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DEVELOPMENT OF A BIM-BASED SIMULATOR FOR WORKSPACE MANAGEMENT IN CONSTRUCTION

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Abstract

In the Architecture, Engineering and Construction (AEC) industry, construction sites can be described as very dynamic operating environments. In this context, activities workspace demand continuously changes across space demanding and time, stressing the need to consider space as a limited and renewable resource.

This issue has not been fully handled yet, neither by traditional scheduling techniques (e.g., Gantt charts) nor by more advanced 4D tools (e.g., Navisworks, Synchro, etc.). For these reasons, construction management teams usually carry out spatial considerations manually with the help of 2D sketches. It is fully agreed that, especially in big construction projects having thousands of activities executed in parallel, this approach not only is highly time-demanding but also error-prone. This is fully demonstrated by statistics about loss, injuries, and productivity slowdown.

To cover these gaps, this study proposes a workspace management framework that integrates the work scheduling phase with spatial analysis, carried out by a spatial conflict simulator developed using a serious game engine. The simulator, given the geometric and semantic information stored in the Building Information Model and the construction process data included in the work schedule, can detect eventual spatial interferences based on geometric computations and physics simulations. The detected conflicts are then judged by means of expert knowledge, formalized in Bayesian networks, to find out non-critical scenarios and avoid conflicts overestimation. Afterwards, the construction management team, made aware about likely future spatial conflicts, can adjust, or if none confirm, the work schedule.

This approach can provide a valuable contribution in detecting spatial conflicts both during the construction planning phase and the works execution one.

In this study, the proposed spatial conflict simulator has been validated by applying it to the construction planning phase of a real use case. The results, that come from this application, has confirmed the contribution expected from the proposed approach. The proposed spatial conflict simulator has demonstrated its capability not only to detect an

increased number of spatial issues (due to a combination of geometric computations and physics simulations) but also to esteem related criticality levels (thanks to Bayesian inference) to avoid overestimations. In addition, the contribution given by the integration of Bayesian networks in the spatial conflict simulator has been demonstrated as crucial for workflow automation.

However, the proposed workspace management framework, embodying the Last Planner System (LPS) principles, can be applied for proactively refining the work schedule during works execution. To this purpose, minor changes should be made in the proposed spatial conflict simulator to be applied at runtime for managing workspace interferences included in the work schedule. In this case, the proposed tool, according to the LPS framework, can be used to simulate activities scheduled in the short-term ahead and carrying out a continuous refinement process.

To my loved ones

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Acronyms

AEC	Architecture, Engineering and Construction
BIM	Building Information Modeling
DSS	Decision Support System
LPS	Last Planner System
ENR	Engineering News Record
CSLP	Construction Site Layout Problem
LBS	Location Breakdown Structure
H&S	Health and Safety
DEW	Dynamic Equipment Workspace
LAEW	Look-Ahead Equipment Workspace
IFC	Industry Foundation Classes
XML	Extensible Markup Language
WBS	Work Breakdown Structure
GUI	Graphical User Interface
CSV	Comma-Separated Values
ASI	Acceptable Spatial Interferences
USI	Unacceptable Spatial Interferences
ES	Entity Spaces
WS	Working Spaces
CR	Conflict Ratio
SCF	Space Capacity Factor
SC	Severity of Conflict
SWC	Severity of Workspace Conflict
CgS	Congestion Severity
WCL	Workspace Criticality Level

RSD	Required Space Decrease
LPR	Labor Productivity Reduction
SCF	Space Capacity Factor
VBA	Visual Basic for Applications
VM	Visualization Management
VR	Virtual Reality
RFID	Radio Frequency Identification
GPS	Global Positioning Systems
AI	Artificial Intelligence
CAD	Computer-Aided Design
FM	Facility Management
DXF	Drawing eXchange Format
IGES	Initial Graphics Exchange Specification
ISO	International Organization for Standardization
STEP	Standard for the Exchange of Product Model Data
SQL	Structured Query Language
CIS/2	CIMsteel Integration Standard Version 2
NBIMS	National BIM Standards
3D PDF	Three-Dimensional Portable Document Format
DWF	Design Web Format
ODBC	Open Database Connectivity
GDL	Geometric Description Language
MDL	MicroStation Development Libraries
SAT	Standard ACIS Text
STL	Standard Triangle Language
3DS	Three-Dimensional Studio
HTML	Hypertext Markup Language

GIS	Geographical Information System
HVAC	Heating Ventilation and Air Conditioning
TPS	Toyota Production System
JIT	Just-in-Time
PDCA	Plan-Do-Check-Act
LCI	Lean Construction Institute
PPC	Percent Plan Complete
FBX	FilBoX
HMD	Head Mounted Display
MMOG	Massively Multiplayer Online Game
BN	Bayesian Network
CPT	Conditional Probability Table
ERD	Entity Relationship Diagram

CHAPTER 1

1. Introduction

1.1. Motivation

In the AEC industry, construction sites, which usually involve large numbers of workers, equipment, adjacent buildings and facilities, and complex weather phenomena, are very dynamic operating environments. As a consequence, safety and constructability issues are most of the times contextual, that is to say they depend on complex geometries, spatial-temporal dependencies, and ever-changing site conditions.

In such dynamic environment, each activity requires a specific workspace to be executed (Mirzaei *et al.*, 2018). A workspace is defined as the suitable occupational volume a crew and/or equipment occupy during the execution of a certain activity on a predefined geometrical element (Hosny, Nik-Bakht and Moselhi, 2020). As the construction progresses, the space occupied by completed activities will be released and reused by other operations (Ma, Zhang and Chang, 2020). As a consequence, the space required by construction activities, i.e., the geometry and the location of workspaces, continuously change over time (Su and Cai, 2014), leading to a sequence of workspaces that are associated with the project's activities (Kassem, Dawood and Chavada, 2015). When the same workspace is occupied simultaneously by two or more activities, a spatial interference occurs, leading to significant problems such as labor safety hazards, construction delay, and loss in productivity. Effects of spatial interferences have been measured qualitatively and quantitatively. On the basis of a questionnaire performed by (Abdul Kadir *et al.*, 2005) to 70 contractors, 11 developers, and 19 consultants, all in residential projects, site congestion has been ranked as the 24th among 50 reasons behind project delays. In (Winch and North, 2006), when the workspace requirement has been cut into one third of the originally planned, a 40% loss of productivity in nuclear power station sites has been estimated. The authors, in (Sanders, 1989), has reported that congested workspaces and restricted access cause efficiency losses of up to 65% in masonry works. In (Riley and Sanvido, 1997), 71 cases of spatial conflicts have been observed between only four trades at a job site during a two-month study period. Another study (Kaming *et al.*, 1998) has reported the loss of productivity up to 40% resulting from worker interference in the electrical work performed for residential construction. In (Akinci, Fischer and Kunz, 2002), the authors have proved through a motivating case of a building construction, consisting of three stories and a penthouse on the roof, a delay of 20%; noting that the case focuses on five activities on one section of the building and the target duration for executing all five activities is 11 days. The study by (Dawood and Mallasi, 2006) has indicated a 30% average non-productive result, due to improper workspace planning by a case study on a construction site at the University of Teesside. In addition to the productivity impacts, a study conducted in the US private industry sector has concluded the death of 323 workers due to poor workspace planning, over a period of 12 years (Zhang *et al.*, 2015). The Engineering News Record (ENR) published a study in 2012 indicating that 46,7% of 700 reported accidents were attributed to workspace poor planning. A survey conducted by the Occupational Safety and Health Branch of the Labor Department of Hong Kong has demonstrated that 79% of the fatalities that occurred in the construction industry during 2011 were related to workspace interferences (Tao *et al.*, 2020). (Azmin *et al.*, 2013) has identified 83 different factors, as the cause of workspace conflicts in projects, categorized under for groups: management issues, jobsite planning, resource and logistic, project features, and external environment. The factors extend from owner related, such as work disruption due to change orders, to contractor related, such as the preparation of the time schedule by inexperienced planners who do not factor in space requirements during the planning of activities. Finally, in (Kaming *et al.*, 1998), a structured questionnaire survey has ranked “worker interference” and “overcrowding”, respectively as the first and eighth among the factors that cause delays.

The dynamic nature of construction activities makes the management of workspaces challenging using conventional planning methods, especially when it relates to micro-scheduling of short duration activities requiring the use of heavy construction equipment. The authors, in (Mallasi, 2006), have asserted that conventional planning methods do not adequately represent and communicate the interference between construction activities and do not consider space constraints in the planning process. They typically focus just on the time and cost aspect (Chau, Anson and Zhang, 2004; Wang *et al.*, 2004; Dawood and Mallasi, 2006; Mallasi, 2006). 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 (Ma, Zhang and Chang, 2020). Similarly, traditional safety planning relies on manual observation, which is labor-intensive, time-consuming, and potentially highly inefficient (Zhang *et al.*, 2015). The resulting safety plans are often error-prone due to subjective judgments of the available decision makers.

The occurrence of spatial interferences in construction sites is mainly due to the fact that workspace planning is usually carried out based on the planners' intuition rather than a formalized process (Akinci, Fischer and Kunz, 2002; Sadeghpour, Moselhi and Alkass, 2006), making it challenging to design workspaces for short-duration activities, especially for large and complex projects (Wang *et al.*, 2004; Hammad *et al.*, 2007; Said and El-Rayes, 2013). The fact that, as of now, workspace planning is being performed through judgment or at most by the aid of 2D sketches (Hosny, Nik-Bakht and Moselhi, 2020), can be explained by the fact that commercial 4D visual planning tools (e.g., Autodesk Navisworks, Synchro, etc.) lack effective workspace management capabilities (Kassem, Dawood and Chavada, 2015). In fact, most of the current 4D models only contain the building components linked with activities, and do not contain any representation of the other resources (e.g., equipment, labor, etc.). One of the significant issues in traditional project management tools is that they do not convey the workspace occupied as the project progresses as well as space availability and needs (Mallasi, 2009). Numerous studies related to construction workspace have been performed, particularly in site planning, construction scheduling, workspace interference and conflict detection. What has emerged is that incorporating workspace consideration from the spatial-temporal perspective in construction and safety planning plays a pivotal role. As primarily suggested by (Hosny, Nik-Bakht and Moselhi, 2019), the space in the construction site must be considered as a limited but renewable resource, similarly to workers, equipment, and materials (Ma, Zhang and Chang, 2020).

1.2. Goals and overview

As emerged in the previous Section 1.1, construction workspaces are a limited but renewable resource whose usage changes across space demanding and time. In addition, work-related spatial information is both contextual and ever-changing. In this dynamic scenario, spatial-temporal conflicts can be of various type according to the spaces conflicting and the severity of the effects (Akinci *et al.*, 2002). Finally, multiple types of spaces, required by an activity, may conflict with multiple types of spaces required by another activity. Therefore, multiple types of conflicts may exist between the same pair of conflicting activities.

The ever-changing scenario, described above, can be hardly managed by traditional scheduling techniques nor by 4D construction management tools currently available on the market. So, a shift into a construction scheduling approach that considers spaces as a limited and renewable resource is hugely needed. In addition, managing the high variability of workspaces and likely interferences requires high-speed computational capabilities that only advanced tools can provide.

This study proposes a workspace management framework, integrated with the work schedule refinement process, that aims to detect spatial conflicts between activities sharing the same workspace. A spatial conflict simulator has been developed by using the serious game engine technology. Given geometric and semantic information of the Building Information Model and work schedule data as inputs, the proposed tool can detect eventual spatial interferences (i.e., both “direct” and “indirect” or “possible” ones) by combining geometric computation and physics simulations. The results of the geometric intersection tests can be judged on the basis of the expert knowledge, formalized in Bayesian networks, in order to avoid conflicts overestimation by excluding non-critical scenarios. In other words, the construction management team, made aware about likely future spatial conflicts and their criticality levels, can take informed decisions during the work schedule refinement process.

This approach can provide a valuable contribution in detecting spatial conflicts both before the construction process has started and during works execution. In the first case, the proposed framework and tool can be applied to detect spatial interferences during the construction planning phase. The testbed, showcased in this study for validating the proposed spatial conflict simulator, refers to this first application case.

In the second case, instead, the proposed workspace management framework, embodying LPS principles, can be applied for proactively refining the work schedule during works execution. The proposed spatial conflict simulator can be easily adapted to this second application case to be used at runtime for managing the construction process. In this case, the tool, according to the LPS framework, can be used to simulate the work schedule in the short-term ahead and carry out a continuous refinement process.

The resulting DSS, based on the proposed spatial conflict simulator integrating Bayesian inference capabilities, paves the way to the future development of a digital twin that can access the full data of the construction site, grasp the holistic context, and return valuable insights. The added value that comes from digital twins is not just the abundance of dynamic data it would manage, but its semantics and constant accrual of knowledge about the physical world. In future research, the BIM shell will be enriched with real-time sensor data ensuring reliability of the look-ahead simulation results.

CHAPTER 2

2. Scientific background

2.1. Construction workspace planning

Ensuring that construction sites are safe and productive is vital for the success of any construction project (Igwe, Nasiri and Hammad, 2020). To this purpose, the two main aspects in construction space planning should be considered. The first one is the Construction Site Layout Problem (CSLP) that deals with the location and size of temporary facilities, whereas the second one is the space scheduling problem that focuses on the workspace for activity execution. The space scheduling problem, as compared to CSLP, presents a different challenge as it focuses on ensuring the availability of activity execution workspaces. Workspaces are one of the critical resources required for the successful management of a project. They accommodate and constrain activities as they form and evolve spatiotemporally, as the project evolves (Luo *et al.*, 2019). Workspace planning aims to align project resources (i.e., personnel and equipment) with available space to ensure that construction activities are carried out safely and productively. Several studies try to structure this process identifying some key steps.

The authors, in (Kassem, Dawood and Chavada, 2015; Ma, Zhang and Chang, 2020), describe the workspace management process referring to three main phases. 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. In literature, mathematical algorithms (i.e., resolving conflicts using methods such as linear programming and integer programming), artificial intelligence methods (i.e., resolving conflicts using intelligent methods such as evolutionary and genetic algorithms), and rule-based heuristic strategies enabled by databases are recognized as possible resolution approaches.

A slightly wider description is provided in (Hosny, Nik-Bakht and Moselhi, 2019). Here, the authors have stated that the workspace management problem can be broken down into three phases (Figure 1). The first one is the so-called “pre-collision” phase, which entails selecting inputs, taking assumptions that govern the resources’ (i.e., crew, labor, and equipment) position and movements throughout the project duration, and simulating the workspaces. In this phase, the “plan” stage deals with creating the nD model. The use of nD modelling is preferred over a 3D model disconnected from the schedule, because an element of the 3D model usually has multiple activities assigned throughout the project duration, hence can be associated with various workspaces at different stages of construction. This stage presents input parameters and assumptions used by current models, which can be categorized into three categories, that are spatial, temporal, and behavioral. Afterwards, in the “simulate” stage, workspaces are decomposed into smaller parts according to inputs of the previous stage, with each part having a defined scope. The second one is the “collisions” phase or “detect” stage, which scans the project timeline to capture temporal overlaps happening between workspaces. The output of the simulate stage is a spatial-temporal layout of workspaces throughout the project duration. Finally, the “post-collision” phase evaluates the intensity of the collisions and accordingly determines the resolution strategy. The output of “detect” stage is the collision information including size and duration of collisions and the number of resources involved in each incident. These outputs must be then translated to a significance measure for the collisions. Collision impact assessment techniques, developed in the literature to evaluate the magnitude of the collisions, can be categorized into three major levels, that are site, workspaces, and activities. The output of the “assess” step sets priorities for the resolution of collisions. Optimization techniques, such as genetic algorithm or heuristic methods, have been used to automate the resolution of detected collisions.

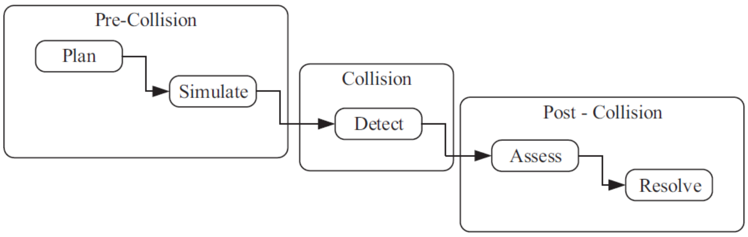


Figure 1. Workspace management process from (Hosny, Nik-Bakht and Moselhi, 2019).

Similarly to the previous study, in (Tao *et al.*, 2020), the workspace planning process is described by means of the following five steps: 4D BIM generation, workspace requirement identification, workspace occupation representation, workspace problem identification, and workspace problem resolution. Here, in addition, the authors identify two main strategies for the workspace management process, namely reactive and proactive. The reactive approach consists in adjusting the construction plan after workspace interferences being detected through real occurrence or computer simulation. The premise of reactive strategy implementation requires a baseline schedule. The proactive approach, rather than just responding to alarming scenarios, aims to anticipate them. However, the authors, in (Tao *et al.*, 2020), state that the results on this topic are rather sparse. In fact, the issue of proactively scheduling construction activities optimization with different types of workspace interference, as introduced by (Akinci *et al.*, 2002) has not been studied yet.

2.2. Taxonomies and metrics of spatial interferences

In construction projects, each activity requires a specific workspace to be executed (Mirzaei *et al.*, 2018), which, in order to avoid time-space conflicts, should be considered as a limited resource. A time-space conflict is a situation in which a workspace is shared by two or more concurrent activities. In addition, the compression of the project schedule, due to pressure for completion on time, increases the probability and the severity of time-space conflicts (Mirzaei *et al.*, 2018).

In this study, a detailed analysis of the state of the art has been carried out to find out the latest contributions provided by previous research. Table 1 provides an overview of workspaces' classifications, conflicts taxonomies, and metrics available in literature. It must be noted that, in the workspaces row, same colors highlight similar workspace functions identified by the studies. The research studies (Thabet, Walid Y.; Beliveau, 1994; Akinci *et al.*, 2002; Dawood and Mallasi, 2006; Kassem, Dawood and Chavada, 2015; Mirzaei *et al.*, 2018) mainly focus on construction management, whereas (Zhang *et al.*, 2015; Getuli *et al.*, 2020; Ma, Zhang and Chang, 2020) on safety management.

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

	Research studies							
	Mirzaei et al., 2018 [1]	Thabet et al., 1994 [27]	Akinci et al., 2002 [24]	Dawood et al., 2006 [12]	Kassem et al., 2015 [5]	Zhang et al., 2015 [28]	Ma et al., 2020 [3]	Getuli et al., 2020 [29]
Workspaces	Labor crew workspace	*Space-based*	Building component space (BCS)	Product space	Main workspaces	Building component space (BCS)	Entity space (ES)	Workers' space
	Equipment space	Work blocks (Zone + Layer)	Labor crew space (LCS)	Workspace	Support workspaces	Worker space	Safey working space (SWS)	Hazard space
	Hazard space	*Activity-based*	Equipment space (ES)	Process space	Object workspaces	Space for material handling path	Efficient working space (EWS)	Equipment space
	Product space	Manpower {Physical Surrounding spaces}	Hazard space (HS)	Equipment space	Safety workspaces	Equipment space/temporary structure space		Safety space
	Temporary structure space	Equipment {Physical Surrounding spaces}	Protected space (PS)	Equipment path		Protective space		
	Material storage space	Material {Physical Surrounding spaces}	Temporary structure space (TSS)	Storage space				
				Path space				
				Protected space				
				Support space				
Conflicts	Labor congestion (RSD<50%)	Can share workspace (Class B)	Design conflict (BCS-BCS)	Design conflict	Temporal/Schedule conflict	Design clashes	ES-ES (h=100)	
	Constructability issue (RSD>50%)	Cannot share workspace (Class A, C)	Safety hazard (HS-LCS)	Safety hazard	Spatial/Physical/Workspace conflict	Congestion	ES-SWS (h=50)	
			Damage conflict (PS-LCS/ES/HS)	Congestion	Workspace congestion	Safety hazard	SWS-SWS (h=20)	
			Congestion (LCS/ES-LCS/ES/TSS)	Access blockage			ES-SWS (h=10)	
				Damage			SWS-EWS (h=5)	
				Space obstruction			EWS-EWS (h=1)	
				Work interruption				
Metrics	Required space decrease (RSD_i)	Space capacity factor (SCF_i)	Conflict ratio (CR_i)	Conflict ratio modified (CR')	Severity of conflict (SC_i)	Conflict ratio (CR_i)	Severity of spatiotemporal conflict (I_{ij})	
					Severity of workspace conflict (SWC_i)	Space capacity factor (SCF_i)		
					Congestion severity (CgS_i)			
					Workspace criticality level (WCL_i)			

2.2.1. Workspace definition and allocation

Generally, a preliminary discretization of the construction site leads to the definition of workspaces. In (Bascoul, Tommelein and Douthett, 2020; Francis, 2020), the authors manage project's physical size and complexity applying a context-based Location Breakdown Structure (LBS); hence, 2D working areas are defined irrespective to the to the type of activities to be performed. According to (Francis, 2020), an LBS should include the following five levels of detail: project, buildings or sections, floors, stage of implementation, and zones. In (Bascoul, Tommelein and Douthett, 2020), the authors divide the floor into same-size areas (zone-LBS) or considering the position of seismic joints (area-LBS). As emerged in (Bascoul, Tommelein and Douthett, 2020), if the adopted LBS does not fit the case study environment (e.g., large open space lacking demarcating zones) or the type of renovation activities, the tool's effectiveness in managing allocated spaces is severely affected. These limitations have been overcome in other works, such as (Akinci *et al.*, 2002; Dawood and Mallasi, 2006; Kassem, Dawood and Chavada, 2015), where an activity-based classification of 3D workspaces has been proposed; this means allocating adjacent volumes, to the building element under construction, for specific functions. To make an example, the micro-level discretization, defined in (Akinci *et al.*, 2002), 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 authors, in (Dawood and Mallasi, 2006), have introduced the concepts of macro-level (e.g., storage areas) and paths (e.g., equipment's and crews' paths) discretization to be addressed in future. Similarly to (Akinci *et al.*, 2002), an activity-based classification focused on Health and Safety (H&S) management is defined in (Getuli *et al.*, 2020) (Table 1). The approach presented in (Akinci *et al.*, 2002) has been absorbed by (Dawood and Mallasi, 2006), where a unique classification for the three discretization categories has been proposed (Table 1). A macro- and micro-level discretization has been presented in (Mirzaei *et al.*, 2018), where the labor crew workspaces have been differentiated into static and dynamic ones. In the first case, the entire workspace is required throughout the activity duration; in the second one, on the contrary, the labor crew occupies a specific portion of the space during each time interval. To simulate labor movement through the subspaces, four execution patterns have been defined. In (Zhang *et al.*, 2015), a micro-level discretization plus the space for material handling path have been defined (Table 1). In the research presented in (Ma, Zhang and Chang, 2020), the workspaces defined by the above-mentioned studies have been grouped in two main categories: entity and working spaces (Table 1). The first one includes the space occupied by laborers, mechanical equipment, and building components, whereas the second one corresponds to the spaces required to ensure smooth operation and tasks. In (Thabet, Walid Y.; Beliveau, 1994), the authors have differentiated an activity-based and a space-based workspace definition, applied respectively to quantify workspace demand and availability (Table 1). In the activity-based workspace definition, the authors have included some of the space categories seen in previous works, such as manpower, equipment, and material spaces. In the space-based workspace definition, the concept of work block, as 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 period of time), is proposed. In (Vahdatikhaki and Hammad, 2015), the authors have proposed a novel method for look-ahead equipment workspace during earthworks. To 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 find a collision-free path for equipment). This method enables different pieces of equipment to ensure that their initially planned paths are collision-free, or alternatively adjust their path planning to avoid potential collisions.

The workspaces' classification adopted in (Kassem, Dawood and Chavada, 2015) has been inherited from the manufacturing industry; here, 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 factual value to the project; on the contrary, transferring materials requires a “support workspace”, being a preparatory activity supporting the first one.

In (Akinci *et al.*, 2002), workspaces have been represented as user input rectangular prisms, whereas, in (Kassem, Dawood and Chavada, 2015; Getuli *et al.*, 2020; Hosny, Nik-Bakht and Moselhi, 2020; Ma, Zhang and Chang, 2020) as user-inputted bounding boxes. Neither one of the above-mentioned studies has provided reliable spatial information, since their workspace input are either estimated based on the authors' background or experience, or it requires a user to determine their own input values. A methodological shift has been provided in (Zhang *et al.*, 2015). In fact, the authors have applied an occupancy model to define distance offsets from the building object under construction; in this way, they have deduced the workspace on the basis of historical workforce location data densities.

Once the workspaces have been defined, they must be associated to specific time slots, in which each correspondent activity has been scheduled. In other words, the 3D model is extended towards the fourth dimension, i.e., the time. The authors, in (Akinci *et al.*, 2002), have presented a 4D WorkPlanner Space Generator which automatically generates the different types of spaces, required by construction activities. As a result, a 4D-CAD model, called “space-loaded production model”, has been defined. In (Dawood and Mallasi, 2006), a 4D-CAD prototype has been developed integrating the adopted project management software, namely Microsoft Project, and the computer-aided design one, that is AutoCAD. In (Kassem, Dawood and Chavada, 2015), the authors have conceptualized the integration of an IFC-based 3D model and the project schedule, saved in the Extensible Markup Language (XML) format. It is worth mentioning that the tool developed in (Kassem, Dawood and Chavada, 2015) gives the possibility to allocate workspaces to activities in several types of relationships (i.e., 1 to 1, 1 to n, and n to n), representing a step forward than existing research, where workspaces were allocated in 1 to 1 relationship. This is possible by linking the work schedule, provided by the planning software (e.g., Microsoft Project), and the 3D model in the gaming environment. In (Mirzaei *et al.*, 2018), a 4D-BIM model has been generated by linking the activities’ WBS code to their corresponding elements’ name, within the product 3D model. This task has been enabled by a Graphical User Interface (GUI) where the user can also define the crew's motion pattern in each workspace. A similar GUI, presented in (Hosny, Nik-Bakht and Moselhi, 2020), has enabled the user linking building elements, loaded from the IFC model, and the activity's name, included in the project schedule, saved in the Comma-Separated Values (CSV) format. In (Zhang *et al.*, 2015), workspaces have been allocated to each building element involved in construction activities directly in BIM. In addition, the authors have extended safety ontologies from literature, also including workspace information. Finally, the authors, in (Ma, Zhang and Chang, 2020), have used Navisworks SDK (i.e., an API toolkit from Autodesk) to integrate the workspaces with the Building Information Model and the schedule.

