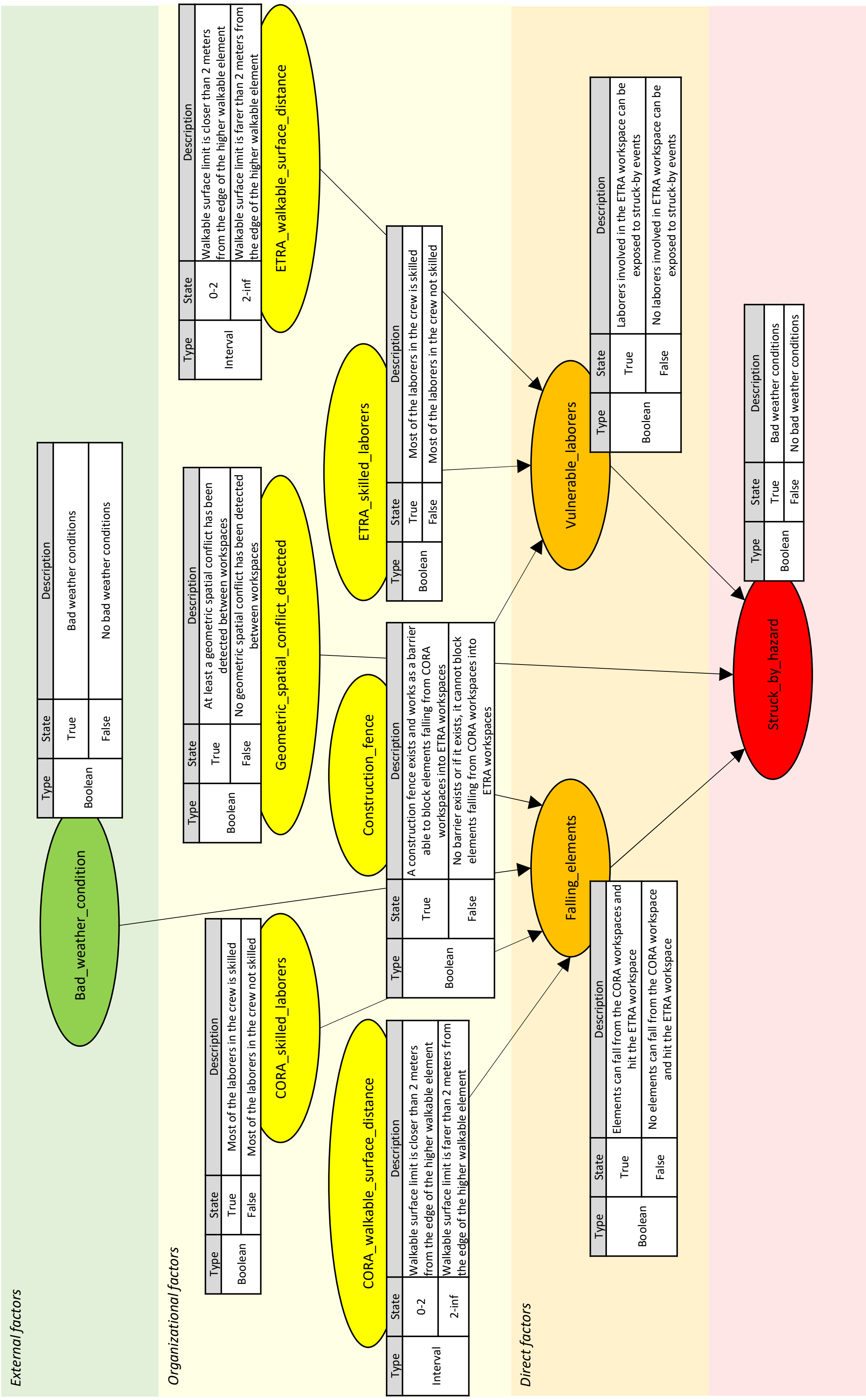


Figure 5. BN, proposed by this study, for assessing the probability that struck-by hazards may occur.

Listing the variables of the proposed BN (Figure 5) from the bottom to the top, the first variable is "Struck_by_hazard". It models the possibility that laborers in the Exposed-to-Risk-Activities (ETRA) workspace (i.e., the lower one) may be struck-by falling objects from the Cause-of-Risk-Activities (CORA) workspaces (i.e., the higher one). The "Direct factors" level's variables are "Falling_elements" and "Vulnerable_laborers". According to [93], the first one is the possible occurrence, whereas the second one is the triggering condition. The "Organizational factors" level's variables of the proposed Bayesian network are "Construction_fence", "Geometric_spatial_conflict_detected", "CORA_skilled_laborers", "ETRA_skilled_laborers", "CORA_walkable_surface_distance", and "ETRA_walkable_surface_distance". The "External factor" level's variable of the proposed Bayesian network is "Bad_weather_condition".

Once the Bayesian network is defined, it must be trained with data from experts [94]. This process is commonly defined elicitation of expert opinion. The authors have carried out this process by filling every CPT according to their experience. In order to make the Bayesian inference fully operational, the overall CPTs, reported in Table 2, are obtained by averaging the probability density functions provided by each author during the survey. These values, representing the authors' knowledge, are assumed only for validation purposes and do not have to be considered as the unique possible configuration. For a reading example of CPTs, reported in Table 2, the reader is referred to [38].

Once the Bayesian network is trained, it is implemented in the serious game engine Unity3D™ by developing the "Struck by hazard BN" C# script (Figure 3). The script automatically gets the results of geometric computations and physics simulations from the spatial conflict simulator and updates the criticality levels of spatial conflicts. In this study, the commercial Discrete Bayesian Network library [95] for Unity3D™ is applied to implement the struck-by hazard BN in the serious gaming environment. The "Struck By Hazard BN" C# script (Figure 3) implements the developed Bayesian network and the methods for carrying out physical simulations and getting the Bayesian network variables' evidence.

An example of the presented Bayesian reasoner is provided in Section 5.2.

Table 2. CPTs, obtained as the average of the authors' ones, corresponding to each child node: (a) "Falling_elements", (b) "Vulnerable_laborers", and (c) "Struck_by_hazards".

Falling_elements																
CORA_skilled_laborers	False								True							
Bad_weather_condition	False				True				False				True			
CORA_walkable_surface_distance	0-2		2-inf		0-2		2-inf		0-2		2-inf		0-2		2-inf	
Construction_fence	False	True	False	True	False	True	False	True	False	True	False	True	False	True	False	True
False	0.1	0.8	0.8	0.9	0	0.7	0.7	0.8	0.2	0.9	0.9	1	0.2	0.8	0.8	0.9
True	0.9	0.2	0.2	0.1	1	0.3	0.3	0.2	0.8	0.1	0.1	0	0.8	0.2	0.2	0.1

(a)

Vulnerable_laborers								
Construction_fence	False				True			
ETRA_walkable_surface_distance	0-2		2-inf		0-2		2-inf	
ETRA_skilled_laborers	False	True	False	True	False	True	False	True
False	0.05	0.15	0.75	0.85	0.75	0.85	0.85	0.95
True	0.95	0.85	0.25	0.15	0.25	0.15	0.15	0.05

(b)

Struck_by_hazard		
Geometric_spatial_conflict_detected	False	True

Vulnerable_laborers	False		True		False		True	
Falling_elements	False	True	False	True	False	True	False	True
High	0	0	0	0.1	0.1	0.33	0.33	1
Medium	0	0.1	0.1	0.2	0.2	0.33	0.33	0
Low	1	0.9	0.9	0.7	0.7	0.33	0.33	0

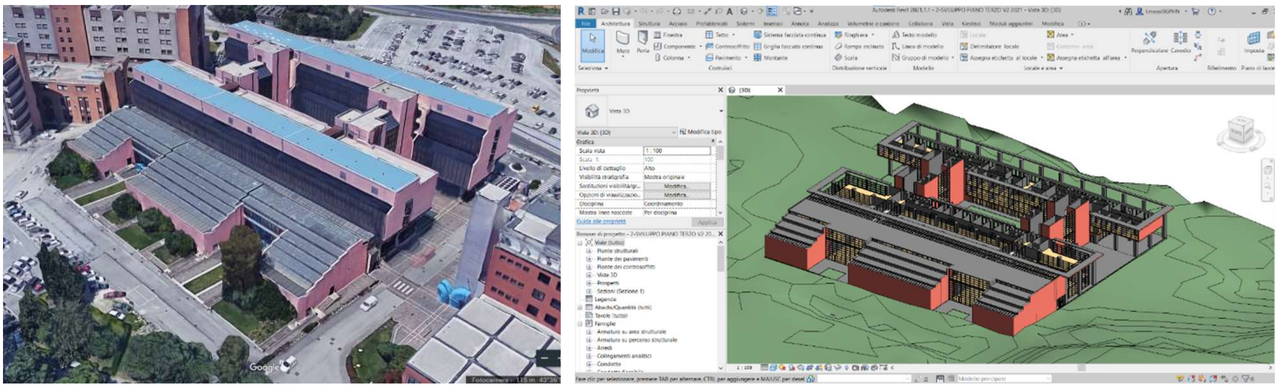
(c)

4. Use case

The workspace management framework, presented in Section 3.2, has been tested on the management of the construction of a public building (known as Eustachio), which hosts the Faculty of Medicine in the campus of the Polytechnic University of Marche (Figure 6 (a)). This building is located in the town of Ancona (Italy). The building is arranged on six floors above ground, it has an area of 16,900 m^2, and it is devoted to classrooms, offices, laboratories, a library, and other faculty-related activities. It dates back to the nineties and comprises two longitudinal blocks, whose longer sides are the main facades, facing north and south.

The technical and project documents necessary to develop the BIM model and a resource-constrained work schedule were made available for this study. A 3D view of the resulting BIM model is depicted in Figure 6 (b). The overall work schedule includes works related to the installation of precast elements, like pillars and facades, and the execution of industrial flooring. For simplicity, three crews, one for each work category, have been assumed. Crews composition and productivities have been derived from one of the most complete Italian price lists for public tenders (i.e., the Florence price list), rectified according to data provided by RS Means [96]. Quantities for each work have been computed according to the BIM model. At this point, the duration of each activity is computed by multiplying productivity and quantity. Afterward, the automatic leveling function and a final manual adjustment were executed in Microsoft Project.

For this demonstrator, a time span as long as two days (i.e., from May 27th at midnight until May 29th at midnight), highlighted in yellow in Figure 7, was considered. During those days, four activities were planned: the installation of pillars and facades on the north wing and the execution of two portions of industrial flooring.



(a) *(b)*

Figure 6. Real (a) and BIM (b) view of the Eustachio building, located in Ancona (Italy).

Figure 7. Excerpt of the overall work schedule reporting the activities scheduled on the selected working days (please use color in print).

5. Running the serious gaming tool

The developed serious gaming tool (Section 3.4) was regulated by the information model reported in Figure 8. The Entity Relationship Diagram (ERD) notation adopted for the model representation makes it possible to express the cardinality of relationships between each pair of entities by the symbols at the ends of the links (e.g., one or many to one or many). The different colors in Figure 8 are referred to different entity domains, such as the BIM model (green), work schedule (blue), main workspaces and spatial conflicts (red), and Bayesian inference (orange).