However, the manual allocation of tasks to workspaces proposed in the previous works (Su and Cai, 2014; Kassem, Dawood and Chavada, 2015; Zhang *et al.*, 2015; Mirzaei *et al.*, 2018; Hosny, Nik-Bakht and Moselhi, 2020), as confirmed also by the planning experts, is time consuming especially for large projects. In order to automatize the linking process for the automatic definition of a 4D model, further investigations must be executed; the aim is identifying an ontology that defines the link between the geometrical model's 3D objects and the tasks defined by the schedule. Similarly, enriching the detection of spatial interferences with semantics, provided by a specific domain ontology, the severity of the conflicts can be assessed more realistically. To make an example, a piece of equipment temporary obstructing a crew's path may represent a weak interference; on the contrary, if the same equipment that obstructs a path is broken, it may cause a more severe spatial issue, which requires an urgent action by the supervisor in order to be resolved.

2.2.2. Time-space conflicts detection

Running 4D simulations of the project activities, eventual interferences included within the project schedule can be detected and visualized. It must be noted that time-space conflicts may occur only between simultaneous activities. Therefore, the detection of time-space conflicts needs to identify clashes not only within 3D geometric space, but also across time (Akinci *et al.*, 2002). As reported in (Hosny, Nik-Bakht and Moselhi, 2020), the areas with higher potentials for collision can be identified by screening the schedule and spotting periods with most simultaneous activities in the same location. Some models use this technique at the beginning of the collision detection process, to minimize the spatial detection and thus the computational efforts. The authors, in (Kassem, Dawood and Chavada, 2015), have described the temporal overlap between tasks, namely the temporal/schedule conflict, as a preliminary condition that needs to be checked prior to spatial conflicts. In addition to the temporal detection, in (Hosny, Nik-Bakht and Moselhi, 2020), the authors have reported other approaches available in literature for detecting spatial issues. For example, the approximation detection compares the length of line connecting center-points for every pair of adjacent workspaces against the combined lengths of workspaces' radii (Hosny, Nik-Bakht and Moselhi, 2020). In the topographical detection, each workspace is assigned a spatial matrix and the entry-wise product of matrices would mark the collisions (Hosny, Nik-Bakht and Moselhi, 2020). Finally, geometrical intersection tests check each workspace against all other ones (pairwise comparison) for detecting eventual overlaps (Kassem, Dawood and Chavada, 2015; Hosny, Nik-Bakht and Moselhi, 2020).

Recently, many studies have tried to classify spatial interferences between tasks which share the same workspace. In (Akinci *et al.*, 2002), the authors have formalized one of the first time-space conflict taxonomy in construction differentiating design conflicts, safety hazards, damage conflicts, and congestions (Table 1). The first category occurs when a building component's geometry conflicts with another building component's one. Since existing commercially available applications (e.g., clash detection and coordination) already solve this issue (Zhang *et al.*, 2015), design clashes are outside the scope of this research. According to (Akinci *et al.*, 2002), 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, an equipment, or a hazard space may cause damage conflicts. The mutual sharing of space between labor crews, equipment and temporary structures identifies a, more or less severe, congestion (Akinci *et al.*, 2002; Kassem, Dawood and Chavada, 2015). In (Thabet, Walid Y.; Beliveau, 1994), instead, the authors have differentiated the activities that can share the workspace and those ones that cannot share it in order to define a work schedule. The taxonomy presented in (Akinci *et al.*, 2002) has been adopted by the authors in (Dawood and Mallasi, 2006; Zhang *et al.*, 2015) (Table 1) and extended, in (Dawood and Mallasi, 2006), with path-related conflicts (e.g., access blockage and space obstruction). In (Mirzaei *et al.*, 2018), the authors have considered two types of spatial interferences, namely labor congestion and constructability issue (Table 1), corresponding respectively to Acceptable (ASI) and Unacceptable Spatial Interferences (USI), introduced in (Tao *et al.*, 2020). Finally, in (Ma, Zhang and Chang, 2020), a time-space conflict taxonomy, including the three available combination between the Entity Spaces (ES) and Working Spaces (WS), has been presented (Table 1). The overlapping of two different entity spaces (ES-ES) causes a breakage in the building element, similarly to the design conflict seen in (Akinci *et al.*, 2002). When 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, discussed by the authors in (Akinci *et al.*, 2002; Hosny, Nik-Bakht and Moselhi, 2020).

2.2.3. Conflict's severity assessment

At this point, the activities' conflicting status must be evaluated adopting metrics that concisely describe the severity of conflicts and their overall trend. To this purpose, several types of metrics for evaluating the magnitude of the collisions are available in literature.

The system developed in (Akinci *et al.*, 2002) calculates a Conflict Ratio (CR) (Equation 1), for each type of space required by the conflicting activities, dividing the total conflicting volume (Equation 2) by the total required volume (Equation 3, Equation 2, and Figure 2). This parameter is used to define three level of congestion, respectively mild, medium, and severe, corresponding respectively to a CR lower than 30%, comprised between 30% and 60%, and greater than 60%. Comparing the lower CR value between two conflicting activities, the level of congestion is determined. It must be noted that the thresholds have been assigned roughly by the authors on the basis of their experiences and interviews with different subcontractors. In addition, no guidance to define the space required by an activity is provided by the authors. In the same study (Akinci *et al.*, 2002), the authors have provided a priority ranking for assessing, in case of multiple conflicts between a pair of activities, which one must be addressed first.

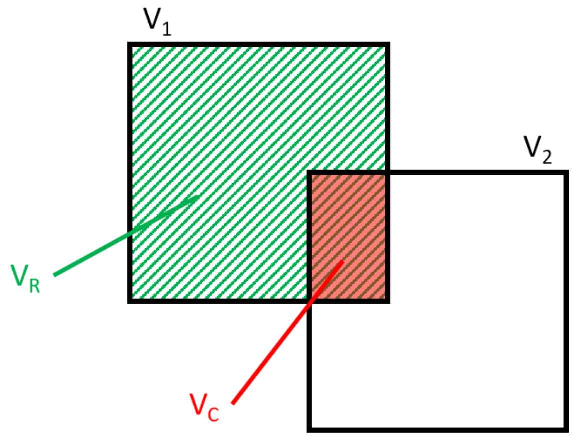


Figure 2. Representation of the total conflicting volume (Vc) and the total required volume (VR), whose ratio defines the Conflict Ratio (CR) (Akinci *et al.*, 2002).

Equation 1. Conflict Ratio (CR).

$$Conflict\ Ratio, CR = \frac{V_C}{V_R}$$

Equation 2. Total conflicting volume (VC).

$$V_C = V_1 \cap V_2$$

Equation 3. Total required volume (V_R).

$$V_R = V_1$$

In (Thabet, Walid Y.; Beliveau, 1994), the authors have defined the Space Capacity Factor (SCF) (Equation 4), as the ratio between the space demand required by the activity (Equation 5) and the current available space of the work block (Figure 3, Equation 6), and correlated it with the productivity rate. The authors have specified that actual SCF-productivity curves need to be developed for different activities or group of activities to reflect the actual variation of crew productivity under various limited space conditions. Such curves may be constructed based on site observations and empirical equations.

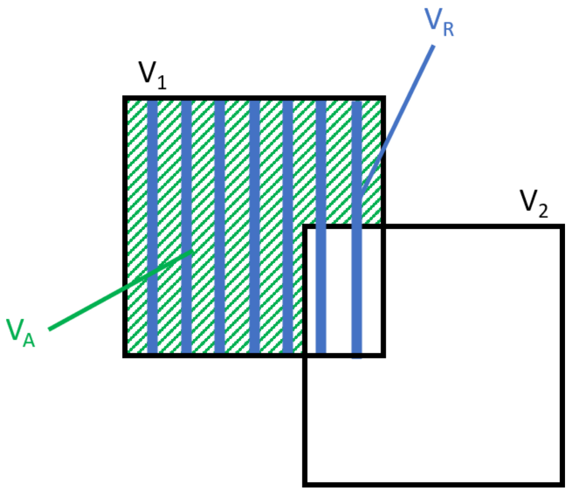


Figure 3. Representation of the space demand required by the activity (V_R) and the current available space of the work block (V_A), whose ratio defines the Space Capacity Factor (SCF) (Thabet, Walid Y.; Beliveau, 1994).

Equation 4. Space Capacity Factor (SCF).

$$Space\ Capacity\ Factor, SCF = \frac{V_A}{V_R}$$

Equation 5. Space demand required by the activity (V_R).

$$V_R = V$$

Equation 6. Current available space of the work block (V_A).

$$V_A = V_1 - (V_1 \cap V_2)$$

The Space Criticality (Equation 7), defined in (Dawood and Mallasi, 2006), is estimated, given two activities, as the ratio between the total volume of the required spaces for both of them (Equation 8) and the total volume of the available execution spaces (Figure 4, Equation 9). For example, if two activities occupy the same execution space, equals to 1 cubic-meter, but the overall available space is only 1 cubic-meter, then, the space criticality value will be 2. The authors have asserted that anything above 1 will be more than critical and 1 will be critical, that is, what is needed is available but without any tolerance; anything below 1 will be noncritical. As observed before, neither these thresholds nor the definition of the space required by an activity are supported by any practical demonstration.

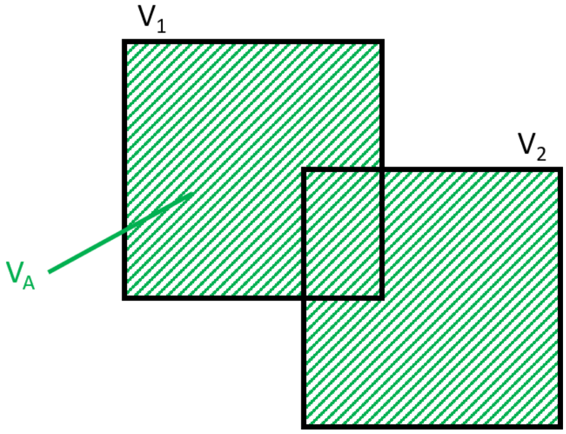


Figure 4. Representation of the total volume of the available execution spaces for the considered activities (V_A), used for calculating the Space Criticality (Dawood and Mallasi, 2006)*.*

Equation 7. Space Criticality.

$$Space\ Criticality = \frac{V_{RT}}{V_A}$$

Equation 8. Total volume of the required spaces for both the considered activities (V_{RT}).

$$V_{RT} = V_1 + V_2$$

Equation 9. Total volume of the available execution spaces for the considered activities (V_A).

$$V_A = V_1 \cup V_2$$

The metrics, applied in (Kassem, Dawood and Chavada, 2015), include four parameters: Severity of Conflict (SC) (Equation 10), Severity of Workspace Conflict (SWC) (Equation 11), Congestion Severity (CgS) (Equation 12) and Workspace Criticality Level (WCL) (Equation 13). SC, calculated as the ratio between the conflicted duration and the current activity duration, is a measure of the simultaneity between two activities; hence, this parameter does not necessarily refer to an effective spatial interference. On the contrary, SWC, defined as the ratio between the volume of the workspace involved in the conflict and the total volume of the workspace available for that activity, depicts the result of an intersection test between the bounding boxes related to two activities (Figure 5). Finally, CgS is the ratio between the volume required for the activity resources and the available one (i.e., the inverse of the SCF defined in (Thabet, Walid Y.; Beliveau, 1994)) (Figure 5). The authors, in (Kassem, Dawood and Chavada, 2015), have identified three default thresholds to define the congestion levels according to the computed CgS value (i.e., low: 1–33%; medium: 34–66%, and high: greater than 66%), specifying that they do not indicate risk severity in H&S terms. Finally, WCL, given by the sum of SWC and CgS, summarizes the spatial criticalities related to a given activity; in this case too, no practical demonstration supports the defined thresholds (non-critical: WCL lower than 100%; critical: WCL equal to 100%; highly critical: WCL greater than 100%).

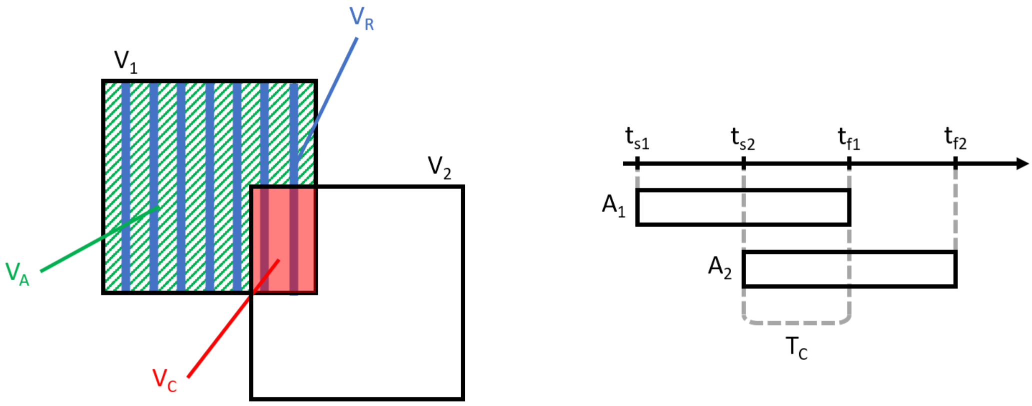


Figure 5. Representation of the volume of the workspace involved in the conflict (V_C), the total volume of the workspace available for the activity (V_A), and the volume required for the activity resources (V_R), used for calculating the Severity of Workspace Conflict (SWC) and the Congestion of Severity (CgS) (Kassem, Dawood and Chavada, 2015).

Equation 10. Severity of Conflict (SC).

$$Severity\ of\ Conflict, SC = \frac{T_c}{T_A}$$

$$T_C = min(t_{f1} - t_{s2}; t_{f2} - t_{s1}), \qquad T_{A1} = t_{f1} - t_{s1}, \qquad t_{s2} > t_{s1}, \qquad t_{f2} > t_{f1}$$

Equation 11. Severity of Workspace Conflict (SWC).

$$Severity\ of\ Workspace\ Conflict, SWC = \frac{V_C}{V_A}$$

$$V_C = V_1 \cap V_2, \qquad V_A = V_1 - V_C = V_1 - (V_1 \cap V_2)$$

Equation 12. Congestion of Severity (CgS).

$$Congestion\ of\ Severity, CgS = \frac{V_R}{V_A}$$

$$V_R = V_1, \qquad V_A = V_1 - V_C = V_1 - (V_1 \cap V_2)$$

Equation 13. Workspace Criticality Level (WCL).

$$Workspace\ Criticality\ Level, WCL = SWC + CgS$$

In (Zhang *et al.*, 2015), the authors have referred to the conflict ratio (CR) (Akinci *et al.*, 2002) and the space capacity factor (SCF) (Thabet, Walid Y.; Beliveau, 1994). It must be noted that the SCF and CgS, used in (Kassem, Dawood and Chavada, 2015), are similar parameters; the first one consider spaces, whereas the second one considers volumes. In the same research (Zhang *et al.*, 2015), the authors, on the basis of the occupancy model of an activity type, have defined the spaces occupied by the crew for the 100% (S100), 75% (S75) and 50% (S50) of the time. Hence, given a space interfering with S100, S75, or S50, a level of, respectively, severe, moderate or minor congestion has been assigned. In this study (Zhang *et al.*, 2015), although the space required by an activity is determined on the basis of an occupancy model, the congestion levels' thresholds, as in previous studies, are just qualitative values since not justified by the authors.

All the metrics reported above try to describe the conflicting status between workspaces simply referring to a volume's ratio and/or defining arbitrary thresholds for different congestion severity levels. A more sophisticated metrics has been proposed by the authors in (Ma, Zhang and Chang, 2020). This severity index is theoretically defined as the combination of conflicts' temporal and volumetric parameters, urgency, and danger weighting factors and a priority grade among the different type of conflicts (Figure 6, Equation 14, Equation 15, and Equation 16).

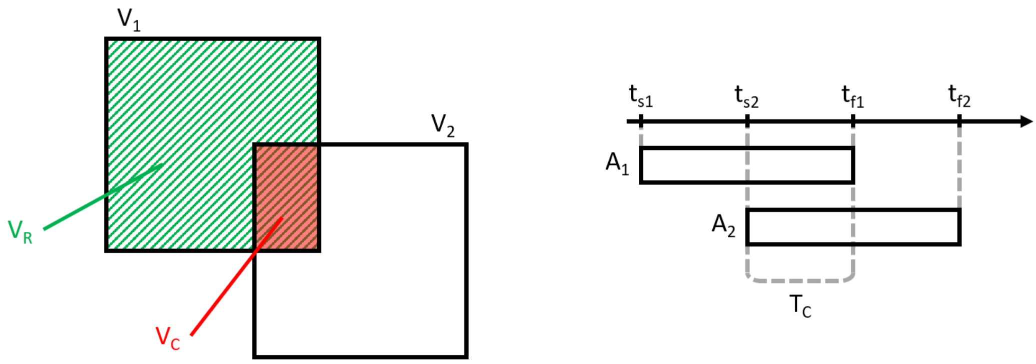


Figure 6. Representation of the total conflicting volume (V_c) and the total required volume (V_R), whose ratio defines the Ratio of Spatial Conflict (S_{v1}) (Ma, Zhang and Chang, 2020).

Equation 14. Ratio of Spatial Conflict (S_{v1}), corresponding to the Conflict Ratio (CR).

$$Ratio\ of\ Spatial\ Conflict, S_{v1} = \frac{V_C}{V_R} = CR$$

$$V_{R1} = V_1, \qquad V_C = V_1 \cap V_2$$

Equation 15. Ratio of Coincident Period (S_{t1}).

$$Ratio\ of\ Coincident\ Period, S_{t1} = \frac{T_C}{T_A}$$

$$T_C = min(t_{f1} - t_{s2}; t_{f2} - t_{s1}), \qquad T_{A1} = t_{f1} - t_{s1}, \qquad t_{s2} > t_{s1}, \qquad t_{f2} > t_{f1}$$

Equation 16. Severity of the Spatial-Temporal Conflict (I_{12}).

$$Severity\ of\ the\ Spatio - Temoporal\ Conflict, I_{12} = h(k_1 S_{v1} S_{t1} + k_2 S_{v2} S_{t2})$$

$$h = 1 \div 100\ (severity\ grade), \qquad k_1, k_2 = 1 \div 10\ (urgency\ and\ danger\ grade)$$

In (Mirzaei *et al.*, 2018), the authors have proposed a novel metrics to assess the conflict severity, based on the decrease of workspace per person for a given activity. The Required Space Decrease, for a given activity A (RSD_1), is computed assuming that the labor crew is distributed uniformly within the workspace (Figure 7, Equation 17). In addition, the authors have considered the correlation between space and productivity, as in (Thabet, Walid Y.; Beliveau, 1994), and assumed that the workspace reduction percentage causes a proportional labor productivity reduction. This means that the relation between RSD and the Labor Productivity Reduction (LPR), for a given activity, is linear. If the labor workspace per person is reduced by more than 50%, it is considered a constructability problem. It must be noted that both the assumptions made by the authors (i.e., uniform distribution of workers within the workspace and linear relation between RSD and LPR) are not justified nor supported by empirical evidence.

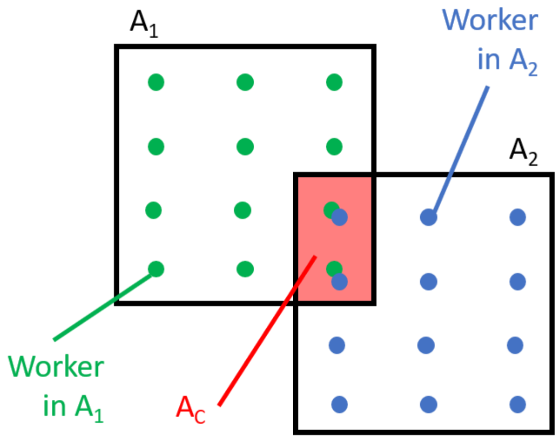


Figure 7. Representation of the uniform workers distribution within workspaces and the total conflicting volume (V_c) (Mirzaei *et al.*, 2018).

Equation 17. Decrease in Workspace per Person (RSD).

$$Decrease\ in\ Workspace\ per\ Person\ for\ Activity\ 1, RSD_1 = 1 - \left(\frac{A_{AP1}}{A_{RP1}}\right),$$

$$Available\ Workspace\ per\ Person\ for\ Activity\ 1, A_{AP1} = \frac{A_{R1}}{W_{12}},$$

$$Required\ Workspace\ per\ Person\ for\ Activity\ 1, A_{RP1} = \frac{A_{R1}}{W_1},$$

$$Worker\ no.in\ A_1, W_{12} = W_1 + \left\{W_2 + \frac{A_C}{A_2}\frac{A_{R2}}{A_{R1}}\right\}, \qquad A_C = A_1 \cap A_2,$$

$$A_{R1} = A_1, \qquad A_{R2} = A_2,$$

2.3. Technologies for workspace management

2.3.1. Applications in construction management

In the field of workspace management, a variety of tools has been developed for use on job sites; some of these are low-tech while some others use more advanced technologies. Examples in the first category have been provided by (Bascoul, Tommelein and Douthett, 2020; Francis, 2020); they have proposed visual management tools based on Excel Visual

Basic for Applications (VBA) programming language. Their main contribution to the traditional activity-based planning approach is the possibility of displaying work schedules and eventual spatial conflicts in a 2D spatial context to support linear planning for teams and facilitate the monitoring of site occupation (see Figure 8 and Figure 9). According to Visualization Management (VM) principles from the Lean theory, visual controls are designed to make problems, abnormalities, or deviations from standards visible to everyone. When these deviations are visible and apparent to all, actions can be taken to correct them immediately. To make this possible, in (Bascoul, Tommelein and Douthett, 2020; Francis, 2020), site plan and time are linked in Microsoft Excel; this software has been chosen due to its widespread adoption by construction practitioners (Bascoul, Tommelein and Douthett, 2020). It must be noted that, in particular scenarios, 2D spatial representation, adopted by (Bascoul, Tommelein and Douthett, 2020; Francis, 2020), may represent a limitation and cause failures in the detection of spatial interferences. In fact, spatial conflicts deriving from the topology of three-dimensional space may not be detected (e.g., indoor use of higher equipment than available workspace).

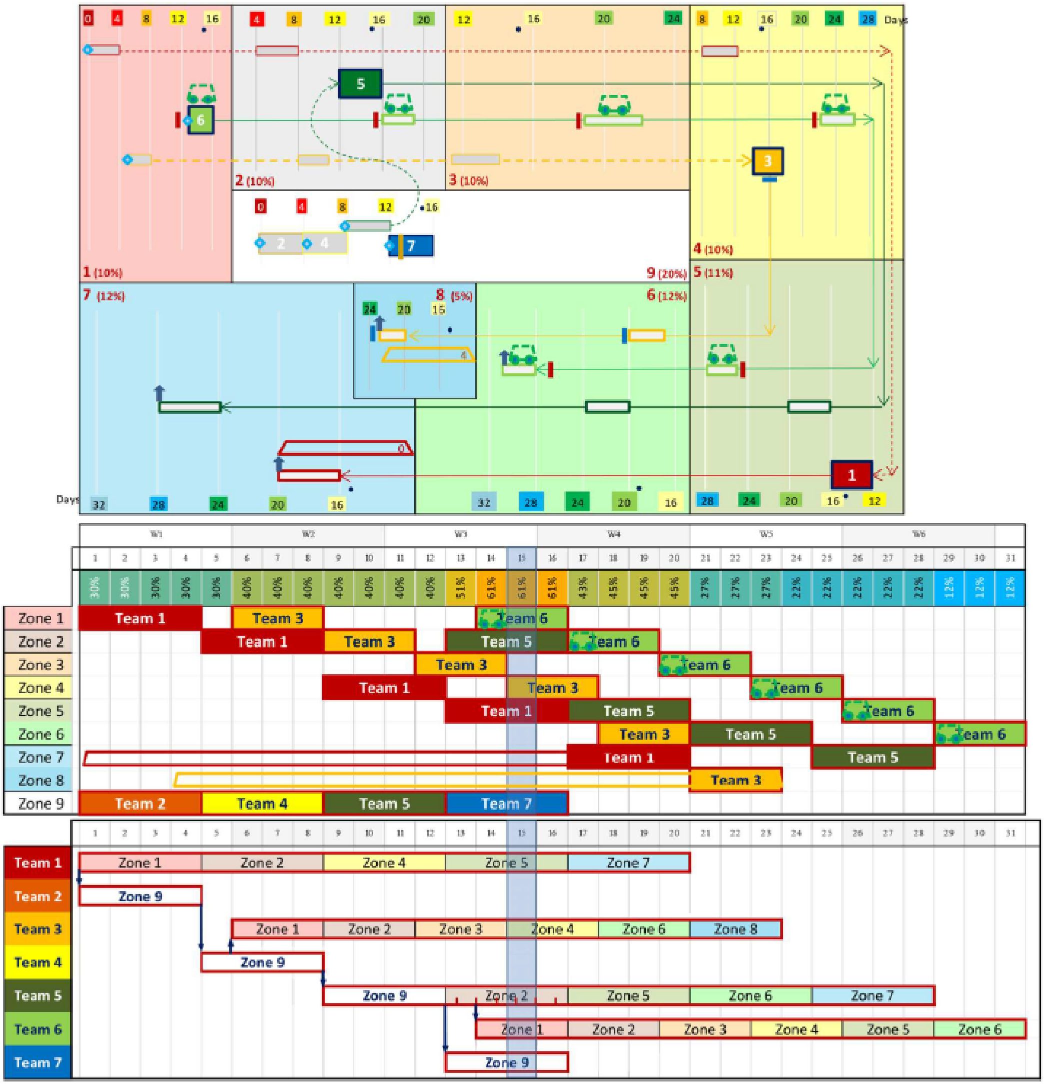


Figure 8. Applied example for the site-spatial-temporal modeling from (Francis, 2020).

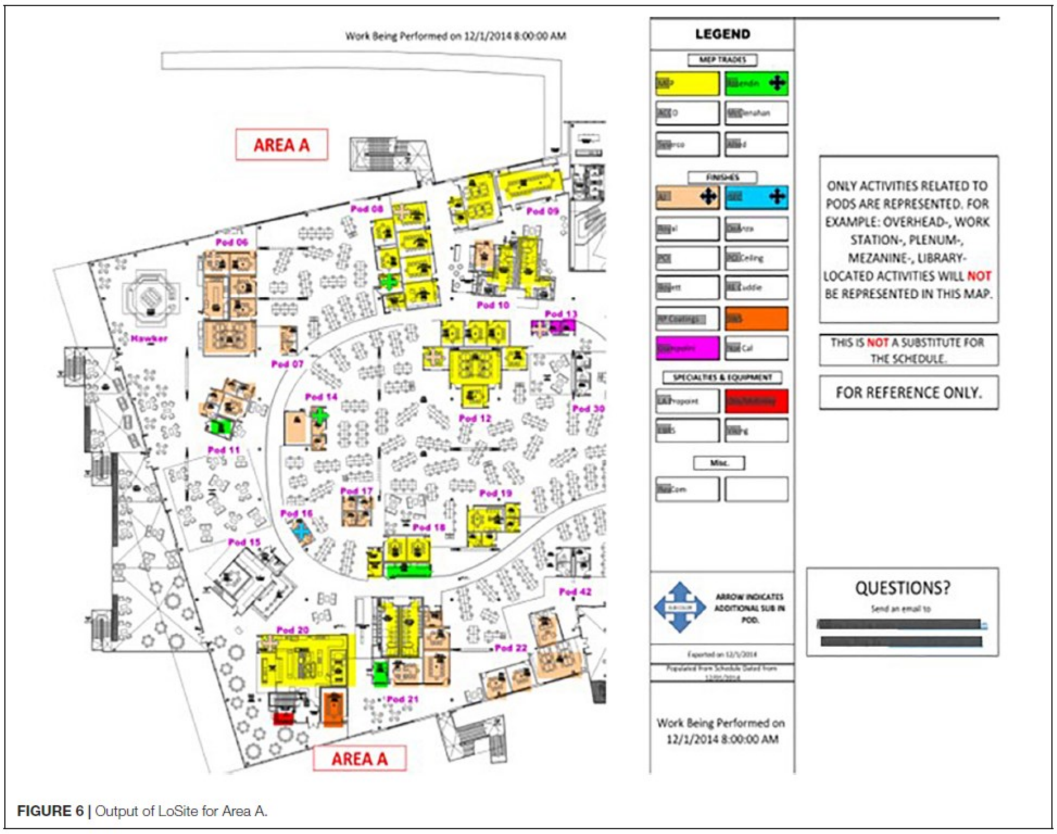


Figure 9. Applied example of the LoSite methodology from (Bascoul, Tommelein and Douthett, 2020).

Nowadays, several 4D tool are available in the market, providing different levels of capabilities and toolkit (e.g., Vico Schedule Planner and 4D Player, Innovaya Visual 4D Simulation, Autodesk Navisworks, Synchro Pro, Elecosoft Powerproject BIM, etc.). Autodesk Navisworks and Synchro Pro, which can be considered as the most popular ones, have been exhaustively compared in (Chen and Tang, 2019; Nechyporchuk and Bašková, 2020). Both implement clash detection functionalities with the possibility to define a clearance threshold around objects (i.e., clearance clash test). Whereas Autodesk Navisworks is more indicated for running clash detection tests between single building elements, in order to adjust the building design and avoid spatial issues, Synchro Pro is better for checking spatial interferences during the construction process and adjust the work schedule accordingly (SYNCHRO Construction, 2015). In fact, as reported in (Bentley System Inc., no date), Synchro Pro enables the user to create workspaces from bounding boxes (SYNCHRO Construction, 2011) and check for related spatial conflicts. In addition, both the 4D software enable the creation of animation for simulating the construction site dynamics, with the not negligible limit that they must be defined point by point by the user (SYNCHRO Construction, 2016). In other words, these software solutions do not enable to carry out automatic realistic physics simulation. This represent a big limit, especially if we consider big construction projects where thousands of agents moving for each time frame should be modelled one by one.

The use of more advanced technologies for workspace management has been presented in (Kassem, Dawood and Chavada, 2015), where XNA serious game engine is applied to develop a 4D simulation environment (i.e., 3D plus time). The authors have declared that game engine technology was selected following an extensive technology review based on the following requirements: capability of alignment, movement and positioning interactively 3D objects within the 3D space; enabling rules for detecting physical clashes (conflicts) between 3D objects; capability of visualizing and rendering transparent and wired meshes; support for WinForms properties and object-oriented methodologies; and, finally, its open-source availability. The possibility to manage workspace conflicts in a three-dimensional environment is a relevant added value to the previous research. The proposed 4D simulation tool is based on the application of open standards, namely IFC for the geometrical model and XML for the schedule (Figure 10). Enabling everyone to use the tool, irrespective of the software used for modelling buildings or describe schedules, represents a relevant contribution to the body of knowledge.

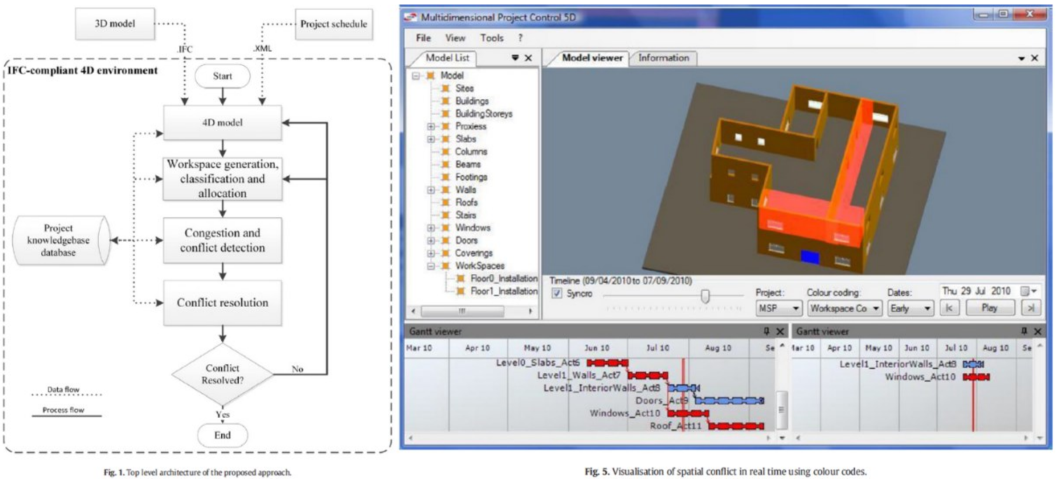


Figure 10. System architecture (left) and GUI (right) from (Kassem, Dawood and Chavada, 2015).

As suggested by (Hosny, Nik-Bakht and Moselhi, 2020), what is missing in existing studies regarding workspace management is the adoption of microsimulation techniques to model crews' behaviors and detect emergent spatial interferences. In this direction, future research can exploit more realistic 4D simulations within a serious gaming environment using pre-installed components or developing new programming scripts.

2.3.2. Applications in safety management

The construction industry is saturated by safety innovations and new injury prevention practices need to be introduced to improve construction safety (Esmaeili and Hallowell, 2013). Since traditional 2D drawings and paper-based sources for safety planning limit the ability to identify and analyze hazards prior to construction, information technology-based approaches, such as BIM, serious game engine, Virtual Reality (VR), and sensing technologies, have been widely studied.

In the AEC industry, the BIM technology has been widely used for project planning, designing, scheduling, and estimating. Related to safety, BIM has been studied in two main aspects: 4D visualization and application of rule sets. Using 4D visualization enhances the detection of spatial conflict or congestion prior to construction (Esmaeili and Hallowell, 2013). In addition, 4D simulation can overcome problems due to the conventional safety planning practice based on 2D drawings and helps safety personnel to detect and analyze hazards effectively (Leite *et al.*, 2011). A series of studies (Rozenfeld, Sacks and Rosenfeld, 2009; Sacks, Rozenfeld and Rosenfeld, 2009; Rozenfeld *et al.*, 2010) have developed a spatial and temporal safety/schedule integration model in a 4D environment. Their preconstruction safety planning tool considered tasks interaction risk factors and used user-provided semi-automated data to analyze hazardous activities in 4D simulations. Similarly, in (Ma, Zhang and Chang, 2020), a 4D-BIM construction management system, namely Navisworks SDK toolkit, has been applied to realize WBS decomposition and 4D schedule compilation in prefabricated construction projects. The combination of these technologies has enabled the implementation of two modules: the working spaces generator and the workspace conflict detector. Advanced information technologies, such as BIM and VR, have been combined in (Getuli *et al.*, 2020) to improve workspace planning related to construction activities. This approach enhances the usual manual workspace planning process, by simulating a real-scale virtual construction activity. Immersive VR technologies can allow the user to enter the simulated construction site with the related activities. By providing an enhanced real-scale spatial perception, they can support a more effective evaluation of the construction plan and schedule, along with the identification and assessment of related risks. In (Getuli *et al.*, 2020), the adoption of a game-engine platform, namely Unity3D™, for the production of VR activity simulations related to the workspace BIM model is preferred over integrated BIM-to-VR solutions available for the main BIM authoring software. This is due to customization features offered by Unity3D™ in terms of the addition of multimedia contents (e.g., 3D geometries, realistic materials, audio contents, etc.) and of scripting related to both user's interaction with the virtual environment and embedded data acquisition algorithms. Another attempt of BIM for safety is applying safety rule checking systems to automatically detect hazards and generate corresponding safety measures (Benjaoran and Bhokha, 2010; Zhang *et al.*, 2013). Sensing technologies have been applied to avoid jobsite collisions involved with heavy construction equipment, such as tower cranes or dump trucks. The authors, in (Choe *et al.*, 2014), have evaluated the reliability of radar- and ultrasonic-based collision warning systems to minimize blind area around pickup and dump trucks. Tag-based wireless Radio Frequency Identification (RFID) systems have been actively applied for the autonomous real-time jobsite monitoring to generate warnings on hazardous zones by detecting and tracking materials or workers on foot (Maalek and Sadeghpour, 2013). In (Zhang *et al.*, 2013), the authors have integrated BIM Global Positioning Systems (GPS) data. In fact, they have proposed a novel framework and prototype methods that collect historical activity-specific workspace information for automated activity-based workspace modelling and visualization of work congestion. The demonstrated prototype shows the feasibility of computing workspace parameters from location tracking data.

2.4. Research gaps

Many efforts have been spent to date by researchers in the fields of workspace definition, conflicts detection and severity assessment. In addition, several technologies have been put in place so far to develop workspace management tools to be used during works execution. However, further contributions are required to fill the gaps emerged above; they can be summarized as follows:

1. The definition of workspaces must be supported by empirical evidence (e.g., as illustrated by the authors in (Zhang *et al.*, 2015)).

2. A construction management ontology, enabling the automatic link between scheduled tasks and the correspondent 3D building elements (and the related workspaces) must be identified. This will enable the execution of 4D look-ahead simulations of resources interactions and related flows to the purpose of assessing the value of the work plan according to detected spatial conflicts.

3. Workspaces and conflicts' taxonomies existing in literature must be revisited, properly scaling them on the construction management field. What emerges from the literature review, reported above, is that most of existing studies consider object-based workspace taxonomies, that allocate workspaces for each building elements under construction for very specific purposes. This means assuming the strong hypothesis that spatial conflicts are likely to happen only around specific building elements under construction, that is between their static object-based workspaces. The possibility of crews and equipment to move, and get eventually

into conflicts within the construction site, have been sporadically taken under consideration. The only examples of moving resources are provided by (Zhang *et al.*, 2015; Mirzaei *et al.*, 2018); the first one has considered moving-overhead loads above crews' workspaces, whereas the second one has focused on the crews' movement within the assigned workspace. Since conflicts due to dynamic workspaces (e.g., crew's path between consecutive workspaces) result uncovered in existing studies, this gap must be addressed in future developments.

4. Spatial conflicts, in existing studies, have been detected by simply carrying out geometric intersection tests between the defined workspaces. This approach, although have provided early valuable results and enabled process automation, on the one hand, overestimates the results and, on the other, misses incompatibilities that are not purely geometric (e.g., struck-by risk from falling objects, electrical risk, etc.). To this regard, expert knowledge can provide a valuable contribution in refining and enhancing the detected spatial interferences.
5. As stated by the authors in (Hosny, Nik-Bakht and Moselhi, 2020), microsimulation techniques must be adopted for identifying those spatial conflicts which go undetected by applying existing methods and emerge only by virtually emulating the real behaviors of crews, equipment and building components.
6. Sounder conflict's metrics, tuned into the effective severity of spatial conflicts, must be developed to concisely describe the overall conflicting status affecting works execution.
7. Finally, a workflow that integrates currently available construction planning methods and the most advanced simulation systems for detecting spatial conflicts must be defined. This would not only improve existing approaches for construction planning by covering their gaps, but also ease assessing the added values provided by novel spatial conflict simulators.

CHAPTER 3

3. Research question

Nowadays, the need of considering the spatial dimension to ensure schedule's feasibility and avoid critical issues, such as safety, productivity, and constructability ones, is unanimously accepted by field experts. In the previous Section 2.4, several research gaps have been identified. As emerged from the literature review discussed above, several approaches, based on geometric intersection tests between workspaces, have been proposed so far by researchers to detect spatial interferences. These geometric approaches, although speeds up and automate the process of detecting spatial interferences, on the one hand, overestimate the results and, on the other, miss incompatibilities that are not purely geometric (e.g., struck-by risk from falling objects, electrical risk, etc.). In this regard, virtual simulations can provide a considerable contribution to figure likely construction scenarios evolutions and detect related spatial interferences that otherwise, considering only the static jobsite configuration, would go undetected. In addition, overestimations due to "false positives" can be addressed by applying artificial intelligence (AI) as an instrument for judging the criticality levels inherent to detected spatial conflicts.

This study, starting from these considerations, tries to answer to the following research questions:

1. Carrying out intersection tests between workspaces, defined on the basis of work schedule information, only static and pure geometric conflicts can be detected. How can physics simulations be integrated with geometric intersection tests between workspaces to detect spatial conflicts due to objects falling from height?

2. How can expert knowledge be integrated with both construction site geometric information and work schedule data in a simulator to assess the criticality of detected geometric spatial conflicts and avoid spatial issues overestimation? What is the framework of a DSS that, combining 4D model data and expert knowledge, enables the project management team to make informed adjustment of a given resource-constrained schedule in order to avoid undue productivity slowdown?

CHAPTER 4

4. Methodology

4.1. Building Information Modeling

The aim of this section is providing a description of the Building Information Modeling (BIM) technology, since the workspace management framework presented in next sections is entirely based on it. After giving a glance of BIM, a description of the main characteristics of BIM models and their interoperability is supplied. All the contents are derived from (Eastman, Chuck; Teicholz, Paul; Sacks, Rafael; Liston, 2011) that represents a milestone of the matter.

The BIM technology is one of the most promising developments in the AEC industry. With BIM technology, an accurate virtual model of a building is constructed digitally. When completed, the computer-generated model contains precise geometry and relevant data needed to support the construction, fabrication, and procurement activities needed to realize the building. BIM also accommodates many of the functions needed to model the lifecycle of a building, providing the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration. All Computer-Aided Design (CAD) systems generate digital files. Older CAD systems produce plotted drawings. They generate files that consist primarily of vectors, associated line-types, and layer identifications. As these systems were further developed, additional information was added to these files to allow for blocks of data and associated text. With the introduction of 3D modeling, advanced definition and complex surfacing tools were added. As CAD systems became more intelligent and more users wanted to share data associated with a given design, the focus shifted from drawings and 3D images to the data itself. A building model produced by a BIM tool can support multiple different views of the data contained within a drawing set, including 2D and 3D. A building model can be described by its content (e.g., what objects it describes) or its capabilities (e.g., what kinds of information requirements it can support). The latter approach is preferable, because it defines what you can do with the model rather than how the database is constructed, which will vary with each implementation.

4.1.1. New tool and processes

As defined in (Eastman, Chuck; Teicholz, Paul; Sacks, Rafael; Liston, 2011), BIM is as a modeling technology and associated set of processes to produce, communicate, and analyze building models. Building models are characterized by:

- Building components that are represented with intelligent digital representations, called objects for simplicity, that "know" what they are, and can be associated with computable graphic, data attributes and parametric rules.
- Components that include data that describe how they behave, as needed for analyses and work processes (e.g., take off, specification, and energy analysis).
- Consistent and non-redundant data such that changes to component data are represented in all views of the component.
- Coordinated data such that all views of a model are represented in a coordinated way.

The following is a definition of BIM technology provided by the M.A. Mortenson Company, a construction contracting firm that has used BIM tools extensively within their practice (Campbell, 2006): BIM has its roots in computer-aided design research from decades ago, yet it still has no single, widely accepted definition. We, at the M.A. Mortenson Company, think of it as "an intelligent simulation of architecture". To enable us to achieve integrated delivery, this simulation must exhibit six key characteristics. It must be:

- Digital,
- Spatial (3D),
- Measurable (quantifiable, dimensionable, and queryable),
- Comprehensive (encapsulating and communicating design intent, building performance, constructability, and including sequential and financial aspects of means and methods),
- Accessible (to the entire AEC/owner team through an interoperable and intuitive interface), and
- Durable (usable through all phases of a facility's life).

The concept of parametric objects is central to understanding BIM and its differentiation from traditional 2D objects. Parametric BIM objects are defined as follows:

- Consist of geometric definitions and associated data and rules.
- Geometry is integrated non-redundantly and allows for no inconsistencies.

When an object is shown in 3D, the shape cannot be represented internally redundantly, for example as multiple 2D views. A plan and elevation of a given object must always be consistent. Dimensions cannot be "fudged". Parametric rules for objects automatically modify associated geometries when inserted into a building model or when changes are made to associated objects. For example, a door will fit automatically into a wall, a light switch will automatically locate next to the proper side of the door, a wall will automatically resize itself to automatically butt to a ceiling or roof, etc. Objects can be defined at different levels of aggregation, so we can define a wall as well as its related components. Objects can be defined and managed at any number of hierarchy levels. For example, if the weight of a wall subcomponent changes, the weight of the wall should also change. Objects rules can identify when a particular change violates object feasibility regarding size, manufacturability, etc. Objects can link to or receive, broadcast or export sets of attributes (e.g., structural materials, acoustic data, energy data, etc.) to other applications and models. Technologies that allow users to produce building models that consist of parametric objects are considered BIM authoring tools. Open interfaces should allow for the import of relevant data (for creating and editing a design) and export of data in various formats (to support integration with other applications and workflows). There are two primary approaches for such integration:

1. To stay within one software vendor 's products, or
2. To use software from various vendors that can exchange data using industry supported standards.

The first approach allows for tighter integration among products in multiple directions. For example, changes to the architectural model will generate changes to the structural model, and vice versa. This requires, however, that all members of a design team use software provided from the same vendor.

The second approach uses either proprietary or open-source, publicly available, and supported standards created to define building objects (Industry Foundation Classes or IFCs). These standards may provide a mechanism for interoperability among applications with different internal formats. This approach provides more flexibility at the expense of reduced interoperability, especially if the various software programs in use for a given project do not support the same exchange standards. This allows objects from one BIM application to be exported from or imported into another one.

4.1.2. Benefits of BIM

BIM technology can support and improve many business practices. Although the AEC/FM (Facility Management) industry is in the early days of BIM use, significant improvements have already been realized (compared to traditional 2D CAD or paper-based practices). The advantages from BIM, despite not all currently in use, are reported below to show the entire scope of changes that can be expected from its full implementation.

4.1.2.1. Pre-construction benefits to owner

Concept, feasibility, and design benefits

Before owners engage an architect, it is necessary to determine whether a building of a given size, quality level, and desired program requirements can be built within a given cost and time budget, i.e., if a given building can meet the financial requirements of an owner. If these questions can be answered with relative certainty, owners can then proceed with the expectation that their goals are achievable. Finding out that a particular design is significantly over budget after a considerable amount of time and effort has been expended is wasteful. An approximate (or macro) building model built into and linked to a cost database can be of tremendous value and assistance to an owner.

Increased building performance and quality

Developing a schematic model prior to generating a detailed building model allows for a more careful evaluation of the proposed scheme to determine whether it meets the building's functional and sustainable requirements. Early evaluation of design alternatives using analysis/simulation tools increases the overall quality of the building.

4.1.2.2. Design benefits

Earlier and more accurate visualizations of a design

The 3D model generated by the BIM software is designed directly rather than being generated from multiple 2D views. It can be used to visualize the design at any stage of the process with the expectation that it will be dimensionally consistent in every view.

Automatic low-level corrections when changes are made to design

If the objects used in the design are controlled by parametric rules that ensure proper alignment, then the 3D model will be constructible. This reduces the user's needs to manage design changes.

Generate accurate and consistent 2D drawings at any stage of the design

Accurate and consistent drawings can be extracted for any set of objects or specified view of the project. This significantly reduces the amount of time and number of errors associated with generating construction drawings for all design disciplines. When changes to the design are required, fully consistent drawings can be generated as soon as the design modifications are entered.

Earlier collaboration of multiple design disciplines

BIM technology facilitates simultaneous work by multiple design disciplines. While collaboration with drawings is also possible, it is inherently more difficult and time-consuming than working with one or more coordinated 3D models in which changes control can be well managed. This shortens the design time and significantly reduces design errors and omissions. It also gives earlier insights into design problems and presents opportunities for a design to be continuously improved. This is much more cost-effective than waiting until a design is nearly complete and then applying value engineering only after the major design decisions have been made.

Easily check against the design intent

BIM provides earlier 3D visualizations and quantifies the area of spaces and other material quantities, allowing for earlier and more accurate cost estimates. For technical buildings (e.g., labs, hospitals, etc.), the design intent is often defined quantitatively, and this allows a building model to be used to check for these requirements. For qualitative requirements (e.g., this space should be near another, etc.), the 3D model can support automatic evaluations.

Extract cost estimates during the design stage

At any stage of the design, BIM technology can extract an accurate bill of quantities and spaces that can be used for cost estimation. In the early stages of a design, cost estimates are based primarily on the unit cost per square foot. As the design progresses, more detailed quantities are available and can be used for more accurate and detailed cost estimates. It is possible to keep all parties aware of the cost implications associated with a given design before it progresses to the level of detailing required of construction bids. At the final stage of design, an estimate based on the quantities for all the objects contained within the model allows for the preparation of a more accurate final cost estimate. As a result, it is possible to make better informed design decisions regarding costs using BIM rather than a paper-based system.

Improve energy efficiency and sustainability

Linking the building model to energy analysis tools allows evaluation of energy use during the early design phases. This is not possible using traditional 2D tools, which require that a separate energy analysis be performed at the end of the design process thus reducing the opportunities for modifications that could improve the building's energy performance. The capability to link the building model to various types of analysis tools provides many opportunities to improve building quality.

4.1.2.3. Construction and fabrication benefits

Synchronize design and construction planning

Construction planning using 4D CAD requires linking a construction plan to the 3D objects in a design, so that it is possible to simulate the construction process and show what the building and site would look like at any point in time. This graphic simulation provides considerable insight into how the building will be constructed day-by-day and reveals sources of potential problems and opportunities for possible improvements (e.g., site, crew and equipment, space conflicts, safety problems, etc.). This type of analysis is not available from paper bid documents. It does, however, provide added benefit if the model includes temporary construction objects such as shoring, scaffolding, cranes, and other major equipment so that these objects can be linked to schedule activities and reflected in the desired construction plan.

Discover design errors and omissions before construction (clash detection)

Because the virtual 3D building model is the source for all 2D and 3D drawings, design errors caused by inconsistent 2D drawings are eliminated. In addition, because systems from all disciplines can be brought together and compared, multi-system interfaces are easily checked both systematically (i.e., for hard and soft clashes) and visually (i.e., for other kinds of errors). Conflicts are identified before they are detected in the field. Coordination among participating designers and contractors is enhanced and errors of omission are significantly reduced. This speeds the construction process, reduces costs, minimizes the likelihood of legal disputes, and provides a smoother process for the entire project team.

React quickly to design or site problems

The impact of a suggested design change can be entered into the building model and changes to the other objects in the design will automatically update. Some updates will be made automatically based on the established parametric rules. Additional cross system updates can be checked and updated visually. The consequences of a change can be accurately reflected in the model and all subsequent views of it. In addition, design changes can be resolved more quickly in a BIM system because modifications can be shared, visualized, estimated, and resolved without the use of time-consuming paper transactions. Updating in this manner is extremely error-prone in paper-based systems.

Use design model as basis for fabricated components

If the design model is transferred to a BIM fabrication tool and detailed to the level of fabrication objects (i.e., shop model), it will contain an accurate representation of the building objects for fabrication and construction. Because components are already defined in 3D, their automated fabrication using numerical control machinery is facilitated. Such automation is standard practice today in steel fabrication and some sheet metal work. It has been used successfully in precast components, fenestration, and glass fabrication. This allows vendors world-wide to elaborate on the model, to develop details needed for fabrication, and to maintain links that reflect the design intent. This facilitates offsite fabrication and reduces cost and construction time. The accuracy of BIM also allows larger components of the design to be fabricated offsite than would normally be attempted using 2D drawings, due to the likely need for onsite changes (i.e., rework) and the inability to predict exact dimensions until other items are constructed in the field.

Better implementation and Lean construction techniques

Lean construction techniques require careful coordination between the general contractor and subs to ensure that work can be performed when the appropriate resources are available onsite. This minimizes wasted effort and reduces the need for on-site material inventories. Because BIM provides an accurate model of the design and the material resources required for each segment of the work, it provides the basis for improved planning and scheduling of subcontractors and helps to ensure just-in-time arrival of people, equipment, and materials. This reduces cost and allows for better collaboration at the job site.

Synchronize procurement with design and construction

The complete building model provides accurate quantities for all (or most, depending upon level of 3D modeling) of the materials and objects contained within a design. These quantities, specifications, and properties can be used to procure materials from product vendors and subcontractors (such as precast concrete subs).

4.1.2.4. Post-construction benefits

Better manage and operate facilities

The building model provides a source of information (graphics and specifications) for all systems used in a building. Previous analyses used to determine mechanical equipment, control systems, and other purchases can be provided to the owner, as a means for verifying the design decisions once the building is in use. This information can be used to check that all systems work properly after the building is completed.