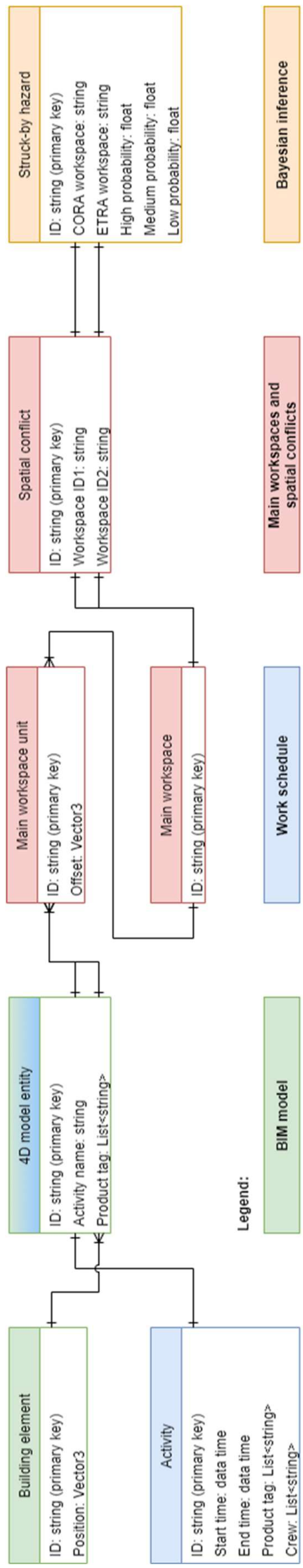


Figure 8. ERD describing the information model that regulates the developed serious gaming tool.

5.1. The spatial conflicts simulator

In the developed simulator, the execution of spatial-temporal analysis starts with the definition of the 4D BIM model by loading the IFC model of the building assumed as the use case onto Unity3D™ (Section 4) along with the CSV-formatted work schedule. These simulation steps are enabled by the "File Chooser" and "Model Input" C# scripts, respectively (Figure 3). In the 4D BIM model, 3D geometric data from the BIM model are linked to temporal data provided by the work schedule. This is shown by the information model (Figure 8), where each "4D model entity" corresponds to one activity (i.e., "Activity name") and includes one or more produced building elements (i.e., "Product tag"). Each building element, defined by the loaded IFC model, is represented by the "building element" entity, whereas each activity, defined in the work schedule, is represented by the "activity" entity (Figure 8).

At this point, the main workspaces can be generated within Unity3D™ (Figure 9). This simulation step is enabled by the "Instantiate main workspace from IFC" C# script (Figure 3). A main workspace is obtained by merging the main workspace units, instantiated for each one of the building elements (e.g., a pillar) associated with the considered activity (e.g., installing an alignment of pillars). This is shown by the information model (Figure 8), where the "Main workspace" entity is defined by merging one or more "Main workspace unit" produced by the considered activity. Each main workspace unit is instantiated in the geometric center of the corresponding building element. The main workspace unit dimensions are obtained by expanding the ones of the considered building element of a given quantity, defined as "Main Workspace Offset Array", and set by default as 1 meter (Figure 9). These parameters can be customized by the user if a bigger main workspace for operational or safety purposes is required. According to this, the information model reports the "Main workspace unit" entity, that is, the workspace generated for each building element, including the "Offset" parameter.

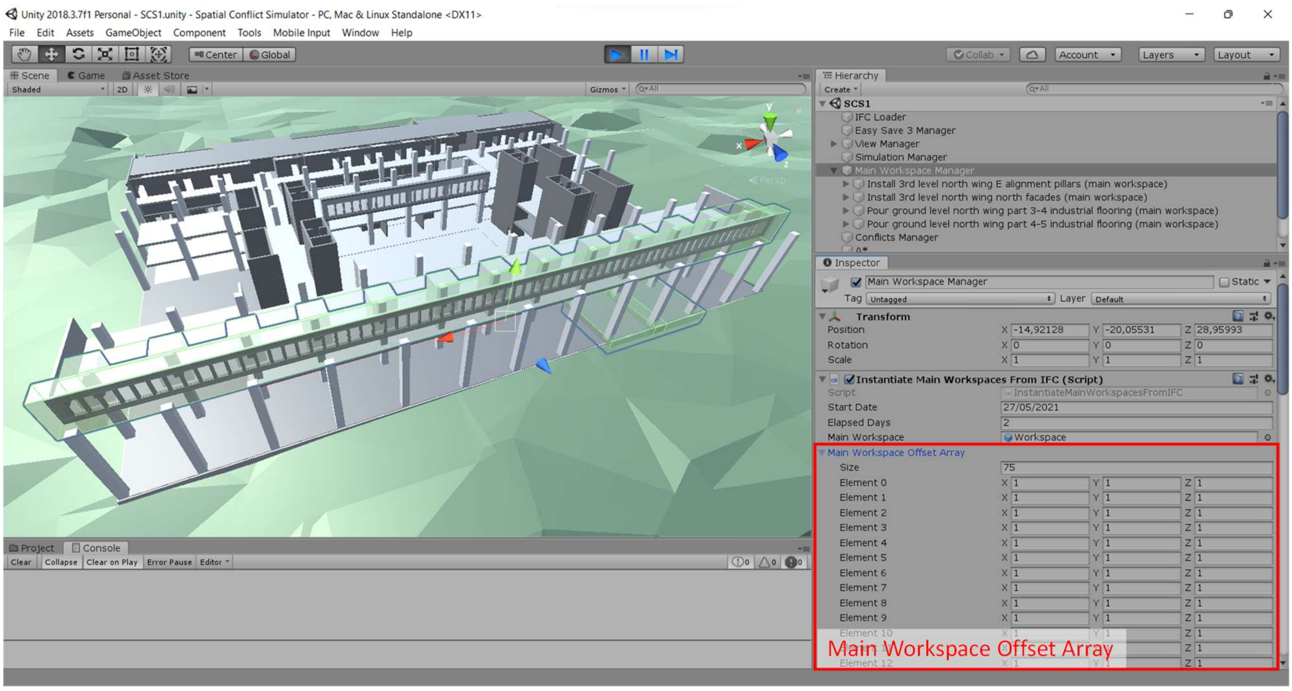


Figure 9. Main workspaces generated assuming the "Main Workspace Offset Array" values filled by default with the 1-meter offset in all three directions (please use color in print).

Once main workspaces are instantiated, "direct" spatial conflicts can be detected by carrying out geometric intersection tests among workspaces in their initial static position, inherited from the corresponding building elements. This simulation step is executed by clicking on the "Find Geometric Spatial Conflict" button (Figure 10) implemented by the "Intersection test" C# script (Figure 3). A spatial conflict is detected between two given workspaces only if their boundaries intersect each other and are assigned to different crews. The developed tool displays a detected spatial conflict by changing the color of the relevant main workspaces from green (Figure 9) to red (Figure 10). In addition, a message reporting the pairs of the conflicting main workspaces is printed in the Unity3D^{TM} console.

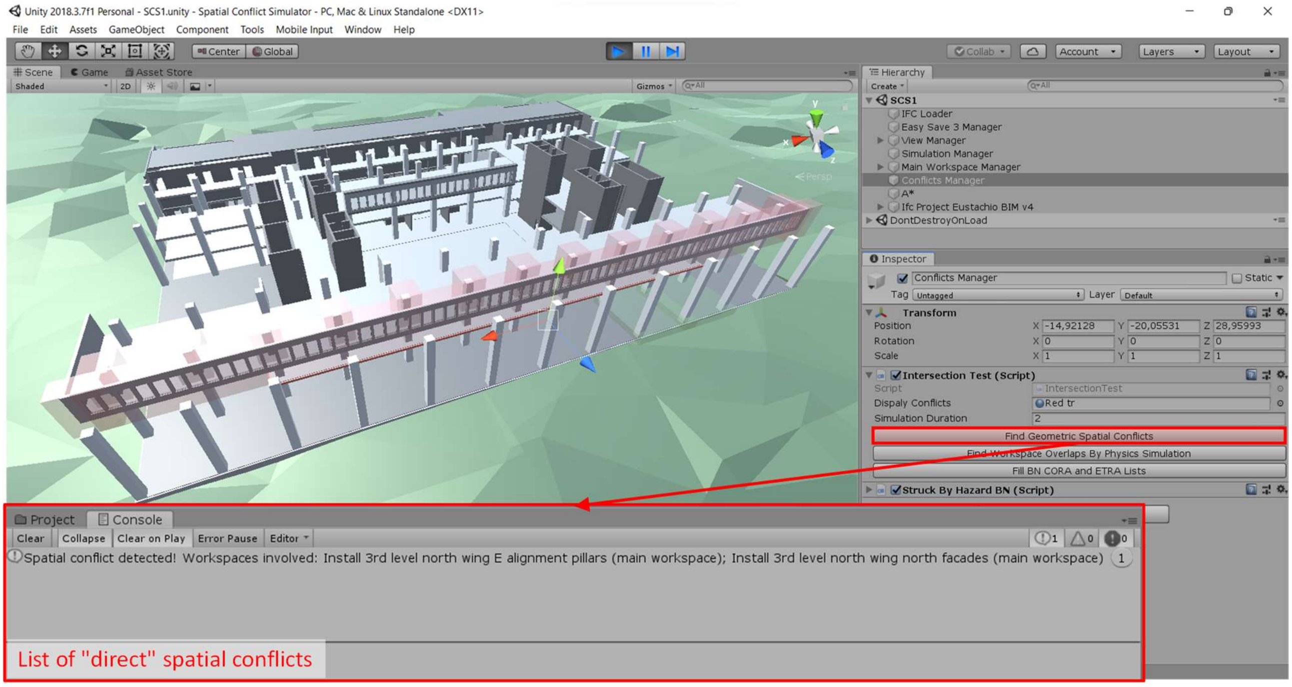


Figure 10. “Direct” spatial conflicts detected by geometric intersection tests, triggered by the “Find Geometric Spatial Conflicts” button showing conflicts in red and associated message (please use color in print).

As already mentioned, due to the construction site dynamics, “direct” spatial conflicts do not include the totality of spatial issues affecting a construction site. To make an example, main workspaces superimposed at different heights, also if not intersecting each other, can be affected by spatial conflicts. In fact, objects involved in the construction process may fall from the main workspace at higher levels and hit laborers working at lower levels. In order to consider this set of conflict scenarios, the proposed tool can carry out physical simulations of main workspaces and detect related spatial conflicts. These spatial conflicts are labeled as “indirect”, meaning that they cannot be directly detected simply by conducting a geometric intersection test among workspaces in their initial static position. On the contrary, virtual physics simulations must be executed to consider “possible” future workspace configurations. In practice, each game object representing a main workspace is let fall down, according to the gravity law, to check if it hits, during the fall, any other main workspace(s) below assigned to another crew. The probability of “indirect” spatial conflicts that virtually occur must be assessed (Section 5.2) since we cannot state for certain if they occur in reality. The developed tool displays the detected spatial conflicts by changing the color of the main workspaces involved from green to red (Figure 11). In addition, a message reporting the pairs of the conflicting main workspaces is printed in the Unity3D^{TM} console (Figure 11). This simulation step is executed by clicking on the “Find Workspace Overlaps By Physics Simulation” button (Figure 11) implemented by the “Intersection Test” C# script (Figure 3).

In the information model, both “direct” and “indirect” spatial conflicts are represented by the “Spatial conflict” entity, which includes the “Workspace ID1” and “Workspace ID2” parameters, inherited from the conflicting “Main workspace” entities’ “ID” (Figure 8).

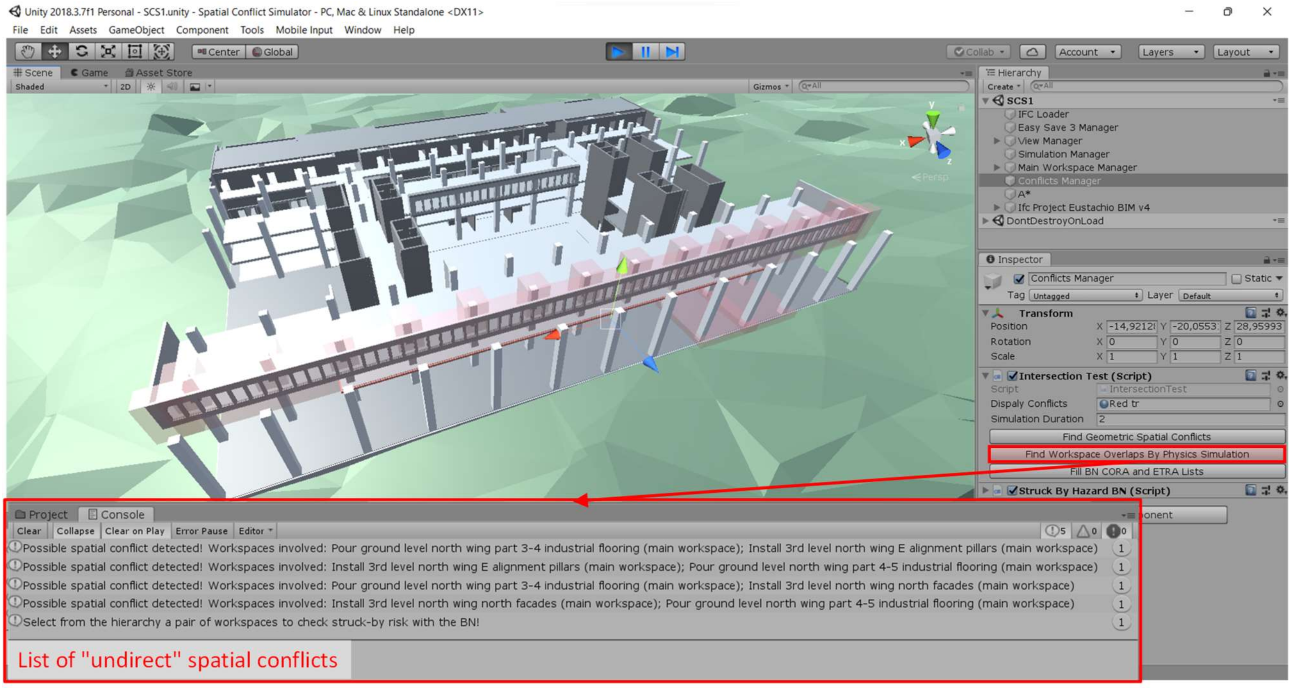


Figure 11. "Indirect" spatial conflicts detected by geometric intersection tests during physics simulations.

5.2. The integrated Bayesian network

The criticality of detected "indirect" spatial conflicts, introduced in the previous Subsection 5.1, is assessed using the developed struck-by hazard Bayesian network (BN) (Section 3.5). In each "indirect" spatial conflict, a pair of main workspaces is involved. The one having the highest initial position is the main workspace from which falling objects may cause struck-by hazards. This workspace, being the source of the struck-by hazard, can be defined as the "Cause-of-Risk Activities" (CORA) workspace. The other one in the pair, placed at the lowest initial position, is the main workspace where falling objects can hit laborers. This workspace is defined as the "Exposed-to-Risk Activities" (ETRA) workspace. The information model (Figure 8) maps this classification, including, within the "Struck-by hazard" entity, both the "CORA workspace" and "ETRA workspace" parameters.

The developed struck-by hazard BN (Section 3.5) is implemented within Unity3D^{TM} by the "Struck-by hazard BN" C# script (Figure 3). In this way, the results of physical simulations and geometric computations, executed in the serious gaming environment, can automatically feed the states of the BN's variables. These simulation steps are triggered by clicking on the buttons numbered from "1." to "5." in Figure 12.

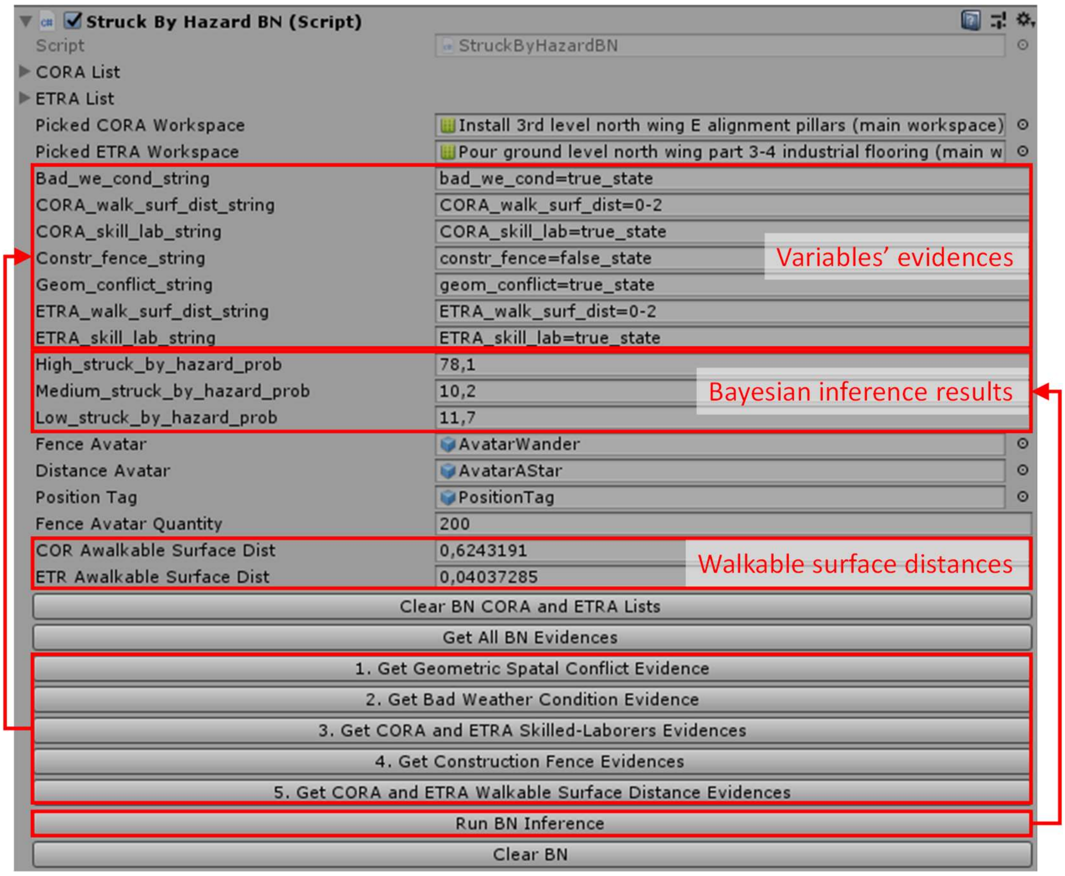


Figure 12. Front end of the "Struck By Hazard BN" component after including the BN evidence.

If at least one possible spatial conflict has been detected by physical simulations, the "Geom_confl_string" variable state will be set to "true", otherwise "false" (Figure 12).

The "Bad_we_cond_string" variable state will be filled as "true" if bad weather conditions are expected according to the weather forecast; otherwise "false" (Figure 12). This functionality was implemented using the commercial Real-time Weather tool for Unity3D™ [97].

The "CORA_skil_lab_string" and "ETRA_skil_lab_string" variables states will be filled with a "true" or "false" state if the majority of the laborers constituting the crew are skilled or not (Figure 12). This information is obtained from the crews' information included in the resource-constrained work schedule.

The "Constr_fence_string" variable state will be filled with a "true" state if any barrier that can protect the laborers at the lower workspace (i.e., ETRA workspace) from falling objects exists (Figure 12). For this purpose, avatars are instantiated in random positions within the higher workspace (i.e., CORA workspace) and able to wander and check if they can fall down or not (Figure 13). These avatars are defined in Unity3D™ as spheres having the same physical properties (e.g., mass, drag, etc.) as objects involved in the construction process. If they hit a thin plastic sheeting placed as a barrier against dust, they will break through it; otherwise, they will be blocked if they hit a barrier made of bricks or concrete. So, if none of the instantiated avatars hit the lower workspace (e.g., ETRA workspace), the serious gaming tool deduces the presence of a barrier that protects the ETRA workspace and the "Constr_fence_string" variable state is set as "true", otherwise "false" (Figure 12).

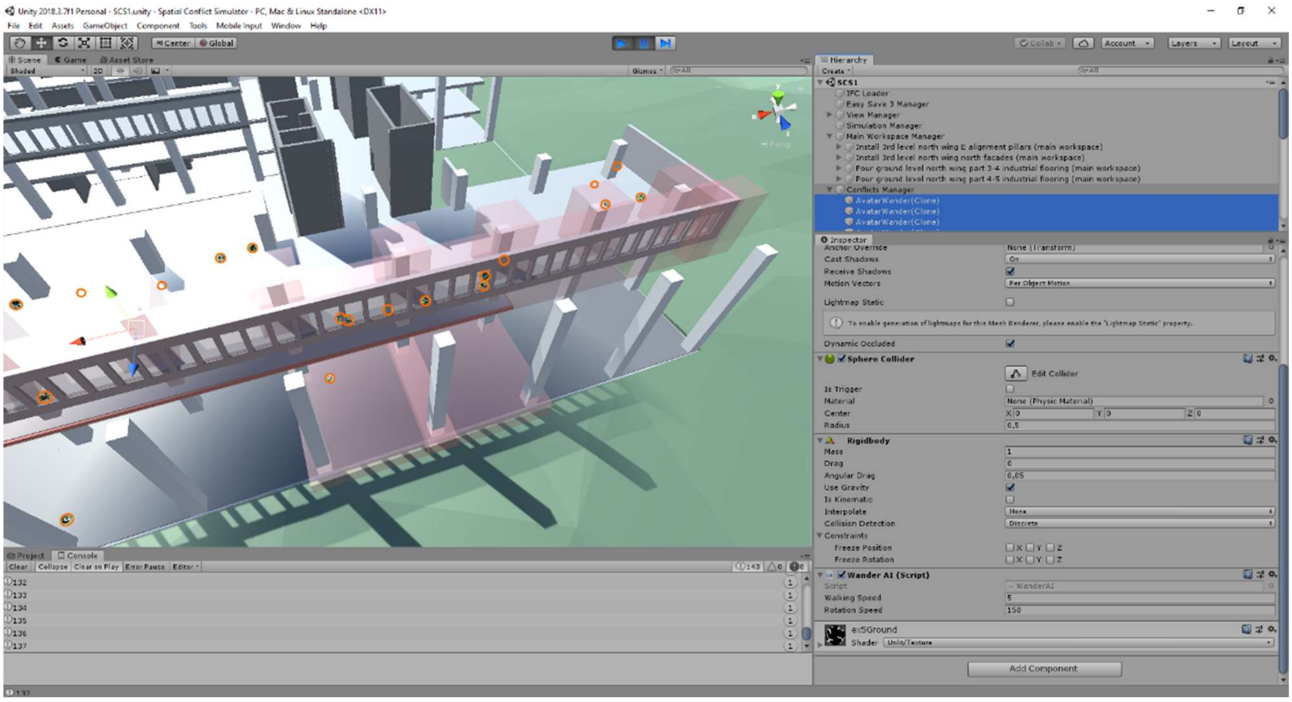


Figure 13. Instantiation of spherical random wandering avatars for checking the presence of any barrier protecting ETRA workspaces.

Finally, the “CORA_walk_surf_dist_string” and “ETRA_walk_surf_dist_string” variables states will be filled with “0-2” or “2-inf”. The first state means that the walkable surface limit is closer than 2 meters from the edge of the higher walkable element, whereas the second is farther than 2 meters (Figure 12). The distance between the walkable surface’s limit and the slab edge was determined using geometric computations using the Recast graph provided by the A* Pathfinding tool for Unity3D™ [98]. Generating a Recast graph means voxelizing the world, that is, constructing an approximation of the world out of lots of boxes. The walkable surfaces are automatically peeled off from the regions by first tracing the boundaries and then simplifying them. In Figure 14, the green area is the walkable surface on the slab where the CORA workspace is placed. In the same Figure 14, the automatic computation of the “CORA Walkable Surface Distance” is depicted. This distance is computed as the distance between the walkable limit on the CORA slab (i.e., “CORA Walkable Surface Limit”) and the edge of the CORA slab (i.e., “CORA Slab Edge”). In Figure 15, the pink area represents the walkable surface on the slab where the ETRA workspace is placed. In the same Figure 15, the automatic computation of the “ETRA Walkable Surface Distance” is depicted. This distance is computed as the distance between the walkable limit on the ETRA slab (i.e., “ETRA Walkable Surface Limit”) and the orthogonal projection of the “CORA Slab Edge” on it (i.e., “CORA Slab Edge Orthogonal Projection”). The distances computed within Unity3D™ are reported in Figure 14 and Figure 15.