Integrate with facility operation and management systems

A building model that has been updated with all changes made during construction provides an accurate source of information about the as-built spaces and systems and provides a useful starting point for managing and operating the building. A building information model supports monitoring of real-time control systems, provides a natural interface for sensors and remote operating management of facilities. Many of these capabilities have not yet been developed, but BIM provides an ideal platform for their deployment.

4.1.3. BIM interoperability

No single computer application can support all the tasks associated with building design and production. Interoperability depicts the need to pass data between applications, allowing multiple types of experts and applications to contribute to the work at hand. Interoperability has traditionally relied on file-based exchange formats, such as DXF (Drawing eXchange Format) and IGES (Initial Graphics Exchange Specification) that exchange only geometry.

Starting in the late 1980s, data models were developed to support product and object model exchanges within different industries, led by the ISO-STEP (International Organization for Standardization - Standard for the Exchange of Product Model Data) international standards effort. Data model standards are developed both through the ISO organization and by industry-led efforts, using the same technology, specifically the EXPRESS data modeling language. EXPRESS is machine-readable and has multiple implementations, including a compact text file format, SQL (Structured Query Language) and object database implementations and XML implementations. All are in use. The two main building product data models are the Industry Foundation Classes (IFC) – for building planning, design, construction, and management – and CIMsteel Integration Standard Version 2, (CIS/2) – for structural steel engineering and fabrication. Both IFC and CIS/2 represent geometry, relations, processes and material, performance, fabrication, and other properties, needed for design and production, using the EXPRESS language. Both are frequently extended, based on user needs.

Because EXPRESS supports applications with multiple redundant types of attributes and geometry, two applications can export or import different information for describing the same object. Efforts are being made to standardize the data required for particular workflow exchanges. In the US, the main effort is called the National BIM Standards (NBIMS) project. Interoperability imposes a new level of modeling rigor that firms are still learning to manage. Other formats for model viewing – 3D PDF (Three-Dimensional Portable Document Format) and DWF (Design Web Format) – provide capabilities that resolve some types of interoperability problems.

While files support exchange between two applications, there is a growing need to coordinate data in multiple applications through a building model repository. Only in this way, consistency, data and change management can be realized for large projects. However, there are still some unresolved issues in the general use of building model repositories.

Data exchanges between two applications are typically carried out in one of the four main ways listed below:

1. Direct, proprietary links between specific BIM tools.
2. Proprietary file exchange formats, primarily dealing with geometry.
3. Public product data model exchange formats.
4. XML-based exchange formats.

Direct links provide an integrated connection between two applications, usually called from one or both application user interfaces. Direct links rely on middleware software interfacing capabilities, such as ODBC (Open Database Connectivity), or proprietary interfaces, such as ArchiCad's GDL (Geometric Description Language) or Bentley's MDL (MicroStation Development Libraries). These are all programming level interfaces, relying on C, C++ or now C# languages. The interfaces make portions of the application's building model accessible for creation, export, modification, or deletion.

A proprietary exchange file format is one developed by a commercial organization for interfacing with that company's application. While a direct linking of applications is a runtime and binary interface, an exchange format is implemented as a file in a human readable text format. A well-known proprietary exchange format in the AEC area is DXF (Data eXchange Format) defined by Autodesk. Other proprietary exchange formats include SAT (Standard ACIS Text), defined by Spatial Technology that is the implementer of the ACIS geometric modeling software kernel, STL (Standard Triangle Language) for stereo-lithography and 3DS (Three-Dimensional Studio) for 3D Studio. Because each of these has their own purpose, they address functionally specific capabilities.

The public level exchange formats involve using an open standard building model, of which the IFC or CIS/2 for steel, are the principal options. Notice that the product model formats carry object and material properties, and also relations between objects in addition to geometry. These are essential for interfacing to analysis and construction management applications.

Software companies quite reasonably prefer to provide exchanges to specific companies using a direct link, because they can support them better, and it keeps customers from using competitor's applications. The functionality supported is determined by the two companies (or divisions within the same company).

However, because they have been developed, debugged, and maintained by the two companies involved, they are typically robust for the versions of the software designed for, and the functionality intended. The resulting interface usually reflects a joint business agreement regarding marketing and sales. The interfaces are maintained as long as their business relationship holds. On the other hand, there is a natural desire to "mix-and-match" applications to provide functionality beyond what can be offered by any single software company. The method of integration becomes critical for projects involving large teams, because gaining interoperability of different systems used by the team is easier than moving all team firms to a single platform. The public sector also wishes to avoid a proprietary solution that gives any one software platform a monopoly. Only IFC and CIS/2 for steel are public and internationally recognized standards today. Thus, the IFC data model is likely to become the international standard for data exchange and integration within the building construction industries. XML (eXtensible Markup Language) is an extension to HTML (Hypertext Markup Language), the base language of the Web. XML allows definition of the structure and meaning of some data of interest; that structure is called a schema. The different XML schemas support exchange of many types of data between applications. XML is especially good in exchanging small amounts of business data between two applications set up for such exchanges.

A summary of the most common exchange formats in the AEC area is listed in Figure 11. Figure 11 groups file exchange formats with regard to their main usage. These include 2D raster image formats for pixel-based images, 2D vector formats for line drawings, 3D surfaces and solid shape formats for 3D forms. 3D object-based formats are especially important for BIM uses and have been grouped according to their field of application. These include the ISO-STEP based formats that include 3D shape information along with connectivity relations and attributes, of which the IFC building data model is of highest importance. Also listed are various game formats, which support fixed geometry, lighting, textures along with actors, and dynamic, moving geometry, and Geographical Information System (GIS) public exchange formats for 3D terrain, land uses, and infrastructure.

All methods of interoperability must deal with the issue of versions. When an application is updated with new capabilities, it may make the exchange mechanism faulty, if it is not maintained and versions of the standard are not well-managed.

Image (Raster) Formats	
JPG, GIF, TIF, BMP, PNG, RAW, RLE	Raster formats vary in terms of compactness, number of possible colors per pixel, transparency, compression with or without data loss
2D Vector Formats	
DXF, DWG, AI, CGM, EMF, IGS, WMF, DGN, PDF, ODF, SVG, SWF	Vector formats vary regarding compactness, line formatting, color, layering and types of curves supported; some are file-based and others use XML.
3D Surface and Shape Formats	
3DS, WRL, STL, IGS, SAT, DXF, DWG, OBJ, DGN, U3D PDF(3D), PTS, DWF	3D surface and shape formats vary according to the types of surfaces and edges represented, whether they represent surfaces and/or solids, material properties of the shape (color, image bitmap, and texture map), or viewpoint information. Some have both ASCII and binary encodings. Some include lighting, camera, and other viewing controls; some are file formats and others XML.
3D Object Exchange Formats	
STP, EXP, CIS/2, IFC	Product data model formats represent geometry according to the 2D or 3D types represented; they also carry object type data and relevant properties and relations between objects. They are the richest in information content.
AecXML, Obix, AEX, bcXML, AGCxml	XML schemas developed for the exchange of building data; they vary according to the information exchanged and the workflows supported.
V3D, X, U, GOF, FACT, COLLADA	A wide variety of game file formats vary according to the types of surfaces, whether they carry hierarchical structure, types of material properties, texture and bump map parameters, animation, and skinning.
SHP, SHX, DBF, TIGER, JSON, GML	Geographical information system formats vary in terms of 2D or 3D, data links supported, file formats and XML.

Figure 11. Common exchange formats in AEC application from (Eastman, Chuck; Teicholz, Paul; Sacks, Rafael; Liston, 2011).

4.1.3.1. Industry Foundation Classes

The Industry Foundation Classes (IFC) has been developed to create a large set of consistent data representations of building information for exchange between AEC software applications. It relies on the ISO-STEP EXPRESS language and concepts for its definition, with a few minor restrictions on the language. While most of the other ISO-STEP efforts focused on detailed software exchanges within specific engineering domains, it has been thought that in the building industry this would lead to piecemeal results and a set of incompatible standards. Instead, IFC has been designed as an extensible "framework model". That is, its initial developers intended it to provide broad general definitions of objects and data from which more detailed and task-specific models supporting particular workflow exchanges could be defined. In this regard, IFC has been designed to address all building information, over the whole building lifecycle, from feasibility and planning, through design (including analysis and simulation), construction, to occupancy and operation (Khemlani, 2004).

IFCs consists of a library of object and property definitions that can be used to represent a building project and support use of that building information for particular use. All objects in EXPRESS are called entities. The conceptual organization of IFC entities is diagrammed in Figure 12. At the bottom are twenty-six sets of base entities, defining the base reusable constructs, such as Geometry, Topology, Materials, Measurements, Actors, Roles, Presentations, and Properties. These are generic for all types of products and are largely consistent with ISO-STEP Resources, but with minor extensions. The base entities are then composed to define commonly used objects in AEC, termed Shared Objects in IFC model. These include building elements, such as generic walls, floors, structural elements, building service elements, process elements, management elements, and generic features. Because IFC is defined as an extensible data model and is object-oriented, the base entities can be elaborated and specialized by subtyping to make any number of sub entities.

The top-level of the IFC data model are the domain-specific extensions. These deal with different specific entities needed for a particular use. Thus, there are Structural Elements and Structural Analysis extensions, Architectural, Electrical, HVAC (Heating, ventilation, and air conditioning), and Building Control Element Extensions.

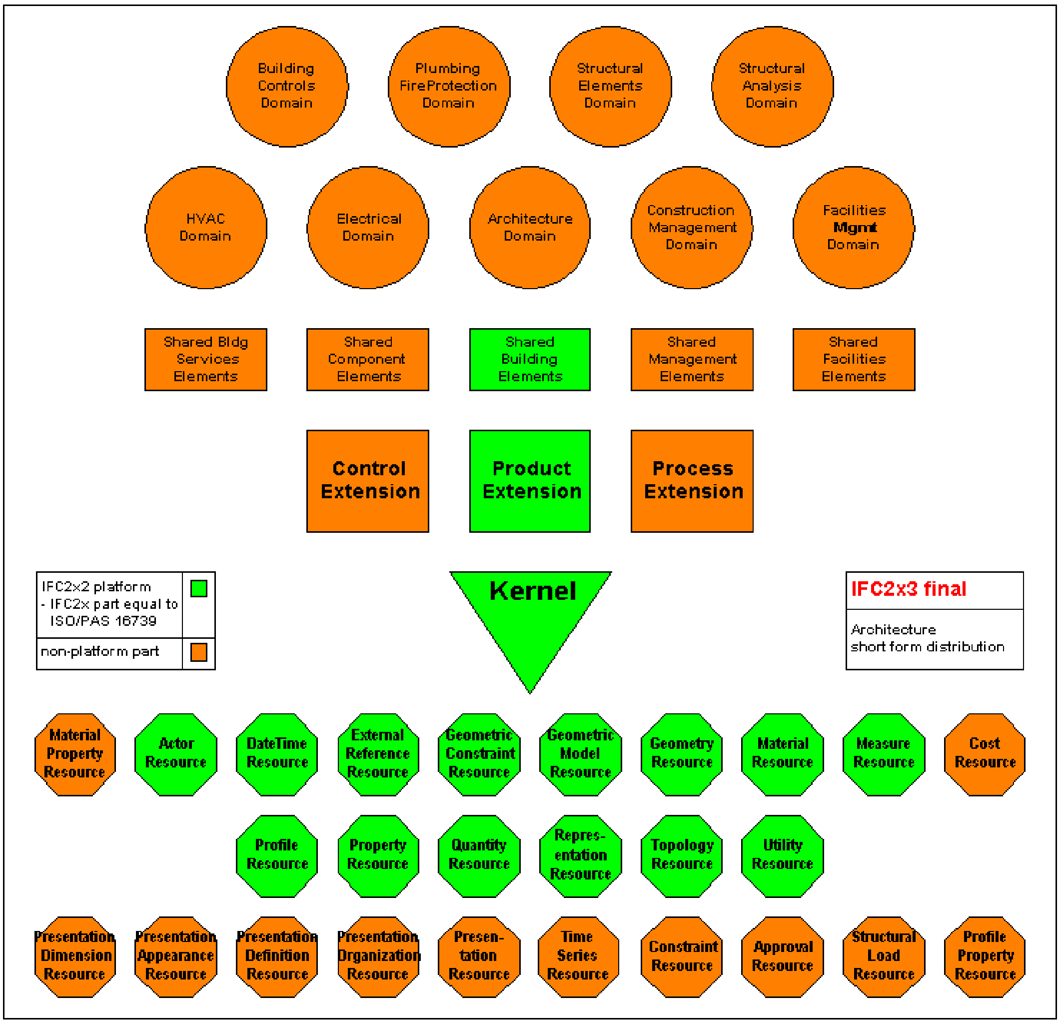


Figure 12. The system architecture of IFC subschemas from (Eastman, Chuck; Teicholz, Paul; Sacks, Rafael; Liston, 2011).

Each of the geometric shapes in the system architecture diagram in Figure 13 identifies a set of EXPRESS language entities, enumerations, and types. The architecture thus provides a type of indexing system into the IFC model, which is also defined in EXPRESS. The IFC model is quite large and still growing. As of the current release 2x3, there are 383 Kernel-level entities, 150 shared entities in the middle level, and 114 domain-specific entities in the top level. Given the IFC hierarchical object subtyping structure, the objects used in exchanges are nested within a deep sub-entity tree. For example, a wall entity has a trace down the tree shown in Figure 13. Each level of the tree introduces different attributes and relations to the wall entity. IfcRoot assigns a Global ID and other identifier information. IfcObjectDefinition optionally places the wall as part of a more aggregate assembly, and identifies the components of the wall, if these are defined. IfcProduct defines the location of the wall and its shape. IfcElement carries the relationship of this element with others, such as wall bounding relationships, and the spaces (including exterior space) that the wall separates. It also carries any openings within the wall and optionally their filling by doors or windows. Many of these attributes and relations are optional, allowing implementers to exclude some of the information from their export routines.

Products, including walls, may have multiple shape representations, depending upon their intended uses. Within the IFC, almost all objects are within a composition hierarchy defined by IfcObjectDefinition; that is, they are both part of a composition and have their own components. IFC also has a general purpose IfcRelation, which has different kinds of relations as subtypes, one of which is IfcRelConnects, which in turn has the subclass IfcRelConnectswithRealizing that is used to reference wall connections. This one example indicates the extensiveness of the IFC model. This type of approach is followed for all IFC modelled objects.

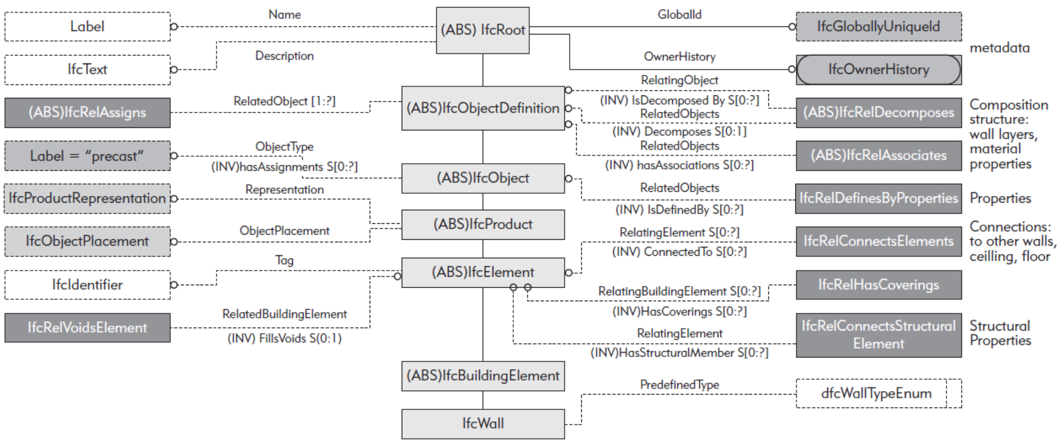


Figure 13. The IFC structure example, reported in (Eastman, Chuck; Teicholz, Paul; Sacks, Rafael; Liston, 2011)*, for defining a wall.*

4.2. Lean construction

The aim of this section is introducing the Lean construction principles that frame the workspace management framework, proposed in this study (Section 4.5). All the content reported in this Section are mainly derived from (Gao and Low, 2014).

The term “Lean production” was first brought to attention through the book “The Machine that Changed the World” (Womack, 1990), in which the authors critically contrasted the differences between Toyota plants and three U.S. Motor giants. The authors claimed that the production philosophy and system of Toyota were superior to all the others, because it used less human effort, less manufacturing space, less investment in tools, less time spent on new product development but generated high quality, less inventory, and a greater variety of products. Since then, a large volume of publications on Lean production emerged, which usually considered the Toyota Production System (TPS), or Just-in-Time (JIT) production, or Lean production as synonymous and equal. In order to understand Lean production more precisely, it requires first of all an understanding of its mother platform, the TPS. Toyota adopted a systematic approach towards problem-solving. Later this approach became known as the Deming-cycle or the Plan-Do-Check-Act cycle (PDCA) which is a pillar for continuous improvement (Kaizen). These techniques evolved into what is now described as Lean production. TPS’s goal is to reduce cost without increasing production volume. The basis to achieve is the elimination of waste and this idea marked the start of the present Toyota Production System. It has been widely acknowledged that the two pillars of the Toyota Production System are Just-in-Time and Jidoka.

Just-in-time manufacturing prescribes the required units needed to produce the required quantities at the required time, wasting neither raw material nor time. A manufacturing company establishing this flow throughout can ideally approach zero inventories. Just in time is hardly an easy task, as it requires the coordination of potentially thousands of components/parts arriving where and when needed in just the right quantities, with all parts meeting the quality parameters.

Jidoka, in Japanese, means “never let a defect pass into the next station and freeing people from machines”. In all Toyota manufacturing plants, most machines, whatever old or new, are equipped with such devices as well as various safety devices to prevent defective products. The idea is to build quality in the process by distinguishing between normal and abnormal conditions, stopping production line once there is a problem being detected. It calls attention to the abnormal to ensure that its root cause is found and eliminated.

According to (Koskela, 1992), 11 important principles are essential to the Lean philosophy, including:

1. Reduce the share of non-value-adding activities (also called waste).
2. Increase output value through systematic consideration of customer requirements.
3. Reduce variability.
4. Reduce cycle time.
5. Simplify by minimizing the number of steps, parts, and linkages.
6. Increase output flexibility.
7. Increase process transparency.
8. Focus control on the complete process.
9. Building continuous improvement into the process.
10. Balance flow improvement with conversion improvement.
11. Benchmark.

These principles of Lean production as reflected in the early days, suggested that Lean principles were focused on the process.

The success of Lean principles in manufacturing and the benefits arising from its use is one of the main motivations for adopting Lean principles in construction. Lean first emerged in the construction industry a few years after it had gained full acceptance in Western manufacturing industries. A simple definition of Lean construction was given by (Koskela *et al.*, 2002): Lean construction is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value.

The Lean Construction Institute (LCI) defines Lean construction as a management-based production approach to project delivery that is particularly useful on complex, uncertain, and quick projects. The definition of Lean construction due (Koskela *et al.*, 2002) indicates that Lean construction strives for the same goals as Lean production, namely to eliminate waste and to maximize value. LCI's definition, on the other hand, implies that industrial approaches in manufacturing are directly applicable to construction.

An alternative interpretation of the concepts of Lean construction is illustrated in Figure 14.

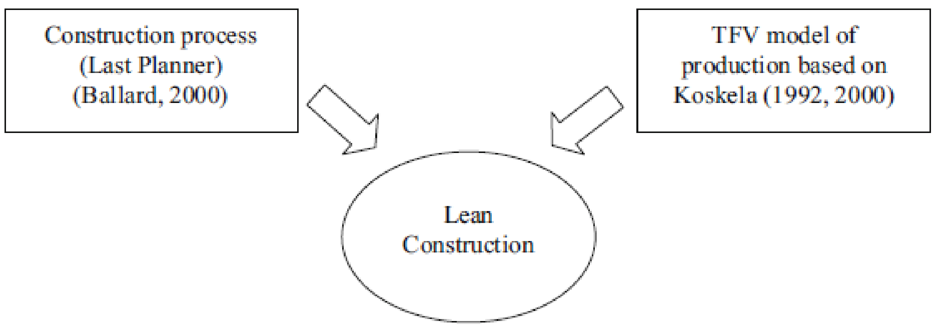


Figure 14. The origins of Lean Construction from (Gao and Low, 2014).

This school of thought discusses the application of Lean production methods to construction. The best known of these is the Last Planner approach to the planning and management of the construction process. Its goal is to create a reliable workflow by having the project team, including all affected firms, collaboratively create a phase plan for a segment of the work (e.g., the foundations). This is a social process involving discussion with site staff and planning to ensure that work is not waiting on workers, and that workers are not waiting on work. Last Planner System serves as one of the theoretical foundations of Lean construction (Koskela *et al.*, 2002), and in some circumstances the

LPS turns out to be synonymous with Lean construction. The LPS is now regarded as the most powerful and well-known planning and control system from all the Lean construction techniques and tools. According to (Ballard, 2000), the LPS builds on the principle of systematic reactive work planning executed on the lowest possible level in the hierarchy of planners – the last planner. The underlying philosophy is to ensure that all the prerequisites needed for performing distinct construction work are in place before it is assigned to a work group (Ballard, 2000). It uses the overall project plan as the general framework but suggests that the daily activities of the production should be managed by a more flexible approach that is cognizant of the actual progress of the project. There are four main categories for any executable project task, namely Should, Can, Will, and Did (Figure 15):

1. Should: tasks that need to be performed in the near future according to the overall project plan.
2. Can: tasks that have all their prerequisites ready: e.g., previous project steps are completed, necessary materials are at hand, and workforce is available.
3. Will: the tasks that are commenced before the next planning round.
4. Did: the tasks that are completed.

The overall objective of the LPS is to increase plan reliability, and thus to serve as a framework for addressing waste deriving from uncertainty and plan deviance. The Last Planner System employs a four-level hierarchy of schedules and planning tools: master plan, phase (pull) plan, look-ahead plan, and weekly work plan (Ballard, 2000).

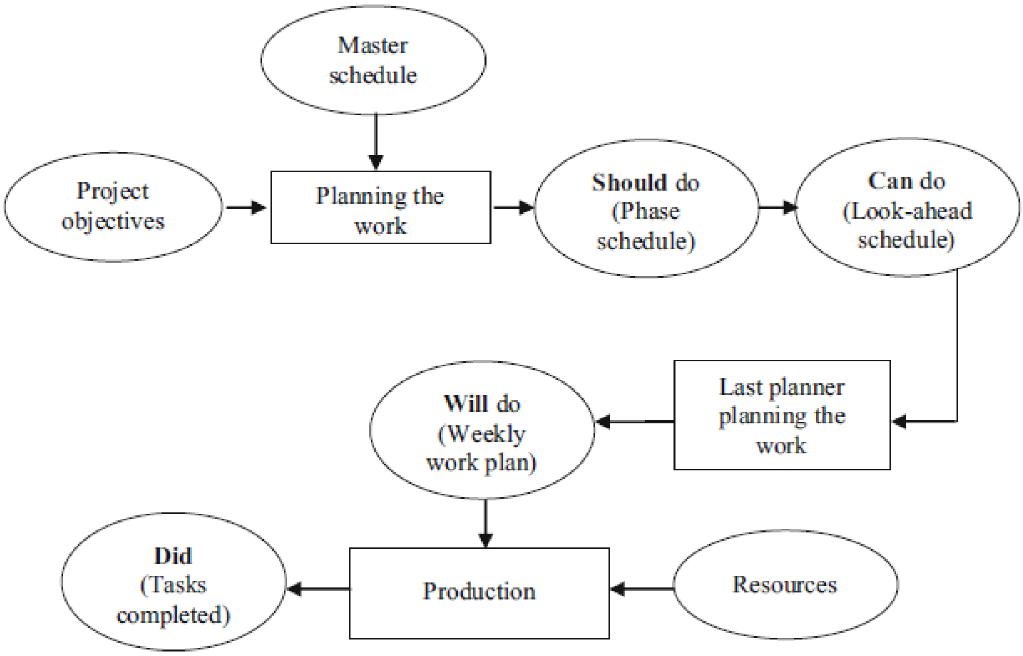


Figure 15. Last Planner System (LPS) workflow from (Gao and Low, 2014).

The master schedule is the overall project schedule, which is developed from the design criteria and supports the client's project objectives. It consists of milestones and items with long lead times. Milestone dates are determined by using the "pull" process from successor milestones. The plan is then developed by those responsible for building the phase together with subcontractors, starting backward from the planned phase completion date. The process reveals what must be done to release work for production.

The Look-Ahead Plan represents an intermediate level of planning. It is a schedule of potential assignments, typically for the next 6-8 weeks. The number of weeks over which a look-ahead process extends is determined by project characteristics, the reliability of the planning system, and the lead times for acquiring information, materials, labor, and equipment. The work is planned on assignment level, which means something that can be communicated to workers. Management continues to break down the activities into more details and screen the resulting smaller activities throughout the look-ahead window, until the activities are essentially assignment level tasks.

The weekly work plan is an assignment-level schedule. Detailed schedules are derived from the look-ahead plans on a weekly basis. The weekly work plan is formed based on the mechanism of Last Planner System, which aims to transform what should be done into what can be done, thus forming an inventory of ready work. In the meanwhile, examination of the prerequisites can take place when this level of detailed schedule can be achieved.

Another key feature of the LPS is known as Percent Plan Complete (PPC). It is calculated by dividing the number of completed assignments (i.e., what "did" get done) by the total number of assignments each week (i.e., what was projected "will" get done) and reasons are identified and acted on for failures to complete assignments. A high PPC means that the LPS allows for reliable forecasting of work, and that tasks made ready are being completed on schedule.

4.3. Simulation engine

The aim of this section is introducing the serious game engines, adopted in this study, as simulation engines due to their capacity to integrate semantically rich models of buildings provided in the form of Building Information Models.

The first application of gaming technology to the area of research can be found in the aircraft industry, with the use of Microsoft Flight Simulator for educational purposes (Moroney and Moroney, 1991) (Figure 16).