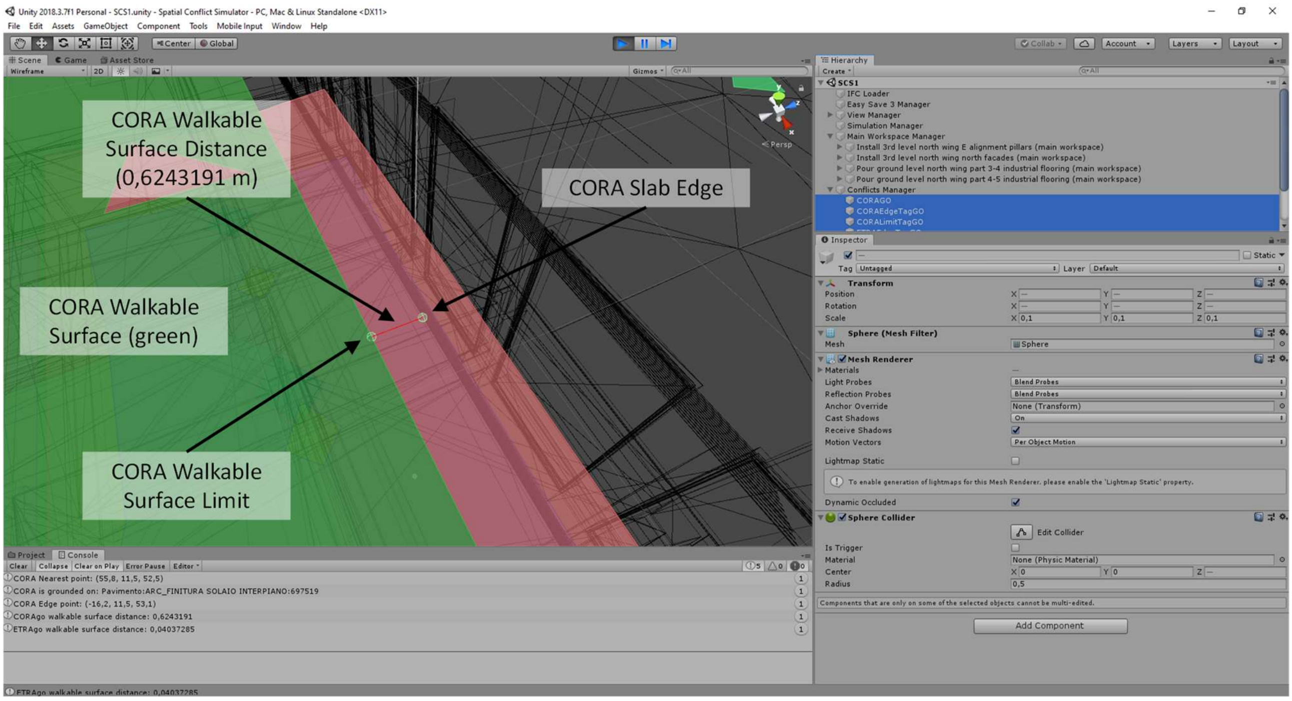


Figure 14. Automatic geometric computation of the "CORA Walkable Surface Distance" made by the serious gaming tool.

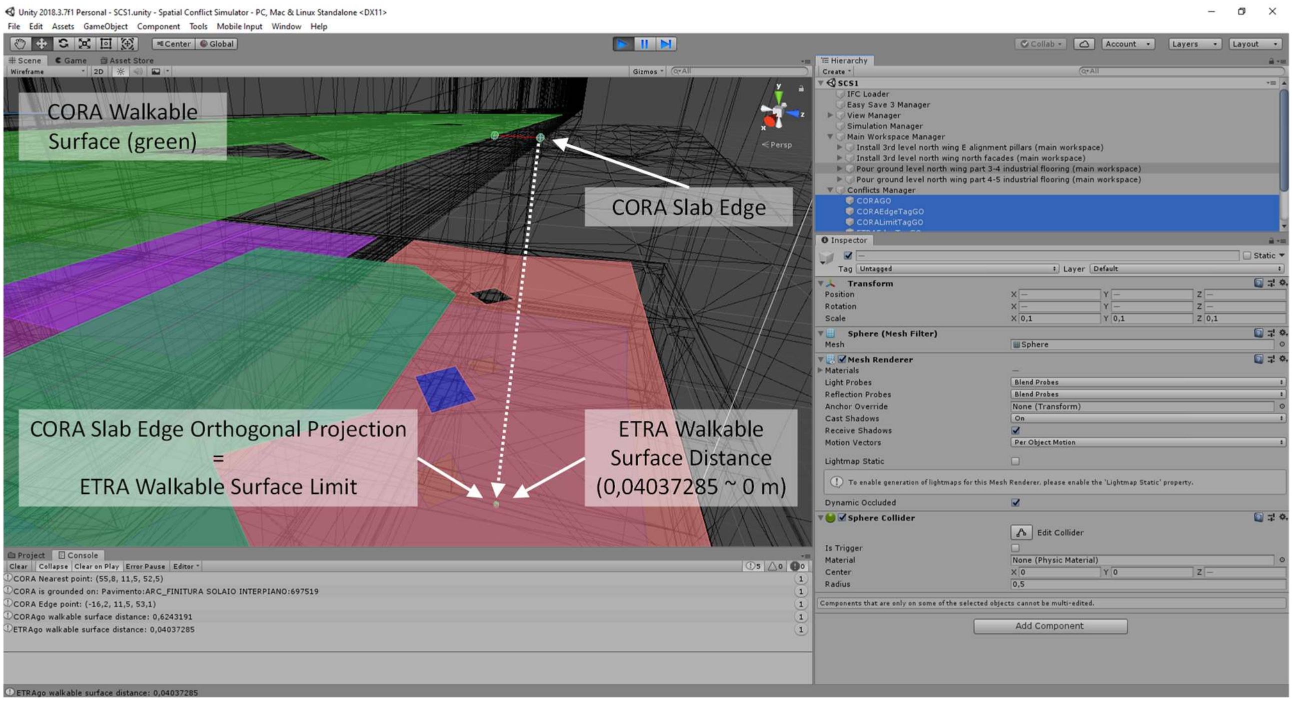


Figure 15. Automatic geometric computation of the "ETRA Walkable Surface Distance" made by the serious gaming tool.

Once evidence for all variables is obtained, the Bayesian inference is triggered by clicking on the "Run BN Inference" button. As a result, the probability values for all the three states of the "Struck-by hazard" variable, namely "High_struck_by_hazard_prob", "Medium_struck_by_hazard_prob", and "Low_struck_by_hazard_prob" are provided (Figure 12). In Figure 12, the higher value is computed for the "High_struck_by_hazard_prob" (i.e., 78%), indicating that, given the states of the variable, the corresponding scenario can be effectively considered critical. Therefore, the construction management team can benefit from the contribution given by this decision support system (DSS) during the refinement process of the work schedule.

6. Implementation and comparison of the proposed tool

The developed spatial conflict simulator (Sections 3 and 5) was compared with the current practice adopted by professionals for managing workspaces. That was done by comparing the proposed workspace management framework (referred to as the "Enhanced" approach) with the most advanced approaches currently applied by professionals for managing workspaces (referred to as "Benchmark" approaches). In particular, the "Navisworks Benchmark" identifies the one based on the commercial 4D BIM software Autodesk Navisworks, whereas the "Synchro Benchmark" approach identifies the one based on the application of the commercial 4D BIM software Synchro 4D Pro. Four experiments have been carried out considering the use case described in Section 4 and a time window of as long as two working days (i.e., May 27th and 28th), highlighted in yellow in Figure 7. (Table 3). The "Navisworks Benchmark" and "Synchro Benchmark" approaches have been tested on the Standard BIM model (i.e., experiments no. 1 and 2 in Table 3). The "Enhanced" approach was tested both on the "Standard" and "Modified" BIM model (i.e., experiments no. 3 and 4 in Table 3). Further details are provided in sub-sections 6.1, 6.2, and 6.3.

Table 3 shows the functionalities implemented by the considered tools. In the "Navisworks Benchmark" approach, Autodesk Navisworks enables loading the BIM model and construction schedule and carrying out geometric intersection tests. In the "Synchro Benchmark" approach, Synchro 4D Pro allows the manual definition of main workspaces. Finally, in the "Enhanced" approach, the proposed tool enables the execution of physics simulations and Bayesian inference.

Table 3. Overview of the main differences between the four experiments.

Experiment No.	Approach	Construction schedule	BIM model	Tool functionalities				
				Loading BIM model and construction schedule	Generating main workspaces	Carrying out geometric intersection tests	Carrying out physics simulations	Running Bayesian network
1	Navisworks Benchmark	May 27th and 28th	Standard	✓	✗	✓	✗	✗
2	Synchro Benchmark			✓	✓	✓	✗	✗
3	Enhanced (proposed tool)			✓	✓	✓	✓	✓
4			Modified	✓	✓	✓	✓	✓

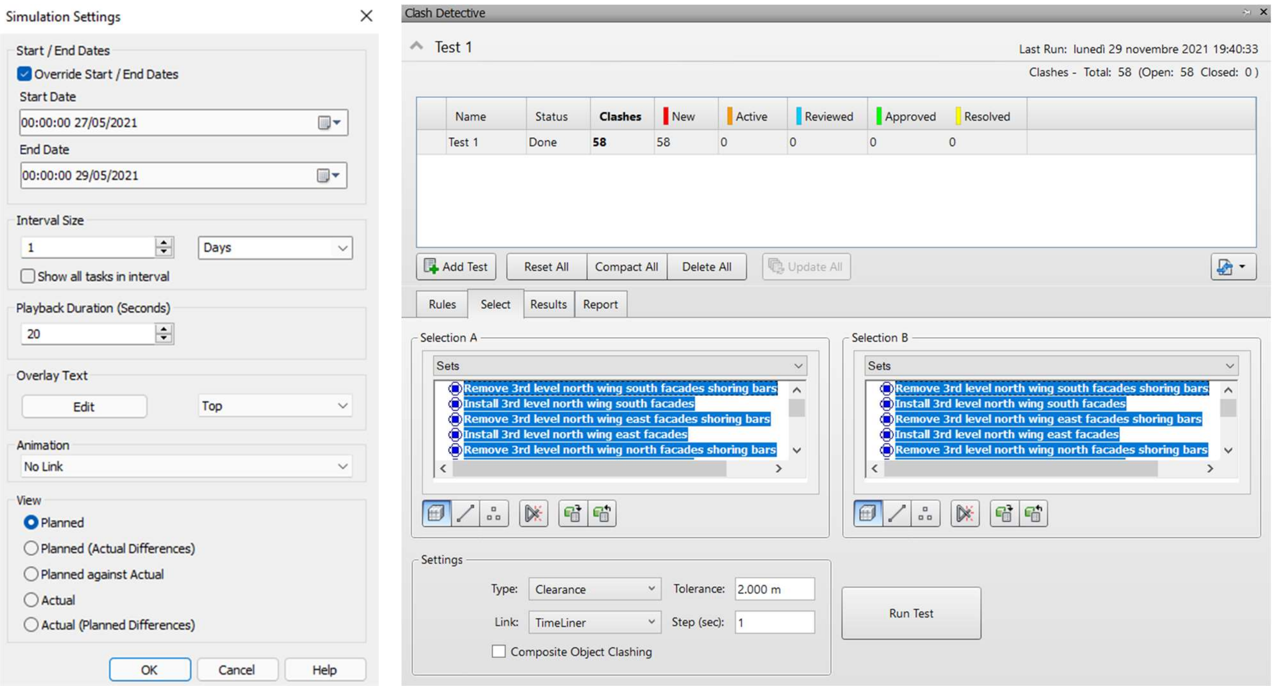
6.1. The "Navisworks Benchmark" approach

Experiment no. 1 was carried out by applying the "Navisworks Benchmark" approach, corresponding to the one applied by professionals to detect spatial conflicts using Autodesk Navisworks.