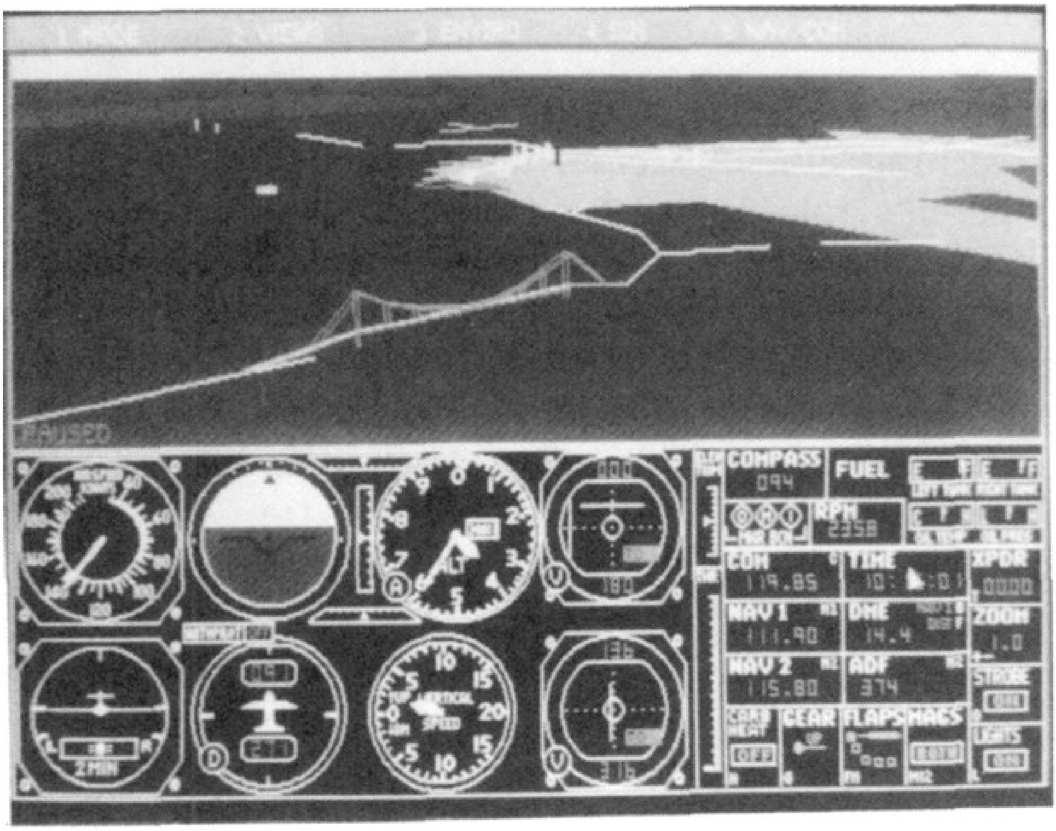


Figure 16. View from the cockpit of a Cessna 182 approaching San Francisco Bay from (Moroney and Moroney, 1991).

Later, serious game engines became widespread for other research purposes such as education and training, collaboration, and simulation and analysis, further demonstrating that mere entertainment is not the only feasible, nor the most promising, application. The great success of this approach is due to the difficulty in carrying out real experiments in some fields, especially in H&S management; in fact, the need to establish safe conditions, so as to avoid direct exposure to risks, would affect participant behavior. The use of game engines facilitates the deployment of virtual testbeds and tests execution. This is due also to the fact that the editors used to modify the games have recently become on the one hand highly sophisticated, and, on the other, simple enough to be considered useful for different end-users (Conway, 2011). Currently, these dedicated game editors, named game engines, have made possible to create games for non-professional, which allow them to easy insert architectural design elements into the video game, and then enables significant architectural visualization in game environment (Keeffe, 2008; Boeykens, 2011;

Conway, 2011; Shiratuddin and Thabet, 2011; Yan, Culp and Graf, 2011). Better still, these releases were not specifically for the benefit of architectural designers, but rather were to support people wanting to use game engines to fulfil their research gaps such as spatial interaction management and building emergency management (Lertlakkhanakul, Choi and Kim, 2008; Rüppel and Schatz, 2011; Tang and Ren, 2012).

4.3.1. Advanced architectural visualization

Several successful research studies that integrate CAD/BIM and serious gaming technologies have shown that game engines can serve as an enabler to improve architectural visualization to a higher level. Specifically, on the one hand, BIM provides several options to control the output of the 3D geometry, which is a valid approach to provide multi-purpose output from its core model. On the other hand, game engines support importing meshes and 3D geometry in certain format from external software, including BIM software to game environment. Therefore, a workflow to combine BIM and game engines, when the latter ones support whatever formats the BIM software outputs, can be proposed. With unique technologies, such as physic engine and artificial intelligence, it is possible to extend functionality of current BIM software by employing a game engine. With the advanced compatibility of technology, it is realistic to propose using game technology in professional design offices (Schreiber, 2009). Several developing methodologies utilizing different game engines to build a bridge between BIM and gaming technology to enhance architectural visualization are described as follows.

Unity3D™ is one of the most famous game engines. It is characterized by its cross-platform system, available in free and non-free versions (Wikipedia, 2017). Moreover, games can be exported as standalone applications for macOS and Microsoft Windows, for consoles such as XBox and Wii, and for smartphones running iOS or Android. More importantly, it supports web applets for online use, which can decrease the size of a game and promote its spread. In this game engine, "assets" are referenced to external files, such as scripts, textures, and models. They are assembled into different game scenes or levels for different purposes with the integration of internal game objects. The imported assets are referenced, instead of being fully embedded, and they can be reloaded after some assets change. Figure 17 illustrates how this game engine works with some CAD/BIM software. Importing FBX (FilBoX) models represents the state of the art. In fact, translating geometry and material information from BIM/CAD model in FBX into the Unity3D™ is quite simple, since enabled by a built-in function of the game engine. However, in practice, when importing FBX format into Unity3D™, materials cannot be automatically attached to the corresponding objects surfaces. In addition, FBX-formatted models, since contain only building elements' geometric information, cannot bring the BIM model semantics within the serious gaming environment. In the future, when this game engine is combined with linking and filter of CAD/BIM assets (i.e., elements), a very flexible system can be created. It is possible to link a filtered version of the BIM model with lower resolution and less details to the real-time game environment to save CPU usage of a computer, while at the same time hosting a higher-resolution version for photorealistic rendering in BIM environment (Figure 18) (Boeykens, 2011).

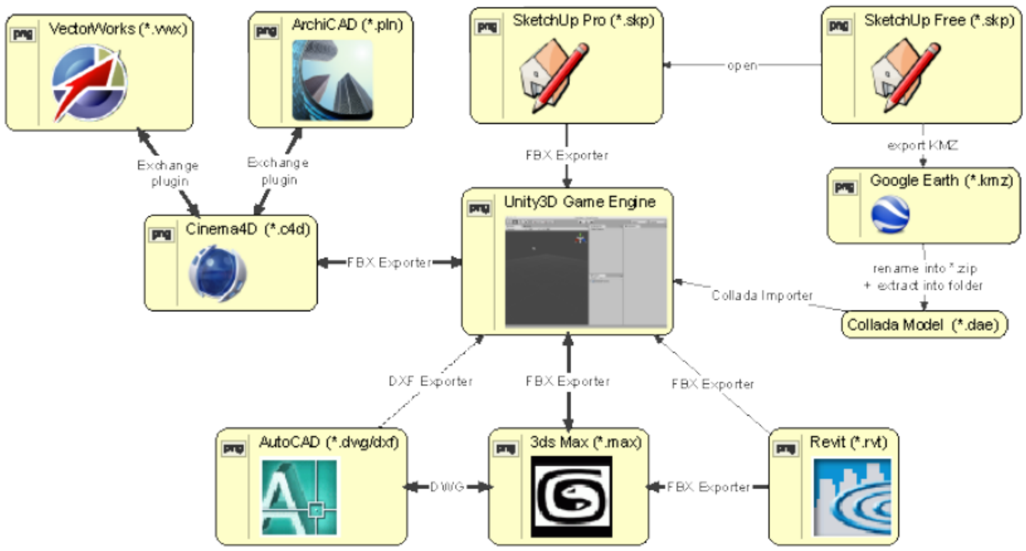


Figure 17. Unity3D™ game engine and preferred integration with CAD/BIM software from (Boeykens, 2011).

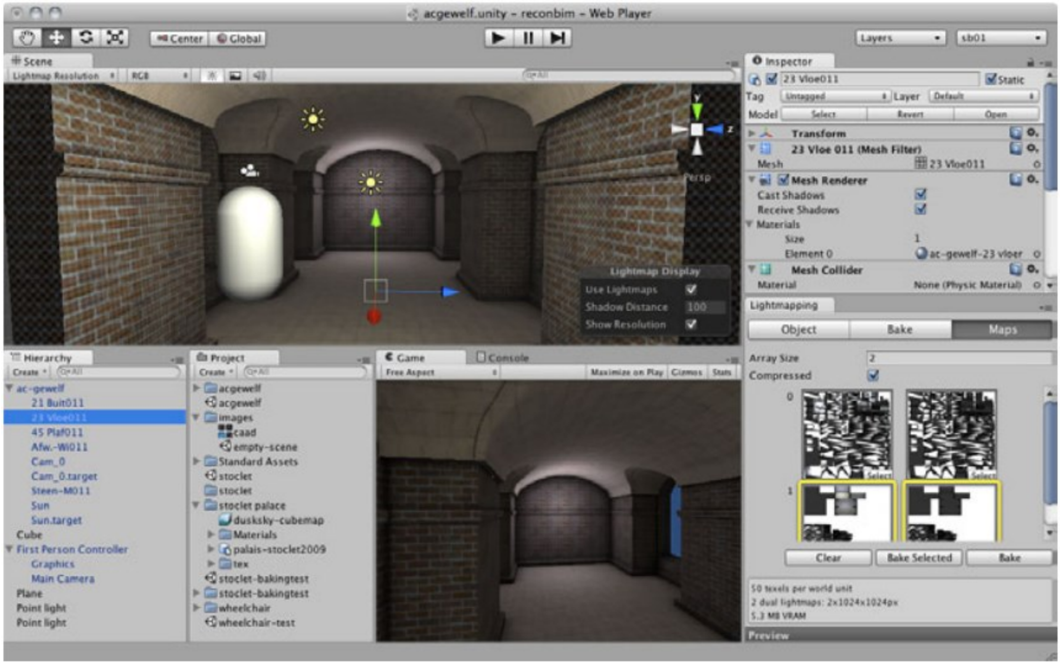


Figure 18. Example of photorealistic rendering in Unity3D™ from (Boeykens, 2011).

Another well-known game engine is XNA, developed by Microsoft. It allows games development for both PC and Xbox360 video game consoles. Better still, the XNA and its related tools are free for everyone. Therefore, XNA game engine is regarded as a cost-saving but efficient tool to combine BIM to games. There are two ways to integrate XNA workflow with CAD/BIM model to enhance architecture visualization: an XNA workflow based on FBX format and another one based on Revit API.

4.3.2. Safety training and education

In the construction industry, game engines usage was first limited to construction safety training purposes (Ezzeddine and García de Soto, 2021). Serious games can research, and train human behaviors based on individual "human factors" during emergency situation (Rüppel and Schatz, 2011). The authors, in (Michael, David; Chen, 2005), have argued that the main purpose of serious games to learn is of primary importance, and if possible, have fun doing it. More broadly speaking, education can be entertaining since the "fun" is only one kind of entertainment. There are a lot of elements that can contribute to the engagement of players. For examples, playing can promote the intense and passionate involvement, rules can generate a rigorous and scientific structure, and goals can motivate players to fulfil their potentials (Prensky, 2001; Mitchell and Savill-Smith, 2004). This training approach, also well-known as gamification, can be defined as "the application of game mechanisms in non-gaming environments with the aim of enhancing the processes enacted and the experience of those involved" (Caponetto, Earp and Ott, 2014). The difference between serious game and entertainment game can be concluded as following Figure 19 (Giessen, 2015).

	Serious games	**Entertainment games**
Task vs. rich experience	Problem solving in focus	Rich experiences preferred
Focus	Important elements of learning,	To have fun
Simulations	Assumptions necessary for workable simulations	Simplified simulation processes
Communication	Should reflect natural (i.e., non-perfect) communication	Communication is often perfect

Figure 19. Differences between serious games and entertainment games from (Giessen, 2015).

Serious game has become a powerful tool to address the wide range of problems since its adoption in the field of science and up-to-minus modern technologies. For example, game technology, communication technologies (e.g., sensors, HMD (head mounted display), etc.) and sciences (e.g., computer science, psychology, and education, etc.) can all be utilized to research emergency human behavior rather than pure entertainment use.

To mix the virtual and physical world, the five main human senses including hearing, seeing, tasting, smelling, and touching should be considered. The immersive factor of virtual environment can also be enhanced by adding audio effects (e.g., crack noise, fire roaring, human shouting, and crying). Indeed, the augmented reality and simulated environments provided by serious games allow participants to conduct experiments that are impossible to conduct in real world due to safety, cost, and time (Corti, 2006). An example is provided by the building emergency management, where emergency drills or experiments are traditionally applied to explore human emergency behavior with the aim to enhance building safety preplan and evacuation process. However, this method has research limitations with regard to human behavior in fire, such as resource cost for emergency experiments and the risk of physical danger to participants (Lawson, 2011). Another limitation is that participants clearly know they are in a safe environment and do not feel stressed. Someone tends to predict possible activities in established scenario according to relative data-collection instead of their instinct response to extraordinary environment. All these limitations make research reliability of people's behaviors under fire emergency questionable. Then, inaccurate human behavior research will subsequently influence the success of emergency management for fire. The emergency drill and experiment can only be held after the construction has been completed. It is too costly and time consuming to rectify the building layout if the defect of building design is found.

It is also consistently shown that serious game can promote learning (Mitchell and Savill-Smith, 2004; Eck van, 2006), stated that serious games can support the development of a number of skills (e.g., analytical and spatial skills, strategic skills and insight, learning and recollection capabilities, psychomotor skills, visual selective attention, etc.), and even violent games can alleviate frustration mood. However, it is difficult to draw any precise conclusion from studies on computer and video games because the conflicting outcomes of “serious” and “games”. Moreover, possible negative impacts may appear, including health issues (e.g., headaches, fatigue, mood swings, repetitive strain injuries, etc.), psycho-social issues (e.g., depression, increased gambling, etc.), and the effects of violent computer games (e.g., aggressive behavior, negative personality development, etc.) (Mitchell and Savill-Smith, 2004).

Positive impacts of serious game on human behavior research and enhancement have been reported by several researchers. The authors, in (Enochsson *et al.*, 2004), have found a positive correlation between three-dimensional perception experience from computer gaming and better performance in endoscopic simulation by medical students. In the field of architecture and design, computer game can be utilized to develop students' confidence and abilities in space modelling and design innovation (Radford, 2000; Coyne, 2003). The authors, in (Guy, Bidwell and Musumeci, 2005), have indicated that three-dimensional models hold a huge potential in enhancing town planning. Experiments conducted by some software for attention training have shown that even the casual experience with computer games improve the attention behaviors of children (Navarro *et al.*, 2003). Other potential benefits of games include improved self-monitoring, problem recognition and problem solving, decision making, better short-term and long-term memory, and increased social skills such as collaboration, negotiation, and shared decision-making (Figure 20) (Lloyd, Rieber, 1996; Mitchell and Savill-Smith, 2004; Heppell, SEllis *et al.*, 2006).

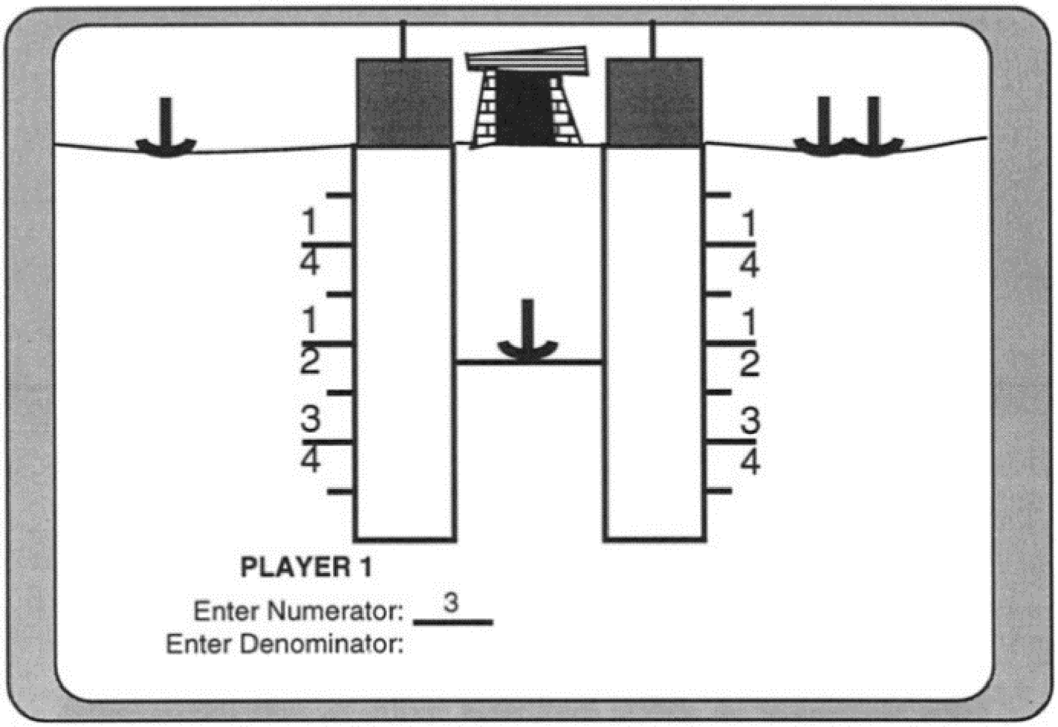


Figure 20. An example of an educational computer game, from (Lloyd, Rieber, 1996)*, that uses an endogenous fantasy to teach middle school students about fractions.*

For example, playing on-line community game develops the ability to find information and solve the problem online. Gamers develop their thinking strategies towards more analogical thinking, rather than trial-and-error thinking (Hong and Liu, 2003). The role-playing games have demonstrated its efficiency in corporate training by the mechanism of competitive scoring and difficult levels (Totty, 2005). In terms of relationship between gaming experience and driving behavior, (Backlund, Engström and Johannesson, 2006) has illustrated that a high experience in computer games can significantly improve the driving skills of traffic school students (Figure 21). Another example is reported in (Baldaro *et al.*, 2004), where violence in video game has been applied to evaluate short term effects on physiological (e.g., arterial pressure and heart rate) and psychological (e.g., anxiety and aggressiveness) factors, revealing that there is no effect on hostility measures. Similarly, a survey by (Durkin and Barber, 2002) has showed that there is no evidence of violent game posing obvious effects on measures of aggressiveness. On the contrary, some experiments indicated reductions in aggression (Griffiths, 1999). Despite the above findings, there is still no conclusive answer to the question of evidence for benefits and potential consequences of playing game. However, (Eck van, 2006) has pointed out the subsequent research direction: there is a need for practical guidance regarding how (i.e., when, with whom, and under what conditions) to integrate games and learning processes to maximize their learning potential and explain why these serious games are engaging and effective.

Figure 21. The gaming environment, reported in (Backlund, Engström and Johannesson, 2006)*, used in ongoing experiments.*

According to Wikipedia, main users of serious games are the military, government, medical professionals, school educators and corporation workers while the popular fields of its application lie in the global education and corporate training market. Advantages of military serious game include improving hand-eye coordination, improving ability to multitask, ability to work in a team using minimal communication, and willingness to take aggressive action, foreign languages, and cultural training (Michael, David; Chen, 2005). In the future, application areas for the military field would integrate with up-to-the-minutes game technologies such as Massively Multiplayer Online Games (MMOGs) and virtual reality training.

Governmental games often focus on various tasks to deal with terrorist attacks, disease outbreaks, biohazards, health care policy issues, city planning, traffic control, firefighting, budget balancing, ethics training, and defensive driving (Michael, David; Chen, 2005). The scenarios of such government games can easily be carried out repeatedly with changeable degree of severity according to different situation to compare the game experiment results. It also allows fire fighters, police, and medical personnel to perform tasks in virtual worlds rather than real experiments that are too dangerous, impossible, or too expensive to be carried out.

Healthcare games are one of most common serious game. There are a great number of serious games related to physical or mental health (Griffiths, 1999). Physical fitness game utilizes input devices like Wii controller and dance pad to promote physical exercise. Health/self-directed care game teaches the end users nutrition and health skills. Distraction therapy game helps patients decrease pain and anxiety before and during surgery. Recovery and rehabilitation game is beneficial for recovery of certain operation such as increasing motor ability of stoke patient. Training and simulation game can improve surgery performance. Game for diagnosis and treatment of mental illness can be used for diagnosing and treatment. Cognitive functioning game can develop memory and analytical/strategic skills. Control game with biofeedback equipment such as sensors that measure heart rate can train emotional and mental control of human being.

Although the benefits brought by education game is controversial (Michael, David; Chen, 2005; Heppell, SEllis *et al.*, 2006), the school educators can get the positive effects of education games in different field, which mainly include developing various human skills like strategic thinking, planning, communication, collaboration, group decision making, and negotiating skills (Gee, 2007). To realize the full potential of games as education tools, some elements should be considered: resources (e.g., lack of education equipment, insufficient technical support, time consuming to be familiar with the game, etc.), how to merge the relevance of a game with statutory curricula, difficulty in persuading stakeholders to foresee the potential benefits of computer games, etc. (Heppell, SEllis *et al.*, 2006). Similar to educators, workers in corporation can utilize serious game to train their various skills (Michael, David; Chen, 2005), including people skills (e.g., how to perform well within teamwork), job specific skill (e.g., how to use specific software and hardware to finish jobs efficiently), organization skills (e.g., how to manage human resources and time), communication skills (e.g., how to express ideas without aggravating others), strategy skills (e.g., how to set goals and achieve them).

Serious computer games, recently developed, enables "real" people to play virtually in their role in certain environment and provides reliable data about human behavior during emergency situation (Kobes *et al.*, 2010). The challenge is to combine virtual reality and computer game technology for a new kind of immersive, multiple-viewed, dynamic, and interactive environment. Beyond that, the system of a building and its occupants can be regarded as a complex sociotechnical system: there are interactions between the building (i.e., technical aspects) and the human behavior (i.e., social aspects) which influence each other. The technical aspects are easier to model and to simulate than the realistic behavior of involved people because it is based on individual decisions in certain situations.

4.4. Assessment by means of expert knowledge

The aim of this section is introducing Bayesian networks as the approach, adopted in this study, to formalize the expert knowledge and provide an estimation of the criticality levels related to each detected "possible" spatial conflict.

Bayesian networks (BNs) represent a powerful knowledge representation and reasoning tool to visually present the probabilistic relationships among a set of variables (Nguyen, Tran and Chandrawinata, 2016). With BNs, expert beliefs about the dependencies between different variables can be articulated and the impact of evidence on the probabilities of uncertain outcomes, such as future system reliability, can be propagated consistently. BNs are based on the conditional probability theory or Bayes' law by Thomas Bayes (Equation 18).

Equation 18. Bayes' rule.

$$P(B|A) = \frac{P(A \cap B)}{P(A)} = \frac{P(A|B)P(B)}{P(A)}$$

P(A) (or P(B)) is the probability of A (or B); P(A|B) (or P(B|A)) is the probability of A (or B) given B (or A); and P(A∩B) is the probability that both A and B occur.

BNs have many advantages such as suitability for small and incomplete data sets, combination of different sources of knowledge, the ability to model causal relationships among variables, and explicit handling of uncertainty for decision analysis (Nguyen, Tran and Chandrawinata, 2016). BNs have been extensively employed to develop DSSs in variety of domains including medical diagnosis, risk assessment and management, human cognition, industrial process and procurement, project scheduling, pavement and bridge management, and ecosystem and environmental management.

The reason why BNs have been widely used is that they constitute a powerful mean to represent phenomena affected by a high level of uncertainty. They are a type of probabilistic graphical model that uses Bayesian inference for probability computations. Bayesian networks aim to model conditional dependence, and therefore causation, by representing conditional dependence by edges in a directed graph. Through these relationships, one can efficiently conduct inference on the random variables in the graph through the use of factors (Soni, 2018). In their easier acceptance, BNs are graphical representations of probabilistic models. In a BN individual events or subsets of events are described using random variables, which, in turn, are represented graphically through nodes. Each node has then a domain and a probability distribution that represents the probability of the occurrence of any event associated with the variable. The domain of a node can be numeric or symbolic. The numerical domains can be continuous, comprising the whole of the real axis, or of discrete, i.e., represented through a set of numerical ranges. In a Bayesian network, the set of nodes represents the universe of events U. As for the general case probabilistic inference, a Bayesian network allows to create a model of the universe of events describing the relationships between the individual events. In the case of Bayesian network relationships are described by a set of conditional probability distributions. Each direct conditional dependence between variables is graphically represented by a directed arc that starts from the conditional variable and ends in the conditioning variable. The distributions are built in the most efficient way, using where possible the properties of conditional independence. Therefore, the topology of a Bayesian Network is defined by a directed acyclic graph, that is, a graph with directed edges where there are no sequences of directed edges that start at a node and return to the same node. These concepts can be deepened by a simple medical example, in which the universe of possible events is represented by a combination of three situations: having toothache, having a caries, and the fact that the probe of the dentist reveals a hole in the tooth (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008). For probability computation, each event can be represented by a variable that takes the value true if the event occurs and the value false otherwise. Therefore, the three variables are introduced: toothache, cavity and catch for the situation related to the probe of the dentist, with the meaning that, for example toothache = true is the event of having toothache, and toothache = false is the event of not having toothache. The simplest form of representation of this fragment of reality is to assign a probability value relatively to the occurrence of each possible combination of events. The values can be tabulated in a table called joint probability table. The only requirement to be met for the moment is related to the probability and requires that the assigned probabilities compound to 1 (Figure 22).

	toothache		*¬toothache*	
	catch	*¬catch*	*catch*	*¬catch*
cavity	0.108	0.012	0.072	0.008
¬cavity	0.016	0.064	0.144	0.576

Figure 22. Joint probability table for the medical example from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008).

Considering the above example, the universe of events was represented through the three random variables: toothache, cavity, catch. The probabilistic model, originally defined by the joint probability distribution, is defined in the Bayesian network, using the distribution of conditional probability. In this example, both the toothache and catch are caused by caries, but none has a direct effect on the other. This conditional independence enables the decomposition of the joint probability distribution P(toothache, cavity, catch) in three parts:

- P(Cavity) the a priori probability on the fact of having caries.
- P(Toothache/Cavity) the probability of having toothache conditioned to the fact of having caries.
- P(Catch/Cavity) the probability that the probe of the dentist reveals a cavity in the tooth conditioned to the fact of having caries.

To this decomposition corresponds a network structured as shown in Figure 23.

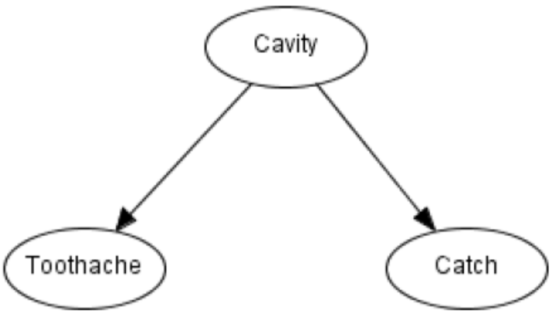


Figure 23. Bayesian network representation for the problem of toothache.

Alternatively, you can build the same network using the relation of cause-effect. This can be done by asserting that Cavity is the direct cause of both of Toothache and Catch, and that there is no causal relationship between the latter relates. In the example, nodes represent random variables of Boolean type. They can be a value from the only two possibilities: (true, false). These variables therefore represent individual events. Each node has a probability distribution that defines the probability value for each single value of the domain of the node. The nodes that have no incoming edges (i.e., Cavity in this case) are called root nodes. For them, the probability distribution is defined as a priori probability of the event relative to the node, in this case P(Cavity), while for the other nodes in the distribution is a conditional distribution, in this case P(Toothache/Cavity) and P(Catch/Cavity). The values related to the distribution can be derived from the table in our example joint probability according as said. Thus, we have:

- P(Cavity) = 0,2.
- P(Toothache/Cavity) = 0,12/0,2 = 0,6; P(Toothache/-Cavity) = 0,08/0,8 = 0,1.
- P(Catch/Cavity) = 0,18/0,2 = 0,9; P(Catch/-Cavity) = 0,16/0,8 = 0,2.

This complete the Bayesian model example of toothache because missing values are calculated as a complement to one. Notice how it was necessary to determine only five of the eight values instead of the joint probability table, thus saving about 37% of the data. This is one of the main advantages of Bayesian networks, the ability to build probabilistic models in a highly efficient way. The other advantage resides in the possibility of constructing the global network as a composition of local models. The Bayesian model thus constructed is perfectly equivalent to the model defined by the joint probability table and allows to perform the same type of inferences. The initial network allows to evaluate the probability of each event (Figure 24). The network also allows to perform Bayesian inference type, that is, to update the probability distributions of the nodes downstream of the observation of one or more events. In Bayesian networks, observing an event means to place the relative probability equal to one. The conditional probability P(Toothache/Cavity) can thus be easily assessed by observing the event Cavity. The node Toothache 0,60 shows the value similar to that calculated from the joint probability table. Obviously, the network, downstream of an observation, calculates the conditional probability for all other events (Figure 25).

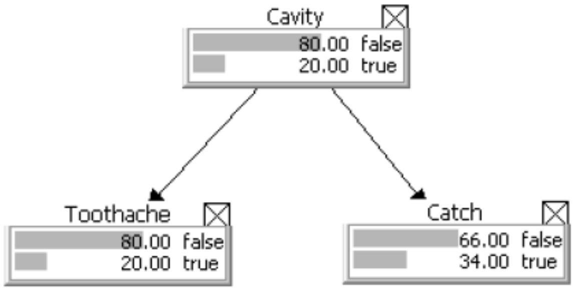


Figure 24. Probability distribution of the Bayesian network nodes for the problem of toothache from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008).

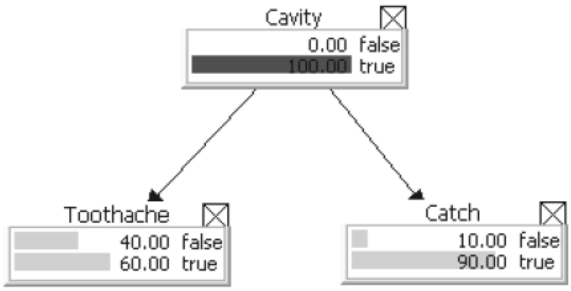


Figure 25. Distribution of conditional probability of occurrence "cavity" in the Bayesian network of the problem related to toothache from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008).

The probability of a joint event, for example P(Toothache^Cavity), can be evaluated using the formula of probability of conditioned probability as: P(Toothache^Cavity) = P(Toothache/Cavity) x P(Cavity) = 0,6 x 0,2 = 0,12.

Finally, the property of conditional independence: P(Toothache^Catch/Cavity) = P(Toothache/Cavity) P(Catch/Cavity) can be highlighted verifying that, downstream of the observation of the node conditioning (Cavity), changing the value of probability of one of the nodes conditioned, the probability distribution of the other does not change (Figure 26).

Figure 26. Example of conditional independence from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008). *Downstream of the observation of the node "cavity", the variation of the probability distribution of node "toothache" has no effect on the probability distribution of node "catch".*

4.4.1. Conditional independence

Due to the Bayesian network, some criteria can be defined to determine topological conditional independence between the nodes (Figure 27):

- A node is conditionally independent of its non-descendants starting from its parents.
- Markov Blanket: a node is conditionally independent of the other nodes in the network starting from his parents, his children, and the parents of his children.
- D-separation is a general topological criterion that determines whether a set of nodes X is independent of another set Y given a third set Z. In order to verify this condition, it is necessary to check whether the set of nodes Z blocks every path from node X to node Y. The path is a sequence of consecutive arcs and of any direction in the network graph. The d-separation is therefore the more general topological property of the networks to verify the condition of conditional independence between groups of nodes. In fact, this principle rules the algorithms of calculation of the networks. The algorithm for the calculation of the d-separation is somewhat cumbersome and not indispensable for the understanding of the arguments.

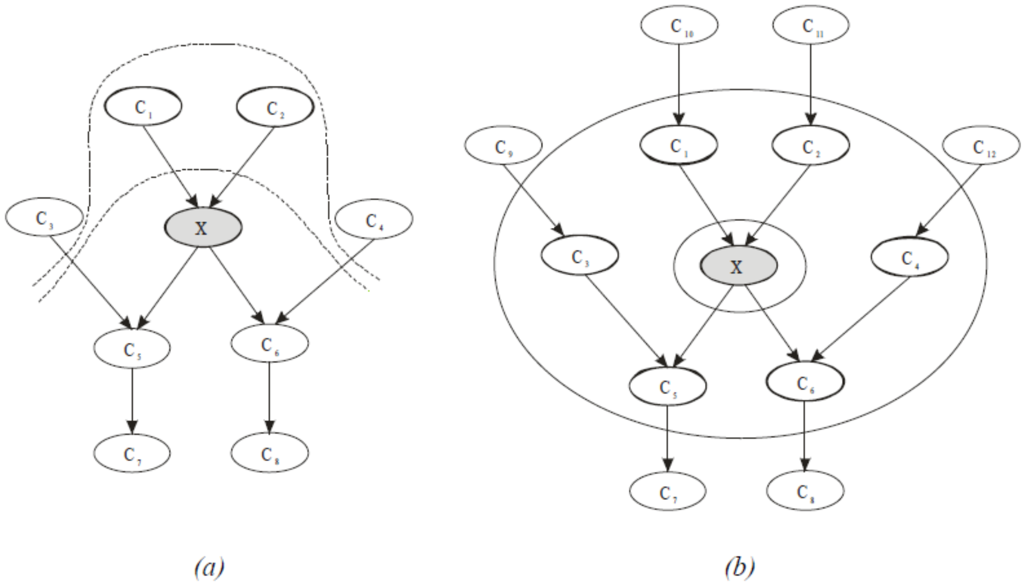


Figure 27. Criteria topological conditional independence: (a) X is independent of C3 and C4 (b) X is conditionally independent of C7, C8, C9, C10, C11, C12.

It has been shown how to derive the formulation of the Bayesian network from the most general form possible of the probabilistic model: the joint probability distribution. This process, although strict, is not the only effective and the simpler to reach the construction of a network. In general, a Bayesian network can be built in three alternative ways:

- Total Direct Synthesis: direct implementation of the nodes, the structure of conditional independence relations and probability distributions.
- Partial Direct synthesis: direct implementation of the nodes, the structure of conditional independence relations and estimation of the probability distributions through statistical learning techniques.
- Indirect Synthesis (structural learning): estimation of the nodes, the structure of conditional independence relations and probability distributions using statistical learning techniques.

4.4.2. Bayesian inference

The inference in Bayesian networks is a particular form of probabilistic inference that allows the estimation of the distributions of posterior probability of a subset of nodes, given the knowledge of the probability distributions of a second subset disjoint from the first. A Bayesian network, in general, calculates the value of the probability distribution of the individual nodes starting from the probability distribution a priori attributed to root nodes and the conditioned probability distributions relative to the other nodes. In the example of burglary alarm, represented in the following Figure 28, we can read the probability distributions of each node. The most interesting aspect of the inference through networks occurs when changing the probability distribution of a node of the network.

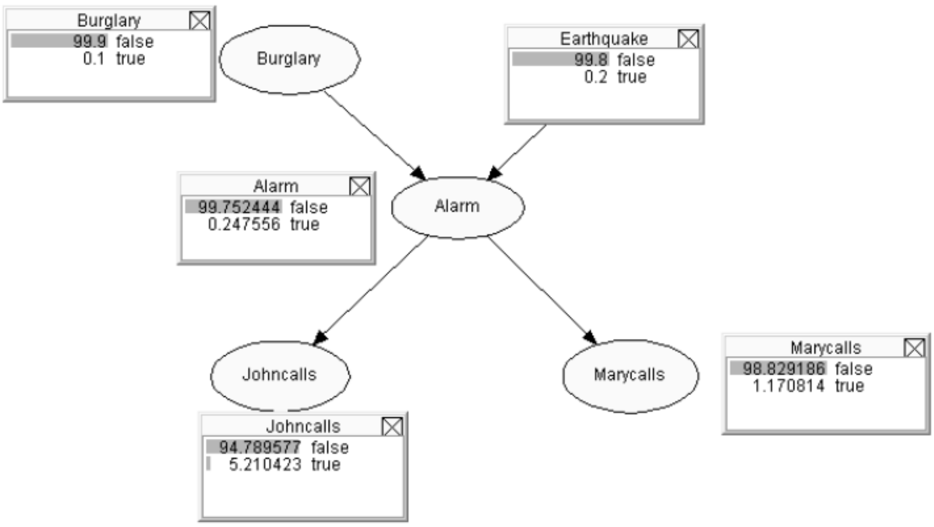


Figure 28. Bayesian network related to the example of the burglary from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008).

From a computational standpoint, a Bayesian network maintains coherence of the probability distributions of the various nodes, according to the distributions expressed by conditioned probability relations. Therefore, if for some reason, a probability value of a variable changes, the network propagates the effects of this change to all the other nodes, as a function of the relationships that connect them. The simplest change of the probability distribution of a node consists of the observation of the event relative to the node. In the Bayesian inference, a node is said to be noted when you have full assurance of his state. Observed node has a probability distribution in which only one, among the possible values, has a probability equal to one. The observation of the state of a node involves the updating of the probability distributions of all the other nodes. For example, the observation of "Earthquake" node in the network of Figure 29 causes the updating of all nodes in the network that are conditionally dependent from it.

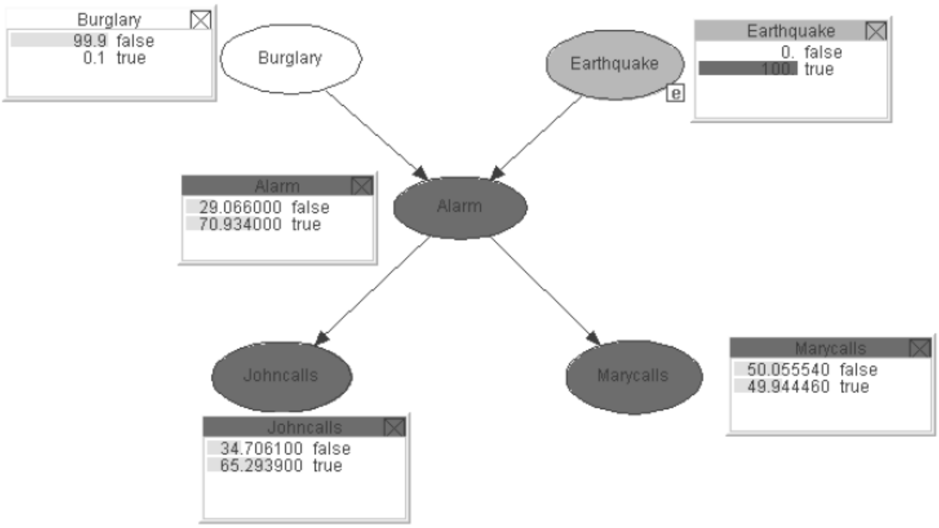
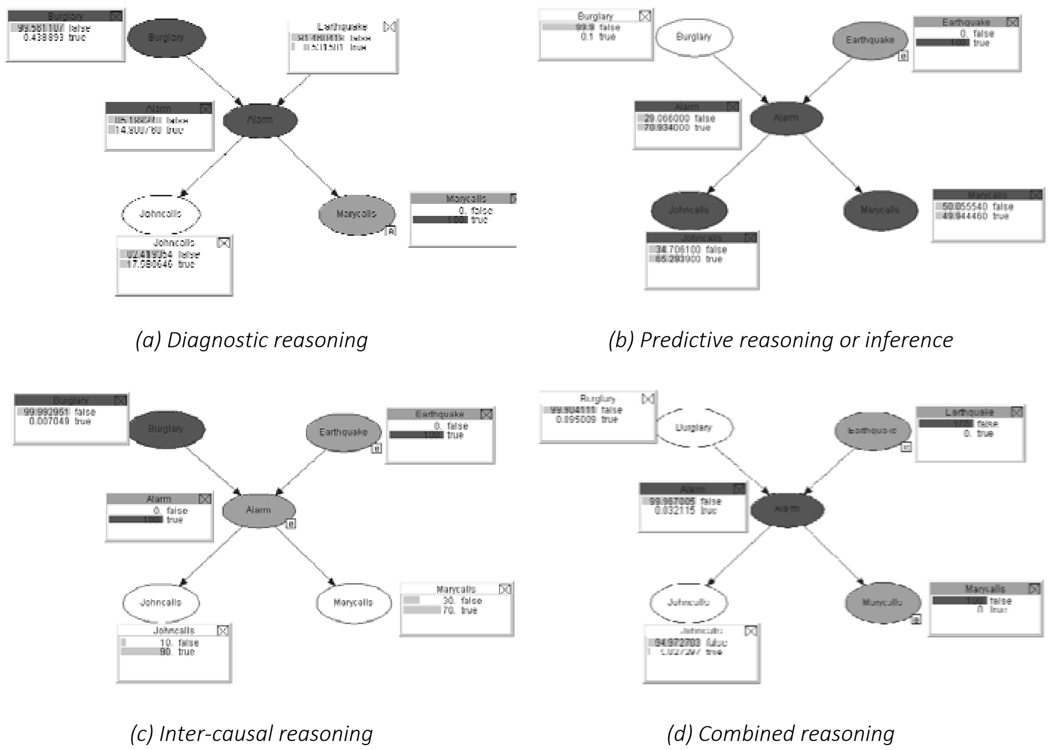


Figure 29. Bayesian network related to the example of the burglary alarm from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008). *The observation of the "Earthquake" node causes the updating of probability distributions of all nodes in the network conditionally dependent (in dark grey).*

The observation can be made for one or more nodes of any network. So, depending on the position of the nodes observed, it is possible to simulate some important types of logical inference:

- Diagnostic reasoning (Figure 30(a)): it is also called back inference (it is a form of induction) and consists of the observation of a leaf node (that has no children) and in the evaluation of possible causes, analyzing the chain from parent nodes to the root nodes (those that do not have parents). The reasoning that proceeds from symptoms to causes, considering the probable causes of a particular symptom.
- Predictive reasoning or inference (Figure 30(b)): it is also called forward inference, the observed nodes are root nodes (that nodes that have no parents) and it is evaluated the impact on leaf nodes (that nodes that have no children). Assuming to have some information about the state of other variables mentioned as effects which follow in the direction of the arcs through the network.

- Inter-causal reasoning (Figure 30(c)): in the case where a node C has two or more parents, the observation of the value in the node C and of one or more of its parents causes the updating of the probability of the remaining nodes parents. If there are two reasons that may have generated the same effect, the evidence of a cause and effect that change the probability of the occurrence of the other cause.



(a) Diagnostic reasoning

(b) Predictive reasoning or inference

(c) Inter-causal reasoning

(d) Combined reasoning

Figure 30. Models of inference with Bayesian networks from (De Grassi, Mario; Naticchia, Berardo; Giretti, Alberto; Carbonari, 2008).

4.4.3. Development of a Bayesian network for the struck-by hazard

In this research study, as already mentioned in Section 1.2, the knowledge expert is applied to judge the real criticality of the spatial conflicts detected by the proposed simulator. A fully description of its integration in the overall framework is provided in the next Section 4.5. More in detail, this study applies Bayesian inference, exhaustively introduced in the previous Sections 4.4.1 and 4.4.2, to support the construction management team in the refinement process of the work schedule. The construction manager, on the basis of the risk assessment provided by the Bayesian network, can take aware decisions about if resolving or not the uncertain geometric spatial conflicts.

In this study, a Bayesian network has been developed with reference to the struck-by hazard, being one of the most diffused and addressed by literature and field experts. The approach adopted in this study for developing the Bayesian network comes from the basic concept presented in (Nguyen, Tran and Chandrawinata, 2016) and illustrated by the following Figure 31.

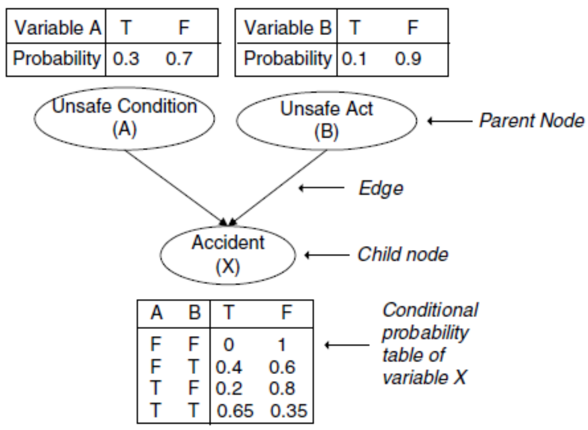


Figure 31. Example of BN for assessment of safety risk from (Nguyen, Tran and Chandrawinata, 2016).

Figure 31 clearly depicts the cause-effect relationship between an accident and the combination of unsafe conditions and acts. In the struck-by hazard, the accident can be described as originated from a combination of both. The unsafe act can be defined by the possibility that whatever element falls to a lower level. The unsafe condition can be defined as the vulnerability of laborers to be potentially hit by elements that can potentially fall.

In (Nguyen, Tran and Chandrawinata, 2016), the authors have synthesized and evaluated the risk factors provided in literature to define a general Bayesian network model that can be used for predicting safety risk of falls from height (Figure 32). To this purpose, the following classification of factors influencing risk of falls has been adopted:

- Level 1: External factors include the factors related to political or external issues. Four factors in this category consist of (1) political impact; (2) regulatory influence; (3) market condition; and (4) social impact.
- Level 2: Policy factors include the factors related to contracting strategy, ownership and control, and construction company culture. Seven factors in this category consist of (1) contracting strategy; (2) ownerships and control; (3) company culture; (4) organizational structure; (5) safety and health (S&H) management; (6) labor relations; and (7) company profitability.
- Level 3: Organizational factors include the factors related to site organization and local management. Twelve factors in this category consist of (1) recruitment and selection; (2) training; (3) procedures; (4) planning; (5) incident management and feedback; (6) management/supervision; (7) communications; (8) safety culture; (9) equipment purchasing; (10) inspection and maintenance; (11) payment conditions; and (12) design process.
- Level 4: Direct factors include the factors related to site operatives and technicians. In this category, the 13 factors consist of (1) competence; (2) motivation/morale; (3) teamwork; (4) situational awareness/risk perception; (5) fatigue/alertness; (6) health; (7) communications; (8) information/advice; (9) compliance; (10) suitable human resources; (11) working condition; (12) operational equipment; and (13) safety equipment/PPE.

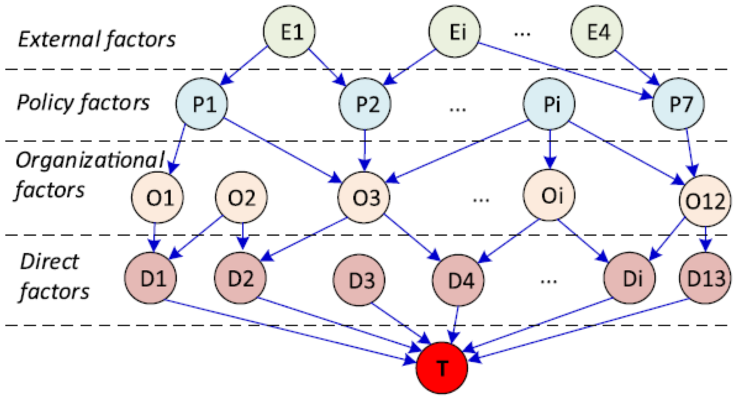


Figure 32. Generic BN model, from (Nguyen, Tran and Chandrawinata, 2016)*, for predicting safety risk of falls from height.*

The Bayesian network proposed in this study (Figure 33) originates from both the basic cause-effect relationship between accident and unsafe act/condition, depicted in Figure 31, and the structural levels, shown in Figure 32.

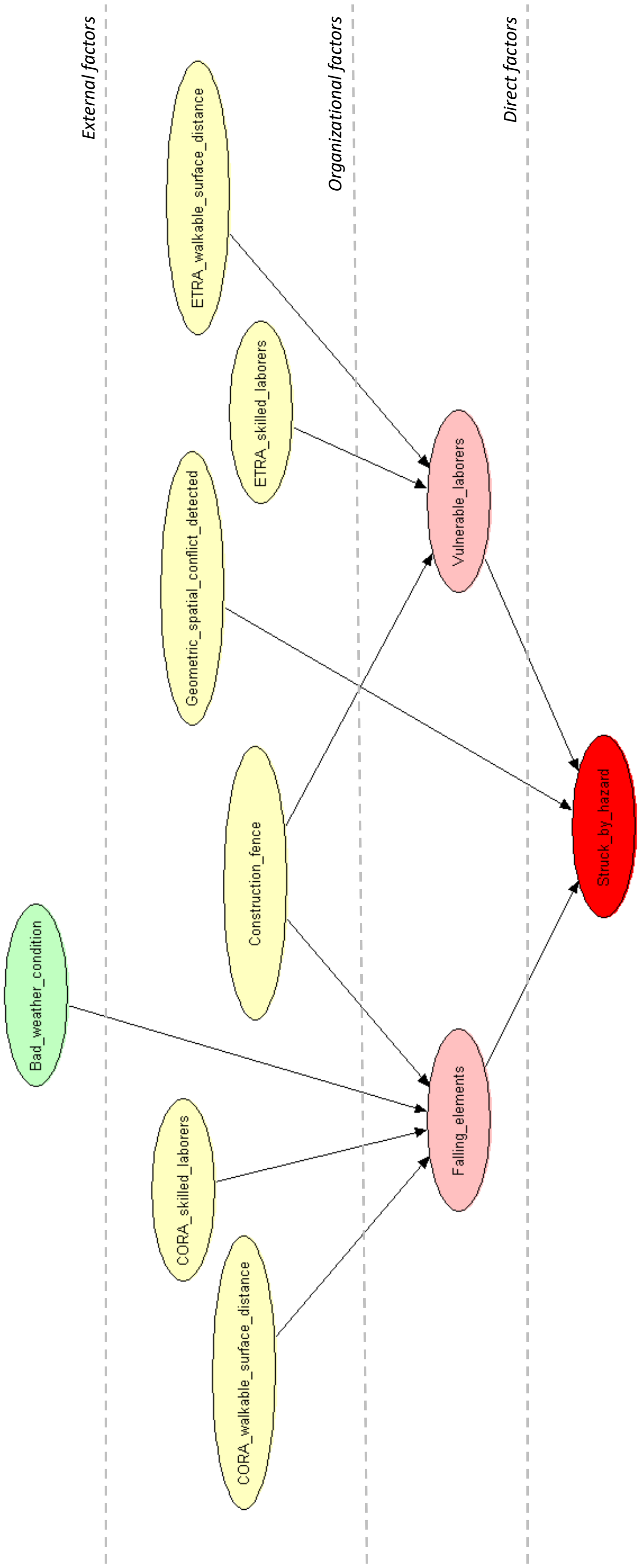


Figure 33. Bayesian network proposed in this study for assessing the struck-by hazard.

Describing the proposed Bayesian network from the bottom to the top, the first variable is the “Struck_by_hazard” one. It is a labelled variable that has three states, namely “high”, “medium”, and “low”, representing the different levels of risk. The higher probability on a specific state, among “high”, “medium”, and “low”, means that there is, respectively, a “high”, “medium”, or “low” risk 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 the “Falling_elements” and the “Vulnerable_laborers”. According to (Nguyen, Tran and Chandrawinata, 2016), the first one is the unsafe act, whereas the second one is the unsafe condition. More details are provided as follows:

- “Falling_elements”: it is a Boolean variable and, as such, it has “true” and “false” states. If this variable state is “true”, it means that elements can fall from the CORA workspaces and hit the ETRA workspace. On the contrary, if this variable state is “false”, it means that no elements can fall from the CORA workspace and hit the ETRA workspace.
- “Vulnerable_laborers”: it is a Boolean variable and, as such, it has “true” and “false” states. If this variable state is “true”, it means that the laborers involved in the ETRA workspace can be exposed to struck-by events. On the contrary, if this variable state is “false”, it means that no laborers involved in ETRA workspace can be exposed to struck-by events.