First, the IFC model of the use case presented in Section 4 was loaded within Autodesk Navisworks. Then, the work schedule was imported in CSV format by clicking on the "Add" button under the "Data Sources" tab of the TimeLiner.

In order to simulate the same working days chosen for the use case (Section 4), the following time interval has been selected in the “Simulate” tab of the TimeLiner: from May 27th at midnight until May 29th at midnight (Figure 16 (a)).

In the Clash Detective window, a new test was added by selecting all the available sets (each set corresponds to an activity in the schedule) both in “Selection A” and “Selection B”. This enabled to check for conflicts by considering all the possible pairs of sets (i.e., activities) (Figure 16 (b)). Then, a “Clearance” type with 2 meters “Tolerance” was set to apply the equivalent offset value of 1 meter used as the default value in the serious gaming tool (Section 5.1). A “Clearance” clash, in Navisworks, was defined as the one in which “the geometry of Selection A may or may not intersect that of Selection B, but comes within a distance of less than the set tolerance” [99]. On the contrary, in the developed serious gaming tool, the offset was applied to the border of each element. Finally, the TimeLiner “Link” was selected to carry out a spatial-temporal analysis within the TimeLiner interval set above (Figure 16 (b)). Finally, the test was launched by clicking on the “Run Test” button. The outcome is shown in Figure 16 (b).



(a) (b)

Figure 16. Setting the “Simulation Settings” (a) and the “Clash Detective” (b) parameters within Autodesk Navisworks.

6.2. The “Synchro Benchmark” approach

Experiment no. 2 has been carried out by applying the “Synchro Benchmark” approach, corresponding to the one applied by professionals to detect spatial conflicts using Synchro 4D Pro.

First, the IFC model of the use case, presented in Section 4, was loaded within Synchro 4D Pro. Then, the work schedule was imported in XML format by clicking on the “Import” button under the “File” section in the main window.

Then workspaces were generated (Figure 17 (a)), for each scheduled activity (Figure 7), by setting an offset equal to 1 m, as described in Section 5.1. This task has been fulfilled by selecting the building elements produced by each activity and clicking on the “Bounding Box” button of the “Create Workspace” function, located under the “3D” tab.

In the “Dynamic Clash Detection” window, a new “New Spatial Test” was added (Figure 17 (b)). In the same window, in order to simulate the same working days chosen for the use case (Section 4), the “Time range” option was selected, and the following time interval was set: from May 27th at midnight until May 29th at midnight (Figure 17 (b)). Then, an “Hard” clash type test that looks for elements overlapping by more than a specified “Tolerance” distance equal to 0 mm was selected.

Finally, the generated workspaces were selected in the “3D Objects” window (Figure 17 (a)), and the spatial-temporal analysis was run by clicking on the “Run Test” function related to the set “New Spatial Test”. The obtained results are shown in Figure 17 (c).

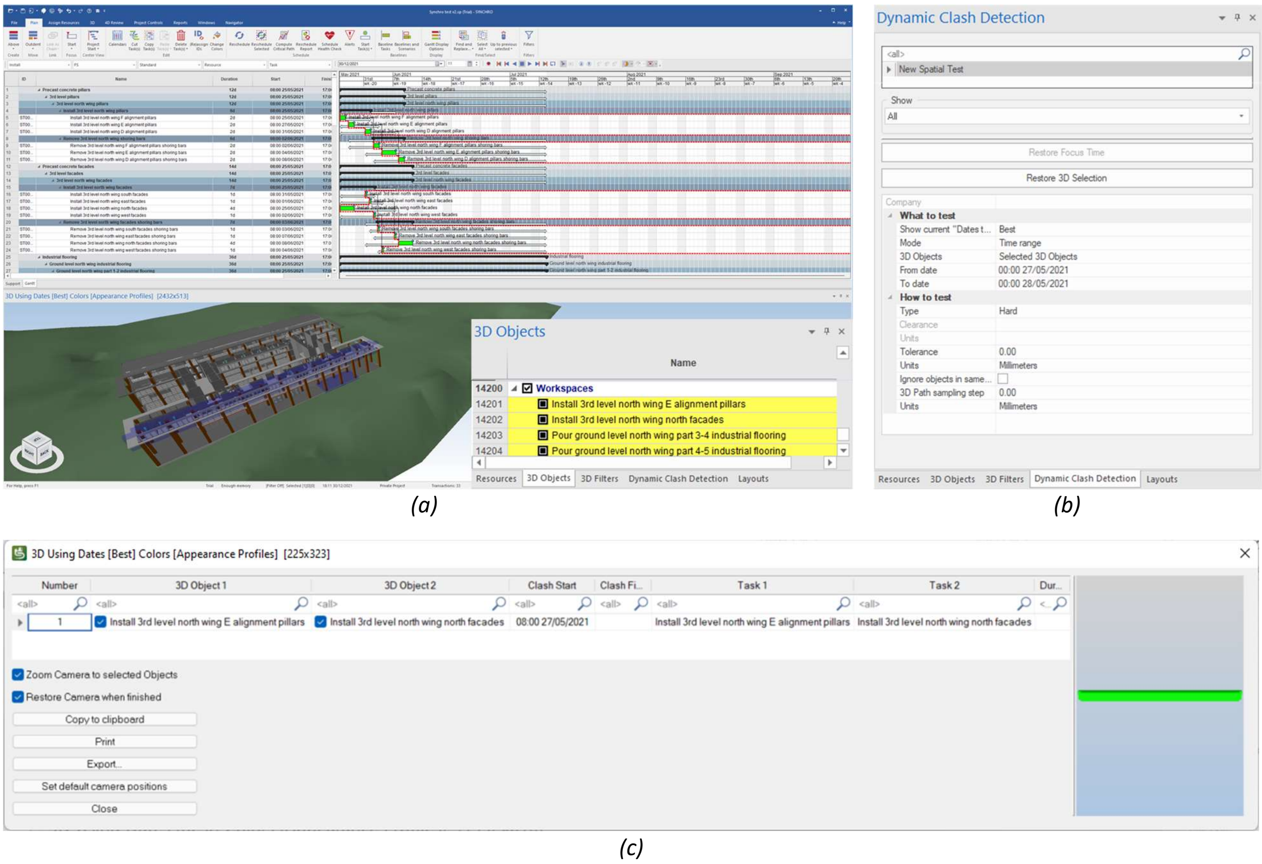
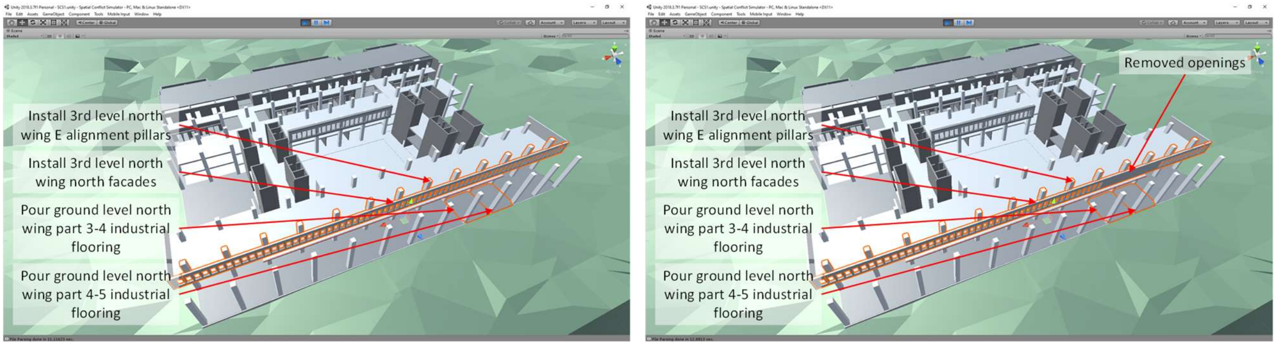


Figure 17. Generating workspaces (a) and setting “Dynamic Clash Detection” parameters (b) to detect spatial conflicts within Synchro 4D Pro (c).

6.3. The “Enhanced” approach

Experiments no. 3 and 4 were carried out with reference to the use case and working days presented in Section 4 by executing the simulation steps described in Section 5.1. As a result, “direct” and “indirect” spatial conflicts were identified. Then, the criticality levels of the latter category were computed by running the struck-by hazards Bayesian network (BN) (Section 5.2).

In order to stress the contribution given by the Bayesian inference, the spatial conflict simulator was first tested on the “Standard” BIM model of the use case (Figure 18 (a)) and then on the “Modified” BIM model (Figure 18 (b)). The latter was obtained by removing some of the openings on the 3rd level north façade to give it the function of a construction fence that can protect laborers below from likely falling objects. The aim of this scenario was to demonstrate that the struck-by hazard BN can automatically catch this information from the serious gaming environment and fire the “Construction_fence” variable’s evidence accordingly. Therefore, a different criticality level than in the Enhanced scenario has been provided.



(a) (b)

Figure 18. Views of the "Standard" (a) and "Modified" (b) BIM models.

7. Results and discussion

This section summarizes the results from the implementation and comparison of the proposed tool (Table 4). The spatial-temporal analysis carried out according to the "Navisworks Benchmark" approach (i.e., experiment no. 1 described in Section 6.1) detected 58 spatial conflicts (Figure 16 (b), Table 4), whereas the "Synchro Benchmark" approach (i.e., experiment no. 2 described in Section 6.2) detected 1 spatial conflict (Figure 17 (c), Table 4).

The spatial-temporal analysis carried out according to the "Enhanced" approach detected 1 "direct" and 4 "indirect" spatial conflicts for both the "Standard" and "Modified" BIM models (i.e., experiments no. 3 and 4 in Section 6.3). In Table 4, the last column reports the criticality levels of the struck-by hazard BN for each "indirect" spatial conflict. As far as the "Standard" model is considered (i.e., experiment no. 3), the Bayesian inference provides a "high" criticality level. Table 5 summarizes the results of the Bayesian inference for the "Enhanced" approach, considering the "Standard" and the "Modified" BIM models. As reported in Table 5, the "high" state of the "Struck_by_hazard" variable has the highest probability value for each "indirect" spatial conflict (e.g., 78%). When the "Modified" BIM model is considered, the Bayesian inference provides a "low" criticality level. As reported in Table 5, the "low" state of the "Struck_by_hazard" variable has the highest probability value for each "indirect" spatial conflict (e.g., 57%).

In the "Navisworks Benchmark" approach (i.e., experiment no. 1), only 15 out of 58 spatial conflicts (i.e., with ID from N.44 to N.58 in Table 4) are actual spatial conflicts and correspond to the "direct" spatial conflicts detected by "Enhanced" approach (i.e., with E.1 in Table 4). Hence, only about 25% of the detected spatial conflicts are "true positive". More spatial conflicts in the "Navisworks Benchmark" approach correspond to anyone in the "Enhanced" approach. This occurs because workspaces are not considered in the first case, and a spatial conflict is detected when two building elements are closer than a given minimum threshold, called "tolerance value". The rest of the spatial conflicts (i.e., with ID from N.1 to N.43 in Table 4), corresponding to about 75% of the total, are "false positive". This shows that the "Navisworks Benchmark" approach overestimates the results. In fact, in the "Navisworks Benchmark" approach, any building element closer than the given threshold to any other building element is detected as a conflict. Hence, although Autodesk Navisworks can effectively check clashes between building elements, it cannot properly be applied for checking spatial interferences between activities' workspaces.