The “Organizational factors” level’s variables of the proposed Bayesian network are:

- “Construction_fence”: it is a Boolean variable and, as such, it has “true” and “false” states. If this variable state is “true”, it means that a construction fence exists and works as a barrier able to block elements falling from CORA workspaces into ETRA workspaces. On the contrary, if this variable state is “false”, it means that no barrier exists or if it exists, it cannot block elements falling from CORA workspaces into ETRA workspaces.

- "Geometric_spatial_conflict_detected": it is a Boolean variable and, as such, it has "true" and "false" states. If this variable state is "true", it means that at least a geometric spatial conflict has been detected between a pair of workspaces. On the contrary, if this variable state is "false", it means that no geometric spatial conflict has been detected between workspaces.
- "CORA_skilled_laborers" and "ETRA_skilled_laborers": both the variables, the first one referring to Cause-of-Risk Activities (CORA) and the second one referring to Exposed-to-risk Activities (ETRA), are Boolean variables and, as such, they have the "true" and "false" states. If these variables have a "true" state, it means that most of the laborers, included within the crew, is skilled, otherwise not skilled.
- "CORA_walkable_surface_distance" and "ETRA_walkable_surface_distance": both the variables, the first one referring to Cause-of-Risk Activities (CORA) and the second one referring to Exposed-to-risk Activities (ETRA), are interval variables. They include two states, namely "0-2" and "2-inf". The first one means that the walkable surface limit is closer than 2 meters from the edge of the higher walkable element, whereas the second one farer than 2 meters.

The "External factor" level's variable of the proposed Bayesian network is:

- "Bad_weather_condition": it is a Boolean variable and, as such, it has "true" and "false" states. If this variable state is "true", it means that there are bad weather conditions. On the contrary, if this variable state is "false", it means that there are no bad weather conditions.

Once the Bayesian network has been defined, it must be fed with data from experts. When insufficient data are available to specify the uncertainty of a variable completely, one or more experts will usually be consulted to provide their opinion of the variable's uncertainty (Boeykens, 2011). This process is commonly defined elicitation of expert opinion. Following the example provided in (Shiratuddin and Thabet, 2011), a survey has been arranged to get, from field experts, the information needed to fill the conditional probability tables (CPTs). This section, since providing an exhaustive description of the developed struck-by hazard Bayesian network, has been provided to experts to guide them in the filling of the CPTs reported in Section 5.2.1.

4.5. Workspace management framework

The stack of concepts and instruments described earlier in Section 4 represents the building blocks of the spatial conflict simulator proposed in this study. The integration of these building blocks into the spatial conflict simulator, along with its interface with the construction planning phase, the latter in charge to the project management team, are described by the workspace management framework, represented by the Business Process Model (BPM) reported in Figure 34. In the same Figure 34, the pool above includes the tasks executed by the project management teams during the construction planning phase, whereas the one below describes the functioning of the proposed spatial conflict simulator. The latter, as described in detail in the next Section 5, has been implemented in the serious gaming environment Unity3D™.

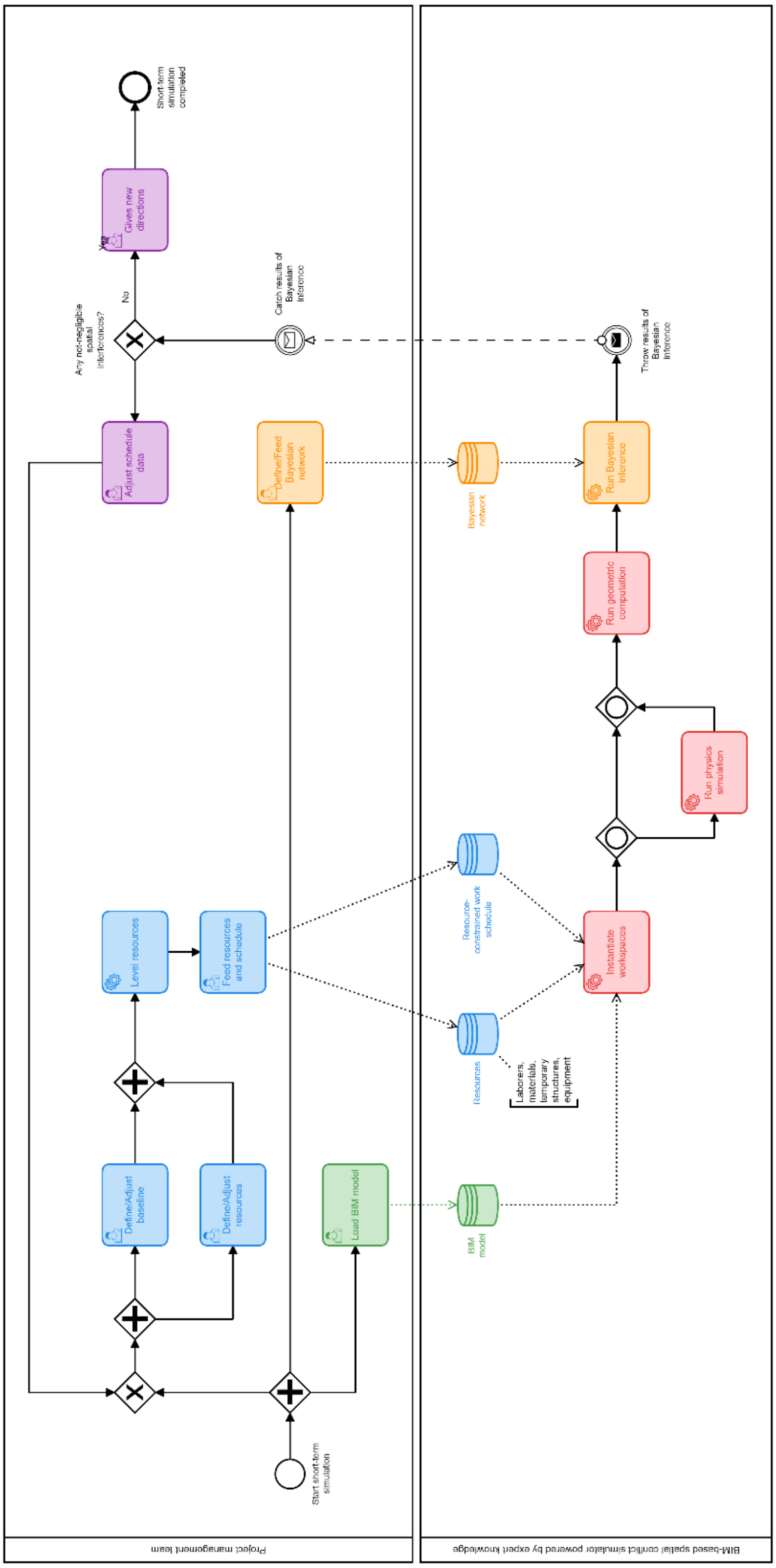


Figure 34. Workspace management framework proposed by this study.

As indicated by the parallel gateway reported at the beginning of the BPM in Figure 34, the construction manager executes three main tasks in parallel. The green nodes describe the process of loading the BIM model within the serious gaming environment Unity3D^{TM} (i.e., "Load BIM model" task). The blue nodes describe the process of defining the resource-constrained schedule and importing it in Unity3D^{TM} (i.e., "Define/adjust baseline", "Define/adjust resources", "Level resources", and "Feed resources and schedule" tasks). As shown in Figure 34, the resource-constrained schedule is generated by defining first both the baseline and allocating resources available in parallel. Then, the resource levelling function, available in any one of the commercial work scheduling software, has been run. The orange nodes summarize the milestones that involve the expert knowledge formalized in Bayesian networks. Practically, this expert knowledge is applied to define the Bayesian networks' structure (i.e., cause-effect relationships between constituting node variables), and then the conditional probability tables (CPTs) (i.e., "Define/Feed Bayesian network" task).

At this point, being all the four data stores (i.e., "BIM model", "Resources", and "Resource-constrained work schedule" data stores) reported in Figure 34 fed, the spatial conflict simulator can be considered as initialized.

The red nodes are related to the workspaces' generation and related geometric computations and physics simulation. First, the workspaces are generated within the serious gaming environment (i.e., "Instantiate workspaces" task). It must be noted that this task requires as inputs both the BIM model and the resource-constrained-schedule, defining together the 4D model. The instantiated workspaces are the input of the geometric computations (i.e., "Run geometric computation" task) and physics simulations (i.e., "Run physics simulation" task). The inclusive gateway, which leads to the physics simulation node, means that this task can be executed or not. In fact, it is not accessed if only geometric intersection tests between main workspaces in their static initial position are detected. As a result, only the so-called "direct" spatial conflicts are detected. On the contrary, if the physics simulation node is accessed, the geometric intersection tests between main workspaces are carried out considering them falling down, under the law of gravity. As a result, also the so-called “indirect” or “possible” spatial conflicts are detected.

It must be noted that the possibility to carry out geometric computations combined with physics simulations constitutes one of the main contributions of this framework, and of the resulting spatial conflict simulator, to the body of knowledge. In fact, commercial 4D tools currently available in the market detect spatial interferences only considering geometric rules. The proposed tool, instead, powered by the computational capability provided by the serious game engine, can effectively carry out dynamic and physic simulations. To make an example, a 4D tool can detect the presence of a barrier that protect the crew below from spatial conflicts simply by verifying if its dimensions respect the thresholds imposed by regulations. The proposed tool, on the contrary, can simulate the heaviest construction equipment hurting the barrier to assess, not only its presence but also its strength.

The results of the simulations represent the input of the Bayesian inference (i.e., “Run Bayesian inference” node). In fact, its role is providing an estimation of the criticality level of each detected spatial conflict, according to the provided expert knowledge. To make an example, each spatial conflict can be assessed by running Bayesian inference, estimating its criticality level as “low”, “medium”, or “high”. It must be noted that the integration of the Bayesian inference with geometric computations and physics simulations constitutes one of the main contributions provided by this research to the body of knowledge. In fact, not all the detected spatial conflicts provided by the geometric computation are critical. Filtering the ones whose criticality level is low would avoid delaying in vain those activities that, given the surroundings conditions, are not going to cause any spatial issues. In this way, both construction site safety and productivity can be ensured.

In the proposed workspace management framework, the Bayesian inference is the corner stone of the overall DSS. In fact, the Bayesian inference’s results, providing an estimation of the criticality level of each detected spatial conflict, guides the construction manager to make aware decisions during the refinement process of the work schedule (i.e., “Adjust schedule data" task). The cycle described by the proposed workspace management framework, trying to validate the given work schedule in the short horizon ahead, embodies the Lean principles formalized by the Last Planner System. This continuous refinement cycle goes on until no critical spatial conflicts has been detected. At this point, the resulting work schedule can be applied on the field and the construction manager can give directions according to it (i.e., "Give new directions" task).

CHAPTER 5

5. Prototype development

In this Section, the functioning of the serious gaming tool is described step by step. The following Section 5.1, structured in subsections corresponding to the most relevant milestones of the tool application, guides the reader through loading the BIM model (Section 5.1.1) and the work schedule (Section 5.1.2) within Unity3D^{TM}, generating the main workspaces (Section 5.1.3), and finally detecting "direct" (Section 5.1.4) and "indirect" or "possible" (Section 5.1.5) spatial conflicts. The implementation of the Bayesian network for struck-by hazard events (Section 5.2.1) and its use within the serious gaming tool (Section 5.2.2) is described in the following Section 5.2. Finally, Section 5.3 describes the integration of the serious gaming tool and its components in the proposed workspace management framework.

The Entity Relationship Diagram (ERD), in Figure 35, depicts the information model that regulates the developed prototype. The ERD notation 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 35, are referred to different entity domains, such as BIM model (green), work schedule (blue), main workspaces and spatial conflicts (red), and Bayesian inference (orange).

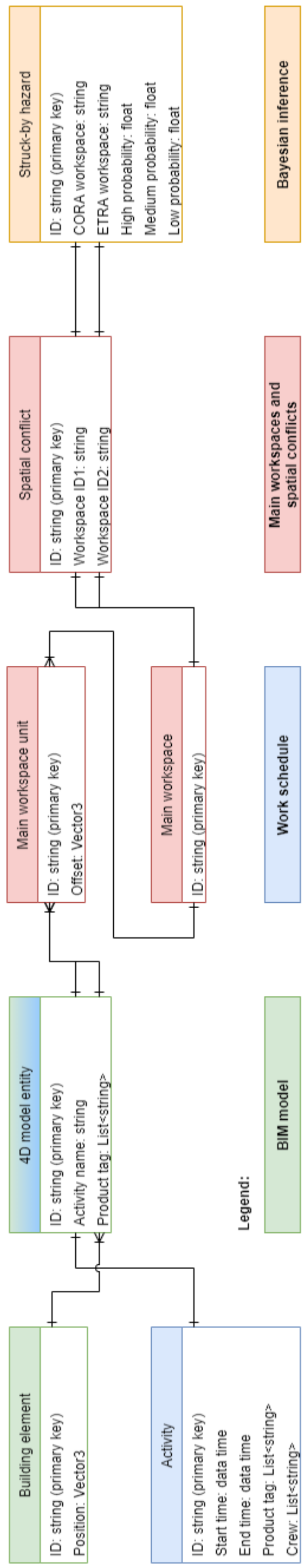


Figure 35. ERD describing the information model that regulates the developed prototype.

5.1. The serious gaming tool

5.1.1. Loading the BIM model

First of all, the Unity3D™ scene must be opened, and the game launched by clicking on the "Play" button. Then, the physical space of the construction site assumed as use case must be imported in Unity3D™. To that end, an IFC Loader for Unity3D™, internally developed by the DICEA Department on the basis of the IFC Engine DLL library (RDF Ltd., 2006), has been applied. The "File Chooser" component (Figure 36), attached to the "IFC Loader" game object, enables the selection and loading of the desired IFC model. By clicking on the "Ifc Model File" button, shown in Figure 36, the IFC model of the use case can be selected from its folder. This step will fill the "Path" and the "File" fields with the information of the IFC file to be loaded.

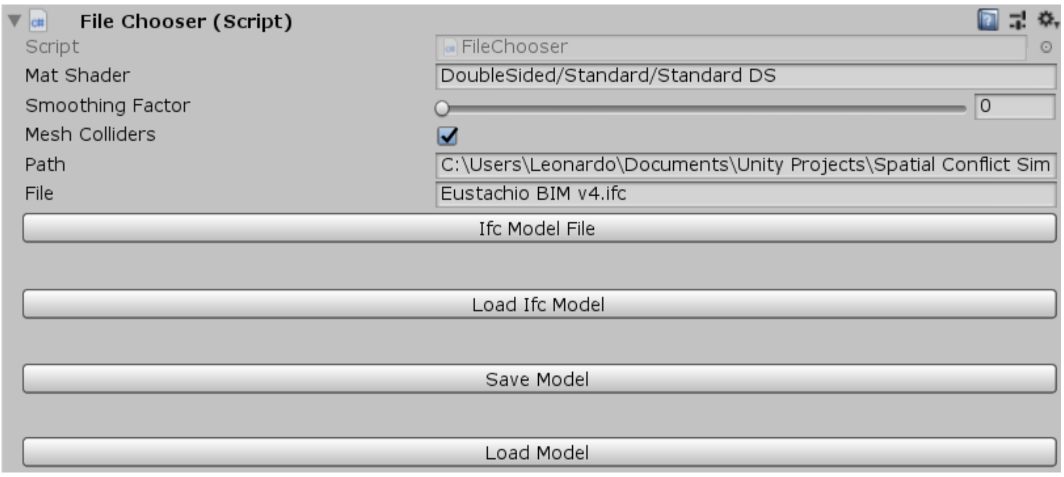


Figure 36. Front end of the IFC Loader for Unity3D™.

Afterwards, by clicking on the "Load Ifc Model" button, the selected IFC model will be loaded and displayed in the Unity3D™ scene (Figure 37). As shown in the Unity3D™ hierarchy, reported in Figure 37, the structure of the IFC is maintained within Unity3D™ and each building element is defined as the Revit family and type names, plus the Revit ID.

In the ERD, reported in Figure 35, the “building element” entity represents each building element of the BIM/IFC model. Its “ID” and “position” parameters correspond, respectively, to Revit ID and space location defined in the BIM/IFC model.

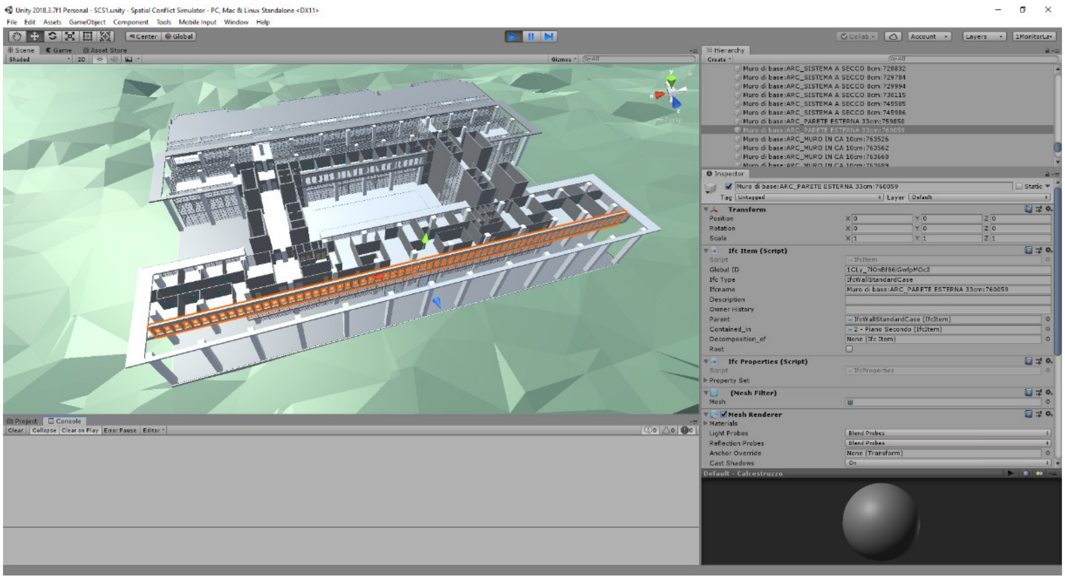


Figure 37. IFC model uploaded in Unity3D™.

5.1.2. Loading the work schedule

In order to define the 4D model, the work schedule must be imported within Unity3D™. The “Model Input” component, attached to the “Simulation Manager” game object, enables this step (Figure 38). The “File Path” field must be filled with the folder location where the CSV-formatted work schedule file is stored. By clicking on “Read Work Schedule” button, the work schedule will be read, and the “Activity Name List” (Figure 39), “Product Tag String List” (Figure 40), and “Crew String List” (Figure 41) filled with the corresponding information. The “Product Tag String List” contains the Revit IDs of the building elements produced by each activity of the work schedule. In this way, since the name of each building element imported within Unity3D™ by the IFC Loader includes this ID, the linkage between each building element and the corresponding activity information is defined. It must be noted that the element index across these three lists links the records of “Product Tag String List” and “Crew String List” to the “Activity Name List” ones.

If the work schedule has changed and another one must be loaded, the "Clear List" button can be used to erase the loaded information and start the process from scratch.

In the ERD, reported in Figure 35, the "activity" entity represents each activity, defined in the work schedule, whose name fills the "ID" parameter. The other parameters store the temporal information (i.e., "Start/end time"), the produced building elements (i.e., "Product tag"), and the allocated human resources (i.e., "Crew"). At this simulation step, having loaded both BIM model and work schedule, the "4D model entity" is defined. Its role is linking the 3D geometric information of the BIM model with the temporal data provided by the work schedule. Hence, each "4D model entity" corresponds to one activity (i.e., "Activity name") and includes one or more produced building elements (i.e., "Product tag").

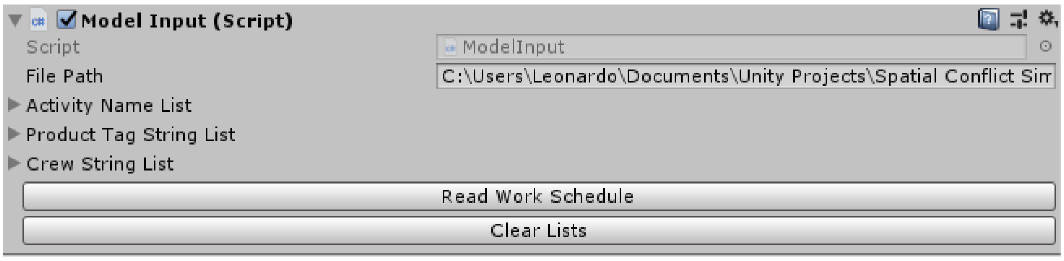


Figure 38. Front end of the "Model Input" component.

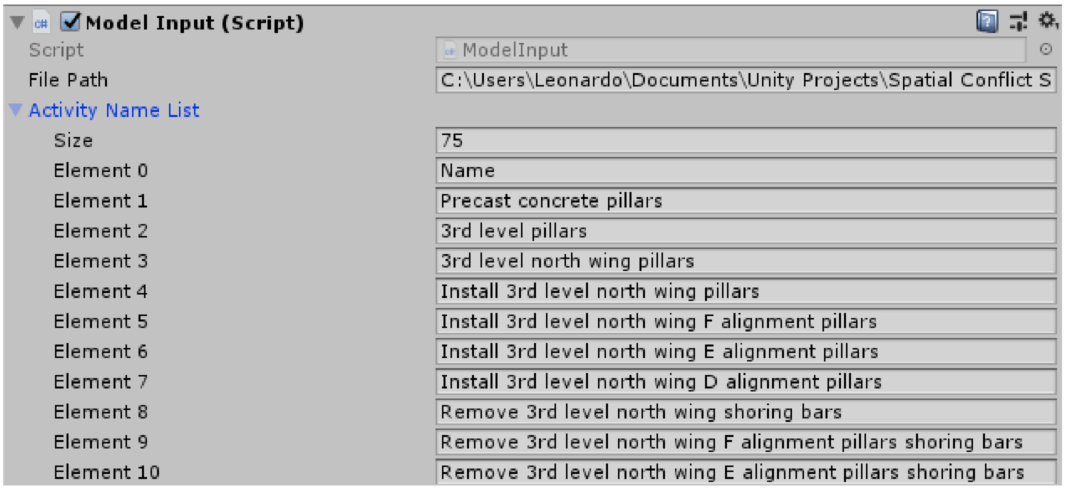


Figure 39. "Activity Name List" filled with the information from the work schedule.

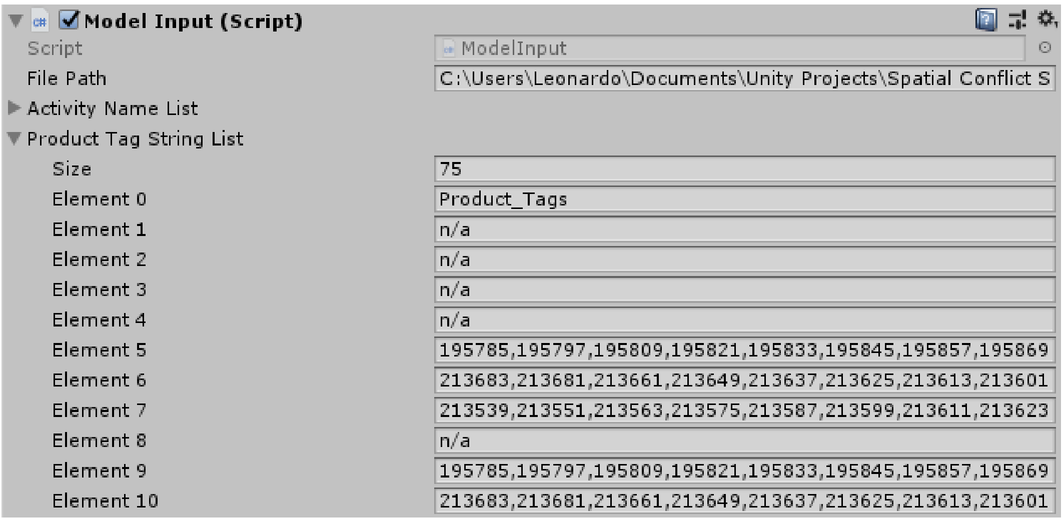


Figure 40. "Product Tag String List" filled with the information from the work schedule.

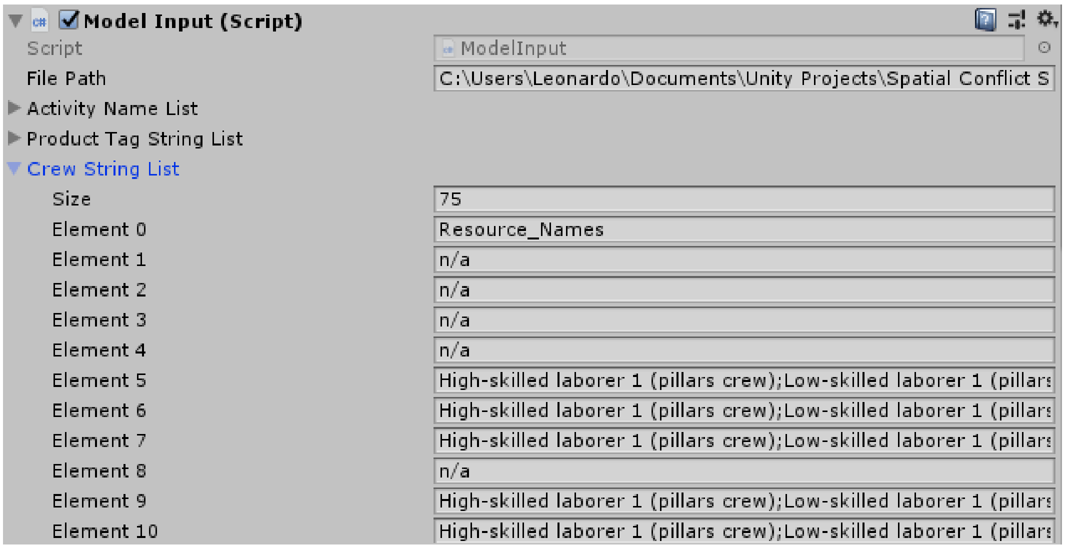


Figure 41. "Crew String List" filled with the information from the work schedule.

5.1.3. Generating main workspaces

At this point, all the information required for generating the main workspaces within Unity3D™ have been imported. This step is enabled by the "Instantiate Main Workspace From IFC" component, attached to the "Main Workspace Manager" game object (Figure 42). The "Start Date" field must be filled with the date of the first work schedule day to simulate. The "Elapsed Days" field, instead, must be filled with the number of days, from the "Start Date" forward, to be simulated.