In the "Synchro Benchmark" approach (i.e., experiment no. 2), only a spatial conflict (i.e., with IDs S.1 in Table 4) corresponding to the "direct" spatial conflict "Enhanced" approach (i.e., with E.1 in Table 4) was detected. The "Enhanced" approach (i.e., experiments no. 3 and 4) detected 4 additional "indirect" spatial conflicts by integrating physics simulations and geometric computations. The "Enhanced" approach can apply Bayesian inference to consider the related criticality level for those conflicts. In the case of the "Standard" BIM model (i.e., experiment no. 3), the "high" state of the "Struck_by_hazard" variable has the highest probability value for each "indirect" spatial conflict (e.g., 78%). Therefore, according to the proposed workspace management framework (Section 3.2), the construction management team must adjust the work schedule to resolve all the 5 detected spatial conflicts having IDs from E.1 to E.5 (Table 4). On the contrary, in the case in which the "Modified" BIM model is considered, the "low" state of the "Struck_by_hazard" variable has the highest probability value for each "indirect" spatial conflict (e.g., 57%). This means that the construction management team must adjust the work schedule to resolve only the "direct" spatial conflict having E.1 as ID (Table 4).

Table 4. Overview of the results from the experiments.

Experiment no.	**Approach**	**ID**	**Pairs of element IDs involved in the spatial conflicts detected by only geometric computation**		**ID**	**Pairs of element IDs involved in the spatial conflicts detected by physics simulations and geometric computation**		**Criticality level**
1	Navisworks Benchmark	N.1	195809	1226040	n/a	n/a	n/a	n/a
		N.2	195809	1226040	n/a	n/a	n/a	n/a
		N.3	759850	760059	n/a	n/a	n/a	n/a
		N.4	760059	1226040	n/a	n/a	n/a	n/a
		N.5	195927	760059	n/a	n/a	n/a	n/a
		N.6	195927	639149	n/a	n/a	n/a	n/a
		N.7	195821	1224989	n/a	n/a	n/a	n/a
		N.8	195821	1224989	n/a	n/a	n/a	n/a
		N.9	195821	1224989	n/a	n/a	n/a	n/a
		N.10	195821	1224989	n/a	n/a	n/a	n/a
		N.11	760059	1225516	n/a	n/a	n/a	n/a
		N.12	1225516	1225516	n/a	n/a	n/a	n/a
		N.13	195809	760059	n/a	n/a	n/a	n/a
		N.14	1226040	1226040	n/a	n/a	n/a	n/a
		N.15	1227080	1225516	n/a	n/a	n/a	n/a
		N.16	639149	1226040	n/a	n/a	n/a	n/a
		N.17	639149	1227080	n/a	n/a	n/a	n/a
		N.18	639149	760059	n/a	n/a	n/a	n/a
		N.19	1224989	760059	n/a	n/a	n/a	n/a
		N.20	1225516	639149	n/a	n/a	n/a	n/a
		N.21	1225516	1224989	n/a	n/a	n/a	n/a
		N.22	1225516	1226040	n/a	n/a	n/a	n/a
		N.23	759850	1226040	n/a	n/a	n/a	n/a
		N.24	759850	1226040	n/a	n/a	n/a	n/a
		N.25	1225516	760059	n/a	n/a	n/a	n/a
		N.26	195809	760059	n/a	n/a	n/a	n/a
		N.27	195797	1225516	n/a	n/a	n/a	n/a
		N.28	195797	1225516	n/a	n/a	n/a	n/a
		N.29	1225516	1226040	n/a	n/a	n/a	n/a
		N.30	1225516	1226040	n/a	n/a	n/a	n/a
		N.31	1225516	1224989	n/a	n/a	n/a	n/a
		N.32	1225516	1224989	n/a	n/a	n/a	n/a
		N.33	760059	1224989	n/a	n/a	n/a	n/a
		N.34	759850	1224989	n/a	n/a	n/a	n/a

		N.35	759850	639149	n/a	n/a	n/a	n/a
		N.36	195797	760059	n/a	n/a	n/a	n/a
		N.37	195797	759850	n/a	n/a	n/a	n/a
		N.38	1227080	1227080	n/a	n/a	n/a	n/a
		N.39	1227080	1227080	n/a	n/a	n/a	n/a
		N.40	1227080	1226040	n/a	n/a	n/a	n/a
		N.41	1227080	1226040	n/a	n/a	n/a	n/a
		N.42	195785	1226040	n/a	n/a	n/a	n/a
		N.43	195785	1226040	n/a	n/a	n/a	n/a
		N.44	213613	1227080	n/a	n/a	n/a	n/a
		N.45	213681	1227080	n/a	n/a	n/a	n/a
		N.46	213565	760059	n/a	n/a	n/a	n/a
		N.47	213649	760059	n/a	n/a	n/a	n/a
		N.48	213589	760059	n/a	n/a	n/a	n/a
		N.49	213601	760059	n/a	n/a	n/a	n/a
		N.50	213553	760059	n/a	n/a	n/a	n/a
		N.51	213541	760059	n/a	n/a	n/a	n/a
		N.52	213541	760059	n/a	n/a	n/a	n/a
		N.53	213661	760059	n/a	n/a	n/a	n/a
		N.54	213577	639149	n/a	n/a	n/a	n/a
		N.55	213683	760059	n/a	n/a	n/a	n/a
		N.56	213625	760059	n/a	n/a	n/a	n/a
		N.57	213637	760059	n/a	n/a	n/a	n/a
		N.58	213661	759850	n/a	n/a	n/a	n/a
Experiment no.	**Approach**	**ID**	**Pairs of workspace names involved in the spatial conflicts detected by only geometric computation**		**ID**	**Pairs of workspace names involved in the spatial conflicts detected by physics simulations and geometric computation**		**Criticality level**
2	Synchro Benchmark	S.1.	Install 3rd-level north-wing E-alignment pillars	Install 3rd-level north-wing north facades	n/a	n/a	n/a	n/a
Experiment no.	**Approach**	**ID**	**Pairs of workspace names involved in the spatial conflicts detected by only geometric computation**		**ID**	**Pairs of workspace names involved in the spatial conflicts detected by physics simulations and geometric computation**		**Criticality level**
3	Enhanced (proposed tool)	E.1	Install 3rd-level north-wing E-alignment pillars	Install 3rd-level north-wing north facades	E.2	Place ground-level north-wing part 3-4 industrial flooring	Install 3rd-level north-wing E-alignment pillars	High (78%)
					E.3	Place ground-level north-wing part 4-5 industrial flooring	Install 3rd-level north-wing E-alignment pillars	High (78%)
					E.4	Place ground-level north-wing part 3-4 industrial flooring	Install 3rd-level north-wing north facades	High (78%)
					E.5	Place ground-level north-wing part 4-5 industrial flooring	Install 3rd-level north-wing north facades	High (78%)
Experiment no.	**Approach**	**ID**	**Pairs of workspace names involved in the spatial conflicts detected by only geometric computation**		**ID**	**Pairs of workspace names involved in the spatial conflicts detected by physics simulations and geometric computation**		**Criticality level**

4	Enhanced (proposed tool)	E.1.	Install 3rd-level north-wing E-alignment pillars	Install 3rd-level north-wing north facades	E.6	Place ground-level north-wing part 3-4 industrial flooring	Install 3rd-level north-wing E-alignment pillars	Low (57%)
					E.7	Place ground-level north-wing part 4-5 industrial flooring	Install 3rd-level north-wing E-alignment pillars	Low (57%)
					E.8	Place ground-level north-wing part 3-4 industrial flooring	Install 3rd-level north-wing north facades	Low (57%)
					E.9	Place ground-level north-wing part 4-5 industrial flooring	Install 3rd-level north-wing north facades	Low (57%)

Table 5. Bayesian inference results for the "Enhanced" approach, considering the "Standard" and the "Modified" BIM models.

Variable		**Variables states for each "indirect" spatial conflict – Experiment no. 3**				**Variables states for each "indirect" spatial conflict – Experiment no. 4**			
		E.2	**E.3**	**E.4**	**E.5**	**E.6**	**E.7**	**E.8**	**E.9**
Bad_weather_condition		True	True	True	True	True	True	True	True
CORA_walkable_surface_distance		0-2	0-2	0-2	0-2	0-2	0-2	0-2	0-2
CORA_skilled_laborers		True	True	True	True	True	True	True	True
Construction_fence		False	False	False	False	True	True	True	True
Geometric_spatial_conflict_detected		True	True	True	True	True	True	True	True
ETRA_walkable_surface_distance		0-2	0-2	0-2	0-2	0-2	0-2	0-2	0-2
ETRA_skilled_laborers		True	True	True	True	True	True	True	True
Struck_by_hazard	High	78%	78%	78%	78%	19%	19%	19%	19%
	Medium	10%	10%	10%	10%	23%	23%	23%	23%
	Low	11%	11%	11%	11%	57%	57%	57%	57%

8. Conclusions and outlook

Much effort has been spent to date by researchers in workspace management. As reported in Section 2, the main gaps existing in the literature point out the need to consider the construction site dynamics and filter non-critical scenarios among pure geometric spatial conflicts.

In order to cover these gaps, this study proposes a workspace management framework that integrates the work scheduling phase with a spatial conflict simulator and a Bayesian reasoner. The simulator and the reasoner have been developed using serious game engine technology, namely Unity3D^{TM}. Thanks to this technological solution, potential spatial interferences can be detected based on given geometric and semantic information stored in the BIM model and construction process data included in the work schedule. Using game engine technology, geometric and physics simulations can be carried out to anticipate likely future scenarios. Contrarily to the rule-based approach adopted by currently available 4D tools, the proposed spatial conflict simulator, embodying an agent-based approach, can effectively simulate the interaction among involved agents. Hence, in addition to interferences between static workspaces, other "indirect" spatial conflicts (e.g., struck-by hazards) can be detected by simulating the physical behavior of objects moving (or dropping down) within corresponding workspaces, eventually retrieving intersections that could fall outside their volumes. In addition, to avoid overestimations, the criticality levels of "indirect" spatial conflicts are considered by running a BN, whose variables' states are automatically fed by the simulation data provided by the serious gaming tool (Section 5.2).

The proposed approach (i.e., "Enhanced" approach) has been tested on a real use case and compared with two benchmarks referring to the most popular 4D BIM tools, namely Autodesk Navisworks (i.e., "Navisworks

Benchmark” approach) and Synchro 4D Pro (i.e., “Synchro Benchmark” approach). The experiments showed that the “Enhanced” approach can detect more spatial conflicts and more accurately by combining geometric computations and physics simulations and filtering those with low criticality levels. In fact, the “Enhanced” approach detected 1 “direct” and 4 “indirect” spatial conflicts. In the same scenario, the “Navisworks Benchmark” approach detected 58 spatial conflicts, of which only 25% were relevant and corresponded to the “direct” conflict detected by the “Enhanced” approach. The “Synchro Benchmark” approach, instead, detected only 1 spatial conflict corresponding to the “direct” one detected by the “Enhanced” approach. This makes the proposed approach relevant for the construction management team in making informed decisions during the refinement process of the work schedule.

Further development of the proposed workspace management framework will focus on the refinement process of the work schedule, given the list of detected spatial conflicts. In this regard, future studies will investigate a system able to support managers in minimizing spatial conflicts, providing them with implications for schedule and cost variations.

Acknowledgments

The research reported in this paper was undertaken during the research stay of the corresponding author at the New York University Abu Dhabi (NYUAD). This research stay was partially funded by the Graduate and Postdoctoral Programs at New York University Abu Dhabi (NYUAD) and the Ph.D. Programs in Civil, Environmental, Building and Architecture at the Polytechnic University of Marche (UNIVPM).

References

[1] A. Mirzaei, F. Nasirzadeh, M. Parchami Jalal, Y. Zamani, 4D-BIM Dynamic Time–Space Conflict Detection and Quantification System for Building Construction Projects, J. Constr. Eng. Manag. 144 (2018) 04018056. https://doi.org/10.1061/(asce)co.1943-7862.0001504.

[2] A. Hosny, M. Nik-Bakht, O. Moselhi, Workspace planning in construction: non-deterministic factors, Autom. Constr. 116 (2020). https://doi.org/10.1016/j.autcon.2020.103222.

[3] H. Ma, H. Zhang, P. Chang, 4D-Based Workspace Conflict Detection in Prefabricated Building Constructions, J. Constr. Eng. Manag. 146 (2020) 04020112. https://doi.org/10.1061/(asce)co.1943-7862.0001883.

[4] X. Su, H. Cai, Life Cycle Approach to Construction Workspace Modeling and Planning, J. Constr. Eng. Manag. 140 (2014) 04014019. https://doi.org/10.1061/(asce)co.1943-7862.0000855.

[5] M. Kassem, N. Dawood, R. Chavada, Construction workspace management within an Industry Foundation Class-Compliant 4D tool, Autom. Constr. 52 (2015) 42–58. https://doi.org/10.1016/j.autcon.2015.02.008.

[6] A. Hosny, M. Nik-Bakht, O. Moselhi, Workspace management on construction jobsites: An industry survey, Proceedings, Annu. Conf. - Can. Soc. Civ. Eng. 2019-June (2019) 1–9.

[7] S.R. Sanders, An Analysis of factors Affecting Labor Productivity in Masonry Construction, (1989).

[8] S. Zhang, J. Teizer, N. Pradhananga, C.M. Eastman, Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning, Autom. Constr. 60 (2015) 74–86. https://doi.org/10.1016/j.autcon.2015.09.009.

[9] Z. Mallasi, Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation, Autom. Constr. 15 (2006) 640–655. https://doi.org/10.1016/j.autcon.2005.08.005.

[10] K.W. Chau, M. Anson, J.P. Zhang, Four-Dimensional Visualization of Construction Scheduling and Site Utilization, J. Constr. Eng. Manag. 130 (2004) 598–606. https://doi.org/10.1061/(asce)0733-

9364(2004)130:4(598).

[11] H.J. Wang, J.P. Zhang, K.W. Chau, M. Anson, 4D dynamic management for construction planning and resource utilization, Autom. Constr. 13 (2004) 575–589. https://doi.org/10.1016/j.autcon.2004.04.003.

[12] N. Dawood, Z. Mallasi, Construction workspace planning: Assignment and analysis utilizing 4D visualization technologies, Comput. Civ. Infrastruct. Eng. 21 (2006) 498–513. https://doi.org/10.1111/j.1467-8667.2006.00454.x.

[13] A. Francis, Chronographical Site-Spatial-Temporal Modeling of Construction Operations, Front. Built Environ. 6 (2020) 1–9. https://doi.org/10.3389/fbuil.2020.00067.

[14] A.M. Bascoul, I.D. Tommelein, D. Douthett, Visual Management of Daily Construction Site Space Use, Front. Built Environ. 6 (2020) 1–13. https://doi.org/10.3389/fbuil.2020.00139.

[15] B. Akinci, M. Fischen, R. Levitt, R. Carlson, Formalization and Automation of Time-Space Conflict Analysis, J. Comput. Civ. Eng. 16 (2002) 124–134. https://doi.org/10.1061/(asce)0887-3801(2002)16:2(124).

[16] V. Getuli, P. Capone, A. Bruttini, S. Isaac, BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach, Autom. Constr. 114 (2020) 103160. https://doi.org/10.1016/j.autcon.2020.103160.

[17] Y.J. Thabet, Walid Y.; Beliveau, Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings, J. Constr. Eng. Manag. 120 (1994) 96–116.

[18] F. Vahdatikhaki, A. Hammad, Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation, Autom. Constr. 58 (2015) 207–220. https://doi.org/10.1016/j.autcon.2015.07.019.

[19] S. Tao, C. Wu, S. Hu, F. Xu, Construction project scheduling under workspace interference, Comput. Civ. Infrastruct. Eng. 35 (2020) 923–946. https://doi.org/10.1111/mice.12547.

[20] W.F. Moroney, B.W. Moroney, Utilizing a microcomputer based flight simulation in teaching human factors in aviation, in: Proc. Hum. Factors Soc., 1991: pp. 523–527. https://doi.org/10.1518/107118191786754806.

[21] D. Zhao, J. Lucas, W. Thabet, Using virtual environments to support electrical safety awareness in construction, Proc. - Winter Simul. Conf. (2009) 2679–2690. https://doi.org/10.1109/WSC.2009.5429258.

[22] O. Golovina, C. Kazanci, J. Teizer, M. König, Using serious games in virtual reality for automated close call and contact collision analysis in construction safety, Proc. 36th Int. Symp. Autom. Robot. Constr. ISARC 2019. (2019) 967–974. https://doi.org/10.22260/isarc2019/0129.

[23] E.L. Jacobsen, N.S. Strange, J. Teizer, Lean Construction in a Serious Game Using a Multiplayer Virtual Reality Environment, Proc. 29th Annu. Conf. Int. Gr. Lean Constr. (2021) 55–64. https://doi.org/10.24928/2021/0160.

[24] E.L. Jacobsen, A. Solberg, O. Golovina, J. Teizer, Active personalized construction safety training using run-time data collection in physical and virtual reality work environments, Constr. Innov. (2021). https://doi.org/10.1108/CI-06-2021-0113.

[25] M. Van Den Berg, T. Hartmann, R. De Graaf, Supporting design reviews with pre-meeting virtual reality environments, J. Inf. Technol. Constr. 22 (2017) 305–321.

[26] Y.C. Lin, Y.P. Chen, H.W. Yien, C.Y. Huang, Y.C. Su, Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital, Adv. Eng. Informatics. 36 (2018) 130–145.

https://doi.org/10.1016/j.aei.2018.03.005.

[27] C. Boton, Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation, Autom. Constr. 96 (2018) 1–15. https://doi.org/10.1016/j.autcon.2018.08.020.

[28] J. Du, Z. Zou, Y. Shi, D. Zhao, Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making, Autom. Constr. 85 (2018) 51–64. https://doi.org/10.1016/j.autcon.2017.10.009.

[29] F. Pour Rahimian, V. Chavdarova, S. Oliver, F. Chamo, OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing, Autom. Constr. 102 (2019) 1–16. https://doi.org/10.1016/j.autcon.2019.02.009.

[30] F. Pour Rahimian, S. Seyedzadeh, S. Oliver, S. Rodriguez, N. Dawood, On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning, Autom. Constr. 110 (2020) 103012. https://doi.org/10.1016/j.autcon.2019.103012.

[31] A. Ezzeddine, B. García de Soto, Connecting teams in modular construction projects using game engine technology, Autom. Constr. 132 (2021) 103887. https://doi.org/10.1016/j.autcon.2021.103887.

[32] W. Yan, C. Culp, R. Graf, Integrating BIM and gaming for real-time interactive architectural visualization, Autom. Constr. 20 (2011) 446–458. https://doi.org/10.1016/j.autcon.2010.11.013.

[33] A. ElNimr, Y. Mohamed, Loosely coupled visualization of industrial construction simulation using a gaming engine, Proc. - Winter Simul. Conf. (2011) 3577–3587. https://doi.org/10.1109/WSC.2011.6148052.

[34] J. Chong, Oscar Wong; Zhang, Game Simulation to Support Construction Automation in Modular Construction Using BIM and Robotics Technology—Stage I, Comput. Civ. Eng. (2019) 105–113. http://toc.proceedings.com/49478webtoc.pdf.

[35] L. Messi, B. Naticchia, A. Carbonari, L. Ridolfi, G.M. Di Giuda, Development of a Digital Twin Model for Real-Time Assessment of Collision Hazards, (2020) 14–19. https://doi.org/10.3311/CCC2020-003.

[36] L. Messi, A. Corneli, M. Vaccarini, A. Carbonari, Development of a Twin Model for Real-time Detection of Fall Hazards, in: Proc. 37th Int. Symp. Autom. Robot. Constr., 2020. https://doi.org/10.22260/isarc2020/0037.

[37] L. Messi, B. García de Soto, A. Carbonari, B. Naticchia, Addressing COVID-19 Spatial Restrictions on Construction Sites Using a BIM-Based Gaming Environment, Proc. 38th Int. Symp. Autom. Robot. Constr. (2021) 521–528. https://doi.org/10.22260/isarc2021/0071.

[38] L. Messi, Development of a BIM-based simulator for workspace management in construction, 2021. http://hdl.handle.net/11566/295537.

[39] L. Messi, B.G. De Soto, A. Carbonari, B. Naticchia, Intelligent BIM-based spatial conflict simulators : A comparison with commercial 4D tools, (2022).

[40] A.A. ElNimr, Y. Mohamed, Application of gaming engines in simulation driven visualization of construction operations, Electron. J. Inf. Technol. Constr. 16 (2011) 23–38.

[41] Y. Kang, Z. Jin, C. Hyun, H. Park, Construction Management Functions for Developing Countries: Case of Cambodia, J. Manag. Eng. 34 (2018) 05018004. https://doi.org/10.1061/(asce)me.1943-5479.0000609.

[42] C.K.H. Hon, C. Sun, B. Xia, N.L. Jimmieson, K.A. Way, P.P.Y. Wu, Applications of Bayesian approaches in construction management research: a systematic review, Eng. Constr. Archit. Manag. (2021).

https://doi.org/10.1108/ECAM-10-2020-0817.

[43] Q. Zhou, D. Fang, X. Wang, A method to identify strategies for the improvement of human safety behavior by considering safety climate and personal experience, Saf. Sci. 46 (2008) 1406–1419. https://doi.org/10.1016/j.ssci.2007.10.005.

[44] A.P.C. Chan, F.K.W. Wong, C.K.H. Hon, T.N.Y. Choi, A bayesian network model for reducing accident rates of electrical and mechanical (E&M) work, Int. J. Environ. Res. Public Health. 15 (2018). https://doi.org/10.3390/ijerph15112496.

[45] Z. Ma, H.Y. Chong, P.C. Liao, Development of a time-variant causal model of human error in construction with dynamic Bayesian network, Eng. Constr. Archit. Manag. 28 (2021) 291–307. https://doi.org/10.1108/ECAM-03-2019-0130.

[46] A. Mofidi, E. Tompa, S.B. Mortazavi, A. Esfahanipour, P.A. Demers, A probabilistic approach for economic evaluation of occupational health and safety interventions: A case study of silica exposure reduction interventions in the construction sector, BMC Public Health. 20 (2020) 1–12. https://doi.org/10.1186/s12889-020-8307-7.

[47] F. Ghasemi, M.H.M. Sari, V. Yousefi, R. Falsafi, J. Tamošaitiene, Project portfolio risk identification and analysis, considering project risk interactions and using Bayesian Networks, Sustain. 10 (2018). https://doi.org/10.3390/su10051609.

[48] I. Mohammadfam, F. Ghasemi, O. Kalatpour, A. Moghimbeigi, Constructing a Bayesian network model for improving safety behavior of employees at workplaces, Appl. Ergon. 58 (2017) 35–47. https://doi.org/10.1016/j.apergo.2016.05.006.

[49] N.D. Nath, A.H. Behzadan, S.G. Paal, Deep learning for site safety: Real-time detection of personal protective equipment, Autom. Constr. 112 (2020) 103085. https://doi.org/10.1016/j.autcon.2020.103085.

[50] X. Luo, W.J. O’Brien, F. Leite, J.A. Goulet, Exploring approaches to improve the performance of autonomous monitoring with imperfect data in location-aware wireless sensor networks, Adv. Eng. Informatics. 28 (2014) 287–296. https://doi.org/10.1016/j.aei.2014.08.004.

[51] L. Zhang, X. Wu, L. Ding, M.J. Skibniewski, Y. Yan, Decision support analysis for safety control in complex project environments based on Bayesian Networks, Expert Syst. Appl. 40 (2013) 4273–4282. https://doi.org/10.1016/j.eswa.2012.11.022.

[52] A. Borg, H. Bjelland, O. Njå, Reflections on Bayesian Network models for road tunnel safety design: A case study from Norway, Tunn. Undergr. Sp. Technol. 43 (2014) 300–314. https://doi.org/10.1016/j.tust.2014.05.004.

[53] F. Abdat, S. Leclercq, X. Cuny, C. Tissot, Extracting recurrent scenarios from narrative texts using a Bayesian network: Application to serious occupational accidents with movement disturbance, Accid. Anal. Prev. 70 (2014) 155–166. https://doi.org/10.1016/j.aap.2014.04.004.

[54] A. Qazi, I. Dikmen, M.T. Birgonul, Prioritization of interdependent uncertainties in projects, Int. J. Manag. Proj. Bus. 13 (2020) 913–935. https://doi.org/10.1108/IJMPB-10-2019-0253.

[55] J.H.M. Tah, V. Carr, A proposal for construction project risk assessment using fuzzy logic, Constr. Manag. Econ. 18 (2000) 491–500. https://doi.org/10.1080/01446190050024905.

[56] L. Wang, X. Zhang, Bayesian Analytics for Estimating Risk Probability in PPP Waste-to-Energy Projects, J. Manag. Eng. 34 (2018) 04018047. https://doi.org/10.1061/(asce)me.1943-5479.0000658.

[57] P. Castaldo, F. Jalayer, B. Palazzo, Probabilistic assessment of groundwater leakage in diaphragm wall joints for deep excavations, Tunn. Undergr. Sp. Technol. 71 (2018) 531–543.

https://doi.org/10.1016/j.tust.2017.10.007.

[58] F. Novi, Bayesian networks as a resilience tool for decision-making processes in uncertainty conditions, Techne. 15 (2018) 341–347. https://doi.org/10.13128/Techne-22100.

[59] O. Špačková, D. Straub, Dynamic Bayesian Network for Probabilistic Modeling of Tunnel Excavation Processes, Comput. Civ. Infrastruct. Eng. 28 (2013) 1–21. https://doi.org/10.1111/j.1467-8667.2012.00759.x.

[60] F. Wang, L.Y. Ding, H.B. Luo, P.E.D. Love, Probabilistic risk assessment of tunneling-induced damage to existing properties, Expert Syst. Appl. 41 (2014) 951–961. https://doi.org/10.1016/j.eswa.2013.06.062.

[61] A. Namazian, S. Haji Yakhchali, Modified Bayesian Network–Based Risk Analysis of Construction Projects: Case Study of South Pars Gas Field Development Projects, ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng. 4 (2018) 05018003. https://doi.org/10.1061/ajrua6.0000997.

[62] A. Qazi, I. Dikmen, From risk matrices to risk networks in construction projects, IEEE Trans. Eng. Manag. 68 (2021) 1449–1460. https://doi.org/10.1109/TEM.2019.2907787.

[63] N. Xia, X. Wang, Y. Wang, Q. Yang, X. Liu, Lifecycle cost risk analysis for infrastructure projects with modified Bayesian networks, J. Eng. Des. Technol. 15 (2017) 79–103. https://doi.org/10.1108/JEDT-05-2015-0033.

[64] I.C. Cárdenas, S.S.H. Al-Jibouri, J.I.M. Halman, W. van de Linde, F. Kaalberg, Using prior risk-related knowledge to support risk management decisions: Lessons learnt from a tunneling project, Risk Anal. 34 (2014) 1923–1943. https://doi.org/10.1111/risa.12213.

[65] H. Zhou, H. Zhang, Risk Assessment Methodology for a Deep Foundation Pit Construction Project in Shanghai, China, J. Constr. Eng. Manag. 137 (2011) 1185–1194. https://doi.org/10.1061/(asce)co.1943-7862.0000391.

[66] G. Kabir, N.B.C. Balek, S. Tesfamariam, Consequence-based framework for buried infrastructure systems: A Bayesian belief network model, Reliab. Eng. Syst. Saf. 180 (2018) 290–301. https://doi.org/10.1016/j.ress.2018.07.037.

[67] Y. Xue, P. Xiang, The social risk of high-speed rail projects in China: A Bayesian network analysis, Sustain. 12 (2020). https://doi.org/10.3390/su12052087.

[68] F.K. Adams, Expert elicitation and Bayesian analysis of construction contract risks: An investigation, Constr. Manag. Econ. 24 (2006) 81–96. https://doi.org/10.1080/01446190500310254.

[69] F.K. Adams, Risk perception and Bayesian analysis of international construction contract risks: The case of payment delays in a developing economy, Int. J. Proj. Manag. 26 (2008) 138–148. https://doi.org/10.1016/j.ijproman.2007.05.007.

[70] K. Karakas, I. Dikmen, M.T. Birgonul, Multiagent System to Simulate Risk-Allocation and Cost-Sharing Processes in Construction Projects, J. Comput. Civ. Eng. 27 (2013) 307–319. https://doi.org/10.1061/(asce)cp.1943-5487.0000218.

[71] Z. Ren, C.J. Anumba, Learning in multi-agent systems: A case study of construction claims negotiation, Adv. Eng. Informatics. 16 (2002) 265–275. https://doi.org/10.1016/S1474-0346(03)00015-6.

[72] Z. Ren, C.J. Anumba, Mascot: A multi-agent system for construction claims negotiation, Agents Multi-Agent Syst. Constr. (2005) 162–185. https://doi.org/10.4324/9780203006979.

[73] W. Lu, L. Zhang, F. Bai, Bilateral learning model in construction claim negotiations, Eng. Constr. Archit. Manag. 23 (2016) 448–463. https://doi.org/10.1108/ECAM-04-2014-0062.

[74] J.S. Chou, Comparison of multilabel classification models to forecast project dispute resolutions, Expert Syst. Appl. 39 (2012) 10202–10211. https://doi.org/10.1016/j.eswa.2012.02.103.

[75] S. Sen Leu, V.H.S. Pham, T.H.N. Pham, Development of recursive decision making model in bilateral construction procurement negotiation, Autom. Constr. 53 (2015) 131–140. https://doi.org/10.1016/j.autcon.2015.03.016.

[76] S.-S. Leu, P.V.H. Son, P.T.H. Nhung, Hybrid Bayesian Fuzzy-Game Model for Improving the Negotiation Effectiveness of Construction Material Procurement, J. Comput. Civ. Eng. 29 (2015) 04014097. https://doi.org/10.1061/(asce)cp.1943-5487.0000434.

[77] S. Sen Leu, P.V. Hong Son, P.T. Hong Nhung, Optimize negotiation price in construction procurement using Bayesian Fuzzy Game Model, KSCE J. Civ. Eng. 19 (2015) 1566–1572. https://doi.org/10.1007/s12205-014-0522-2.

[78] I.S. Abotaleb, I.H. El-adaway, Construction Bidding Markup Estimation Using a Multistage Decision Theory Approach, J. Constr. Eng. Manag. 143 (2017) 04016079. https://doi.org/10.1061/(asce)co.1943-7862.0001204.

[79] X.X. Yuan, Bayesian method for the correlated competitive bidding model, Constr. Manag. Econ. 30 (2012) 477–491. https://doi.org/10.1080/01446193.2012.666802.

[80] W. Jang, J.K. Lee, J. Lee, S.H. Han, Naive Bayesian Classifier for Selecting Good/Bad Projects during the Early Stage of International Construction Bidding Decisions, Math. Probl. Eng. 2015 (2015). https://doi.org/10.1155/2015/830781.

[81] S. Kim, G.-H. Kim, D. Lee, Bayesian Markov Chain Monte Carlo Model for Determining Optimum Tender Price in Multifamily Housing Projects, J. Comput. Civ. Eng. 28 (2014) 06014001. https://doi.org/10.1061/(asce)cp.1943-5487.0000297.

[82] F. ul Hassan, T. Le, Automated Requirements Identification from Construction Contract Documents Using Natural Language Processing, J. Leg. Aff. Disput. Resolut. Eng. Constr. 12 (2020) 04520009. https://doi.org/10.1061/(asce)la.1943-4170.0000379.

[83] C. Sabillon, A. Rashidi, B. Samanta, M.A. Davenport, D. V. Anderson, Audio-Based Bayesian Model for Productivity Estimation of Cyclic Construction Activities, J. Comput. Civ. Eng. 34 (2020) 04019048. https://doi.org/10.1061/(asce)cp.1943-5487.0000863.

[84] B.-C. Kim, K.F. Reinschmidt, Combination of Project Cost Forecasts in Earned Value Management, J. Constr. Eng. Manag. 137 (2011) 958–966. https://doi.org/10.1061/(asce)co.1943-7862.0000352.

[85] Y. Ko, S. Han, Development of construction performance monitoring methodology using the bayesian probabilistic approach, J. Asian Archit. Build. Eng. 14 (2015) 73–80. https://doi.org/10.3130/jaabe.14.73.

[86] T.E. Tischer, J.A. Kuprenas, Bridge Falsework Productivity—Measurement and Influences, J. Constr. Eng. Manag. 129 (2003) 243–250. https://doi.org/10.1061/(asce)0733-9364(2003)129:3(243).

[87] M.Y. Cheng, C.C. Huang, A.F. Van Roy, Predicting project success in construction using an evolutionary gaussian process inference model, J. Civ. Eng. Manag. 19 (2013). https://doi.org/10.3846/13923730.2013.801919.

[88] T.H. Chung, Y. Mohamed, S. Abourizk, Bayesian Updating Application into Simulation in the North, J. Constr. Eng. Manag. (2006) 882–894.

[89] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models, J. Comput. Civ. Eng. 29 (2015) 04014025. https://doi.org/10.1061/(asce)cp.1943-5487.0000205.

[90] B. McCabe, S.M. AbouRizk, Performance measurement indices for simulated construction operations, Can. J. Civ. Eng. 28 (2001) 383–393. https://doi.org/10.1139/cjce-28-3-383.

[91] Wikipedia, Unity (game engine), (2017). https://en.wikipedia.org/wiki/Unity_(game_engine) (accessed November 27, 2021).

[92] RDF Ltd., IFCEngine DLL Library, (2006). http://rdf.bg/product-list/ifc-engine/ (accessed November 27, 2021).

[93] L.D. Nguyen, D.Q. Tran, M.P. Chandrawinata, Predicting Safety Risk of Working at Heights Using Bayesian Networks, J. Constr. Eng. Manag. 142 (2016) 04016041. https://doi.org/10.1061/(asce)co.1943-7862.0001154.

[94] S. Boeykens, Using 3D design software, BIM and game engines for architectural historical reconstruction, Des. Together CAADFutures 2011 - Proc. 14th Int. Conf. Comput. Aided Archit. Des. (2011) 493–509.

[95] J. Chen, Discrete Bayesian Network, (2017). https://assetstore.unity.com/packages/tools/ai/discrete-bayesian-network-61312 (accessed November 27, 2021).

[96] Gordian, RSMeans data: Construction Cost Estimating Software, (n.d.). https://www.rsmeans.com/.

[97] ASSIST Software, Real-Time Weather, (2021). https://assetstore.unity.com/packages/tools/utilities/real-time-weather-169843 (accessed November 28, 2021).

[98] A. Granberg, A* Pathfinding Project Pro, Documentation. (2020). https://arongranberg.com/astar/docs/ (accessed November 27, 2021).

[99] Autodesk, Glossary: Clearance Clash, (n.d.). https://knowledge.autodesk.com/support/navisworks-products/learn-explore/caas/CloudHelp/cloudhelp/2017/ENU/Navisworks-Manage/files/GUID-27EA59E6-1A15-4372-9D7D-90508936B512-htm.html#GUID-27EA59E6-1A15-4372-9D7D-90508936B512--WS1A9193826455F5FF-7F10494411F (accessed November 29, 2021).