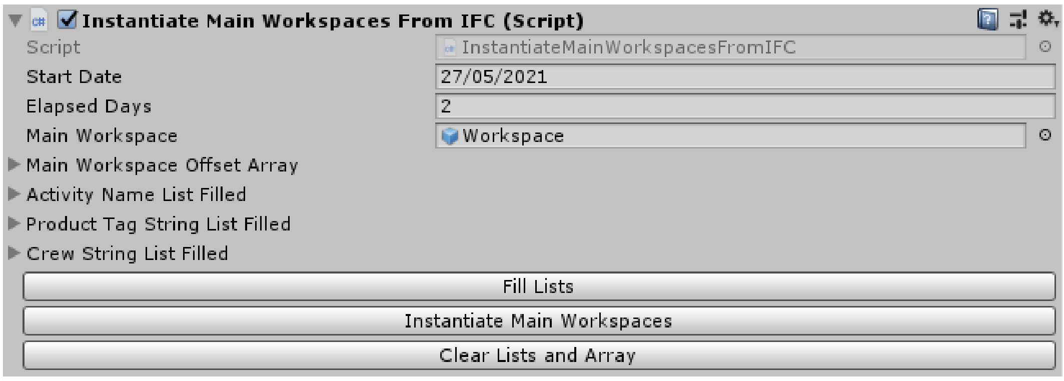


Figure 42. Front end of the "Instantiate Main Workspace From IFC" component.

Afterwards, by clicking on the "Fill List" button, the work schedule information will be filtered according to the selected time interval. "Activity Name List Filled", "Product Tag String List Filled", and "Crew String List" reports only the information of the activities executed in this period. The "Main Workspace Offset Array", instead, includes the offsets that are applied in the three directions to each building element executed by each activity. These parameters, set by default as 1 meter, mean that the main workspace unit, instantiated for each building element executed (e.g., a module of precast facade), is obtained by expanding its dimensions of 1 meter in all the three dimensions. These parameters can be customized by the user, just in case a bigger operational or safety space is required.

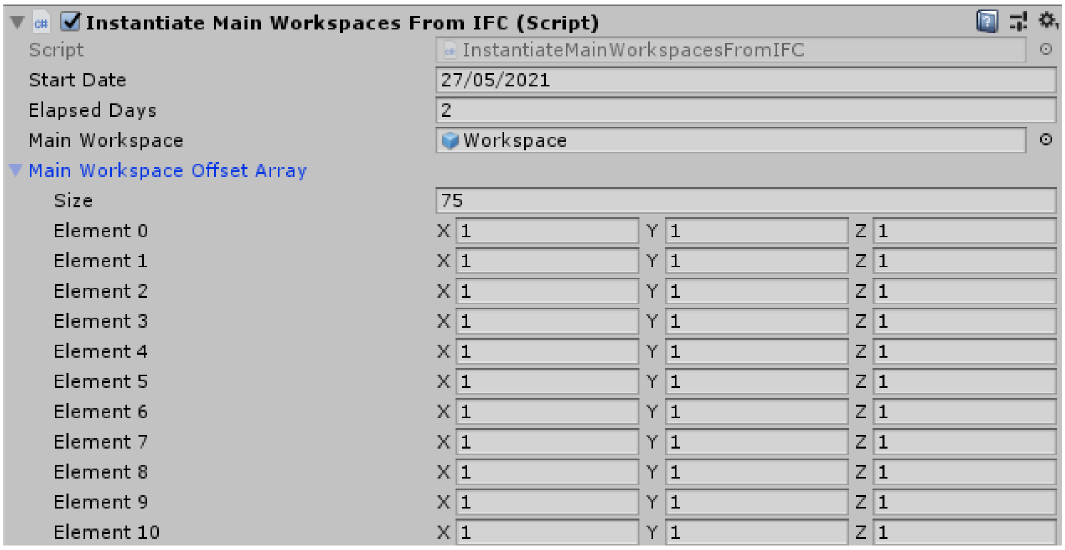


Figure 43. "Main Workspace Offset Array" filled by default with the 1-meter offset in all the three directions.

The “Instantiate Main Workspace” button enables the generation of the main workspaces of the activities executed in the selected time interval. In detail, a main workspace is obtained by merging the main workspace units, instantiated for each one of the building elements (e.g., a module of precast facade) associated to the considered activity (e.g., install an alignment of module of precast facade). Following the example of the precast facade module, its main workspace unit is instantiated in the geometric center of the considered facade module. Figure 44 shows the main workspaces generated for the activities scheduled within the selected simulation time interval. In the Unity3D™ hierarchy (Figure 45), the main workspaces are instantiated as children game objects of the “Main Workspace Manager” component. The name of each main workspace is defined as the name of the corresponding activity plus the wording “(main workspace)”. The children of each main workspace (e.g., “Install 3rd level north wing north facades (main workspace)”) are the main workspace units defined for each building element executed by the considered activity. As shown in Figure 45, the name of each main workspace unit is defined as the Revit ID of the single building element plus the name of the corresponding activity.

The “Clear Lists and Array” button triggers the automatic cancellation of all the fields of the “Main Workspace Offset Array”, “Activity Name List”, “Product Tag String List”, and “Crew String List Filled”.

In Figure 35, the “Main workspace unit” entity represents the workspace generated around each building element on the basis of the default or customized “Offset” parameter. As mentioned above in this Section, the “ID” of the “Main workspace unit” inherits the “Activity name” and “Product tag” parameters from the “4D model entity”. The “Main workspace” entity is then defined by merging one or more “Main workspace unit” produced by the considered activity.

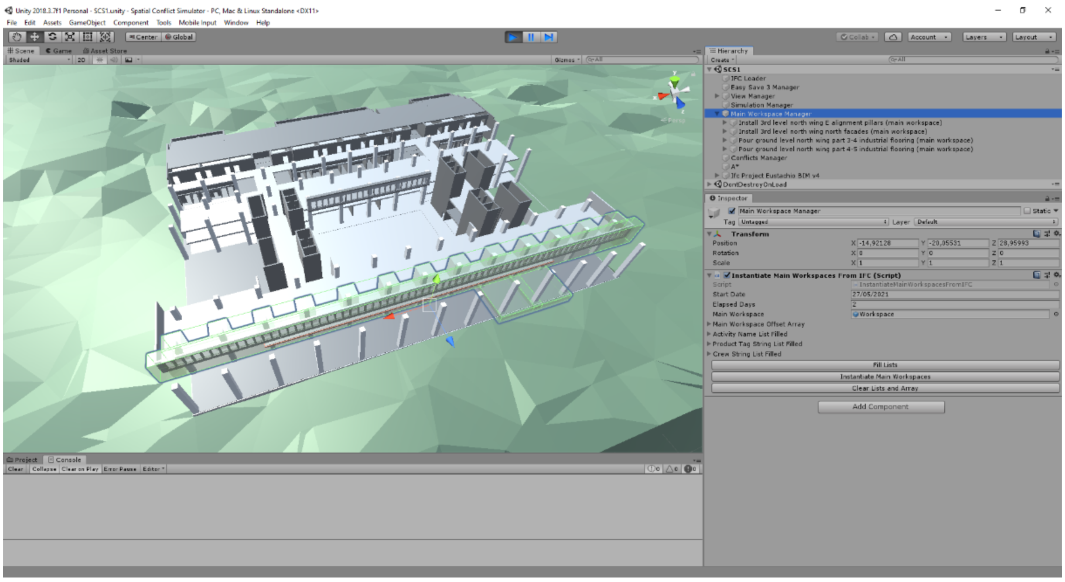


Figure 44. Main workspaces generated for the simulation time interval.

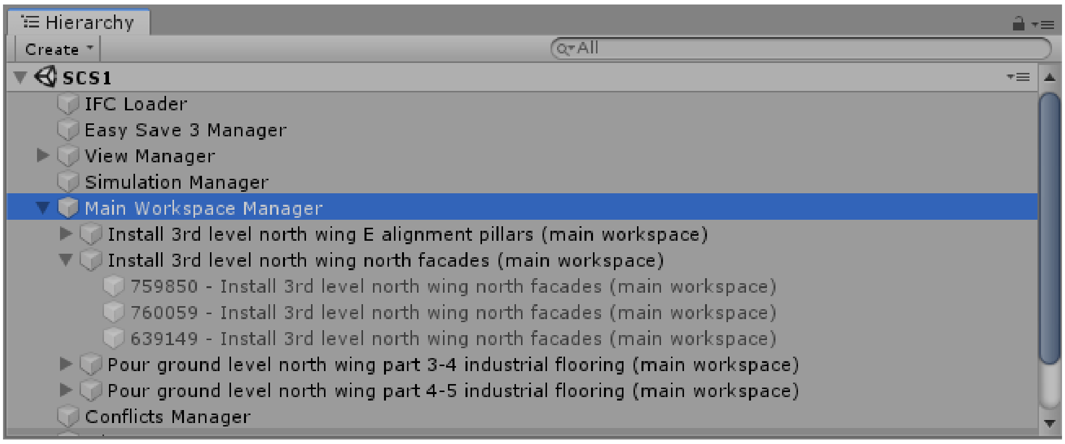


Figure 45. View of the Unity3D™ hierarchy after the generation of the main workspaces.

5.1.4. Carrying out geometric intersection tests

Once main workspaces have been instantiated for activities scheduled in the selected time interval, "direct" spatial conflicts can be detected by carrying out geometric intersection tests among workspaces in their static initial position, inherited from the corresponding building elements' ones.

This tool identifies a spatial conflict between two given workspaces only if their boundaries intersect and are assigned to different crews. The second condition must be included to consider only realistic spatial issues between workspaces. In fact, considering the intersection between two workspaces assigned to the same crew as a spatial issue is not properly correct for several reasons. First of all, a crew assigned at the same time to different workspaces indicates that it is overallocated. Secondarily, even accepting this condition, the crew, being aware about the space shared by the two workspaces, would internally manage this interference.

Detecting this kind of spatial conflicts is included in the state of the art of workspace management. In the developed serious gaming tool, the geometric intersection tests are triggered by clicking on the "Find Geometric Spatial Conflicts" button of the "Intersection Test" component, the latter attached to the "Conflicts Manager" game object (Figure 46).

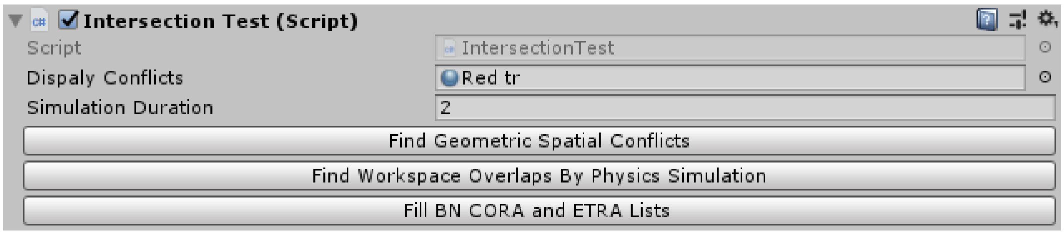


Figure 46. Front end of the "Intersection Test" component.

The developed tool displays a detected spatial conflict by changing the color, of involved main workspaces, from green to red (Figure 47). In addition, a message reporting the pairs of the conflicting main workspaces is printed in the Unity3D^{TM} console (Figure 48). The format of the message is reported as follows:

"Spatial conflict detected! Workspaces involved: " +

+ name of the 1st overlapping workspace + "; " +

+ name of the 2nd overlapping workspace + "."

In Figure 35, the "Spatial conflict" entity is defined by means of the "Workspace ID1" and "Workspace ID2" parameters, inherited from the conflicting "Main workspace" entities' "ID".

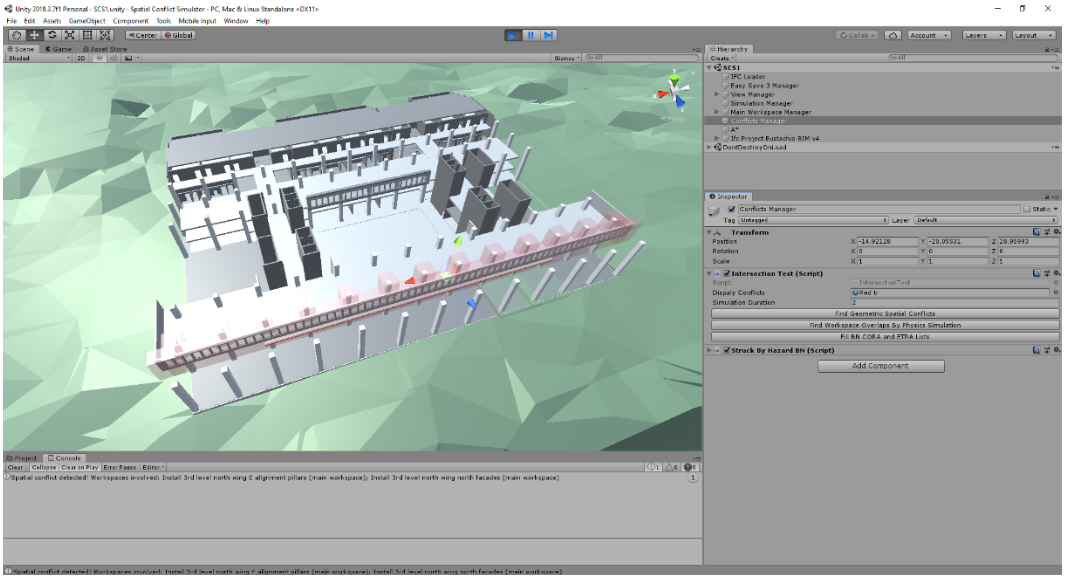


Figure 47. "Direct" spatial conflicts detected by geometric intersection tests.

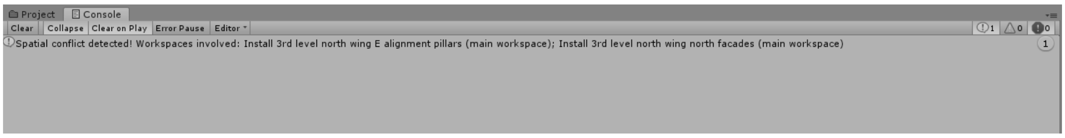


Figure 48. View of the Unity3D^{TM} console reporting the list of "direct" spatial conflicts.

5.1.5. Carrying out physics simulations and geometric intersection tests

The "direct" spatial conflicts have been described in the previous Section 5.1.4 as the result of geometric intersection tests among workspaces in their static initial position. It must be noted that, due to the construction site dynamics, "direct" spatial conflicts do not include the totality of spatial issues affecting the 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 higher main workspace and hit laborers below. In order to consider also this kind of conflict scenarios, the proposed tool can carry out physical simulations of main workspaces and detect related spatial conflicts. This kind of spatial conflicts are named, here on for simplicity, as "indirect" or "possible". The "indirect" definition comes from the fact that this kind of spatial conflict cannot be directly detected simply by carrying out geometric intersection test among workspaces in their static initial position. On the contrary, virtual physics simulations must be executed to consider "possible" future workspace configurations. Therefore, the resulting spatial conflicts, relying on the assumption that they virtually occur (but we cannot state if also in reality), are labelled as "possible" one.

Physics simulation and geometric intersection tests are triggered by clicking on the "Find Workspace Overlaps by Physics Simulation" button. In details, each main workspace is dropped, according to the gravity law, in order to check if it intersects any other main workspace below assigned to a different crew. The developed tool displays the detected spatial conflicts by changing the color of the main workspaces involved from green to red (Figure 49). In addition, a message reporting the pairs of the conflicting main workspaces is printed in the Unity3D™ console (Figure 50). The format of the message is reported as follows:

"Possible spatial conflict detected! Workspaces involved: " +

+ name of the 1st overlapping workspace + "; " +

+ name of the 2nd overlapping workspace + "."

In Figure 35, the "Spatial conflict" entity is defined by means of the "Workspace ID1" and "Workspace ID2" parameters, inherited from the conflicting "Main workspace" entities' "ID".

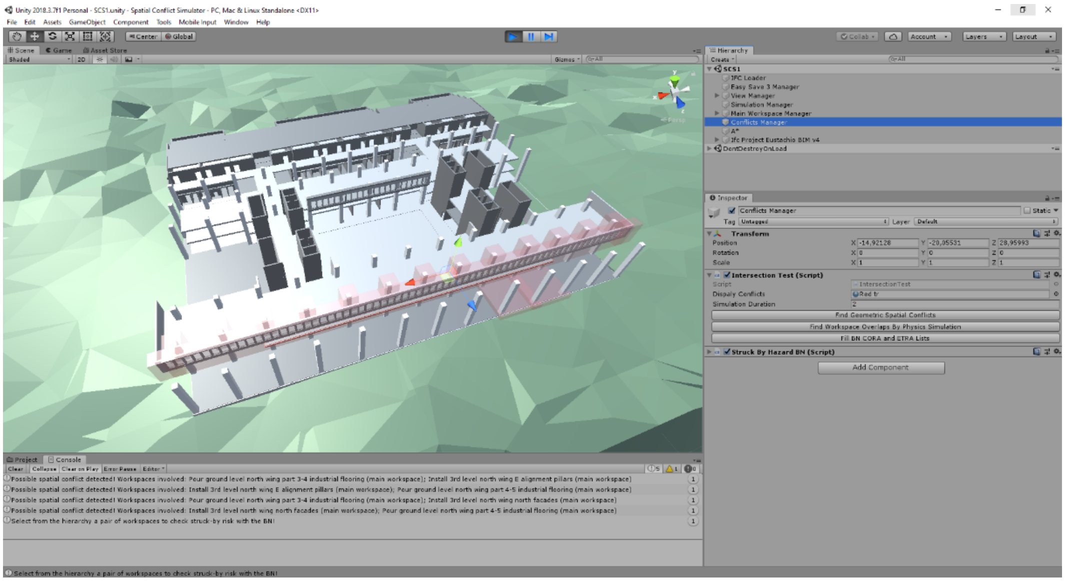


Figure 49. "Indirect" or "possible" spatial conflicts detected by geometric intersection tests during physics simulations.

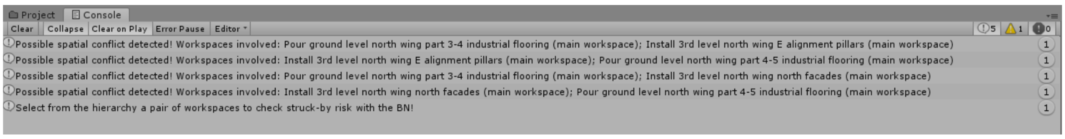


Figure 50. View of the Unity3D™ console reporting the list of "indirect" or "possible" spatial conflicts.

As explained above, the resulting spatial conflicts are "possible" since cannot be considered as certain but only as likely to happen. Hence, expert knowledge, formalized in Bayesian networks, can provide a valuable support in assessing the criticality level of each spatial conflict detected. To this purpose, a Bayesian network, which will be fully described in the next Section 5.2, has been developed for assessing the struck-by hazard probability related to each detected spatial conflict.

5.2. Implementation of the Bayesian network

In the previous Section 5.1, the serious gaming tool has been described in order to provide the reader a kind of guide for its application. "Direct" and "indirect" or "possible" spatial conflicts have been detected by carrying out geometric computations and physics simulations. As already mentioned in the previous Sections 4.5 and 5.1.5, not all the spatial conflicts detected by geometric intersection tests during physics simulations are critical. In fact, the so-called "indirect" or "possible" spatial conflicts need to be assessed by applying expert knowledge. To this regard, the Bayesian inference can help to assess the criticality levels of "possible" spatial conflicts by estimating the probability of its occurrence on the basis of the influencing variables' evidence. In the next Section 5.2.1, the process of eliciting expert knowledge for the developed struck-by hazard Bayesian network is described. Section 5.2.2, instead, describes how this Bayesian network can be run within Unity3D^{TM}, on the basis of the simulation results provided by the serious gaming environment.

5.2.1. Expert knowledge elicitation

As already mentioned in Section 4.4.3, when insufficient data are available to specify the uncertainty of a variable completely, one or more experts should be consulted to provide their opinion about the variable's uncertainty (Vose, 2008). In this Section, the process of eliciting expert knowledge for the developed struck-by hazard Bayesian network is described. This step is crucial to feed the conditional probability tables (CPTs) and make the Bayesian inference fully working.

A survey, to be submitted to field experts, has been defined. It includes Section 4.4.3, which describes the general logic behind the developed Bayesian network, and the CPTs, corresponding to each child node of it (Table 2).

In this study, a field expert has been interviewed with the aim to validate the structure of the survey and check that the Bayesian inference results are reasonable. The CPTs filled by the interviewed expert and adopted for feeding the developed struck-by hazard Bayesian network are reported in Table 3.

A reading example can be useful to ease the interpretation of the CPTs by the reader. The first column of Table 3 (c), related to the "Struck_by_hazard" variable, has been filled considering the following states of the parent nodes:

- "Geometric_spatial_conflict_detected" = false.
- "Vulnerable_laborers" = false.
- "Falling_elements" = false.

Under these conditions, the interviewed expert has assigned a probability equals to 1 to the "low" state and equals to 0 to both the "medium" and "high" states of the "Struck_by_hazard" variable. Having assigned to the "low" state the higher value means that the interviewed expert has judged an eventual struck-by event as unlikely under the above-mentioned conditions.

The last column of Table 3 (c), related to the "Struck_by_hazard" variable, has been filled considering the following states of the parent nodes:

- "Geometric_spatial_conflict_detected" = true.
- "Vulnerable_laborers" = true.
- "Falling_elements" = true.

Under these conditions, the interviewed expert has assigned a probability equals to 1 to the "high" state and equals to 0 to both the "medium" and "low" states of the "Struck_by_hazard" variable. Having assigned to the "high" state the higher value means that the interviewed expert has judged an eventual struck-by event as likely under the above-mentioned conditions.

Table 2. CPTs 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																
True																

(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								
True								

(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								
Medium								
Low								

(c)

Table 3. CPTs, filled by the expert interviewed during the survey, 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)

In future research developments, more than one expert will be interviewed and the overall CPTs adjusted accordingly. As in other studies (Nasir, McCabe and Hartono, 2003), if more than one expert is interviewed, the overall CPTs can be obtained by making the average of the values of the CPTs filled by each one. Where the maximum and minimum opinions differ by more than 30%, the experts must be asked to review their responses. The limit of 30%, determined in other studies (Nasir, McCabe and Hartono, 2003), although it was defined rather arbitrarily, can be adopted since representing a reasonable difference of opinion.

5.2.2. The Bayesian network in the serious gaming tool

Implementing the Bayesian network in Unity3D™, results of physical simulations and geometric computations can automatically feed the states of its variables for running the Bayesian inference. In this study, the commercial Discrete Bayesian Network library (Chen, 2017) for Unity3D™ has been applied for the implementation of the struck-by hazard Bayesian network in the serious gaming environment. The "Struck by Hazard BN" component, attached to the "Conflicts Manager" game object (Figure 51), implements the developed Bayesian network, along with the methods for carrying out physical simulations and getting the Bayesian network variables' evidence.

In each "indirect" or "possible" 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 hazard events. 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, having the lowest initial position is the main workspace that can be hit by falling objects. This workspace, instead, being potentially exposed to possible struck-by events, can be defined as the "Exposed-to-Risk Activities" (ETRA) workspace. For each detected "possible" spatial conflict, the serious gaming tool automatically classifies the pair of main workspaces into CORA and ETRA types, by storing them, respectively, into the "CORA List" and the "ETRA List". These lists are automatically filled after the completion of the process triggered by the "Find Geometric Spatial Conflicts" button (Figure 46).

Just in case the user wants to recall this filling, the “Fill BN CORA and ETRA lists” button, shown in Figure 46, can be pressed. It must be noted that the element index across these two lists links the records of the “CORA List” and the “ETRA List” ones (Figure 51).

Figure 51. Front end of the “Struck by Hazard BN” component before getting the Bayesian network evidences.

At this point, the user must select the main workspaces to which apply the Bayesian inference. To do this, the main workspaces with the same element index must be selected and dragged-and-dropped from the Unity3D^{TM} hierarchy to, respectively, the "Picked CORA workspace" and the "Picked ETRA workspace" (Figure 55).

Afterwards, the "1. Get Geometric Spatial Conflict Evidence" button must be pressed to fill the "Geom_confl_string" variable of the Bayesian network with the corresponding state. If a pair of CORA and ETRA workspace has been picked, meaning that at least one possible spatial conflict has been detected by physical simulations, this variable state will be "true", otherwise "false" (Figure 55).

Then, the "2. Get Bad Weather Condition Evidence" button must be pressed in order to have the "Bad_we_cond_string" variable of the Bayesian network filled with the corresponding state. If the bad weather conditions are expected according to the weather forecast, the variable state will be filled as "true", otherwise "false" (Figure 55). This functionality has been implemented by using the commercial Real-time Weather tool for Unity3D^{TM} (ASSIST Software, 2021).

The "3. Get CORA and ETRA Skilled-Laborers Evidences" button enables to fill both the "CORA_skil_lab_string" and "ETRA_skil_lab_string" variables of the Bayesian network with a "true" or "false" state, respectively if the majority of the laborers constituting the crew are skilled or not (Figure 55). This kind of information is read from the crews' information included within the resource-constrained work schedule (Figure 55).

The "4. Get Construction Fence Evidence" button enables to fill the "Constr_fence_string" variable of the Bayesian network with a "true" or "false" state, respectively if any barrier exists and can protect the laborers at the lower workspace (i.e., ETRA workspace) from falling objects. To this purpose, this button triggers the instantiation of a set number of avatars, defined by the "Fence Avatar Quantity", in a random position within the higher workspace (i.e., CORA workspace) and able to wander around in order to check if it can fall down or not (Figure 52). These avatars have been defined in Unity3D^{TM} as spheres having the same physical properties (e.g., mass, drag, etc.) of objects involved in the construction process. Hence, if they hit, ad absurdum, a barrier made of paper, then they will break through it; otherwise, if they hit a barrier made of bricks or concrete, then they will be blocked. So, if no one of the instantiated avatars hit the lower workspace (e.g., ETRA workspace), the serious gaming tool deduces the presence of a barrier that protect the ETRA workspace and the "Constr_fence_string" variable state is set as "true", otherwise "false" (Figure 55).

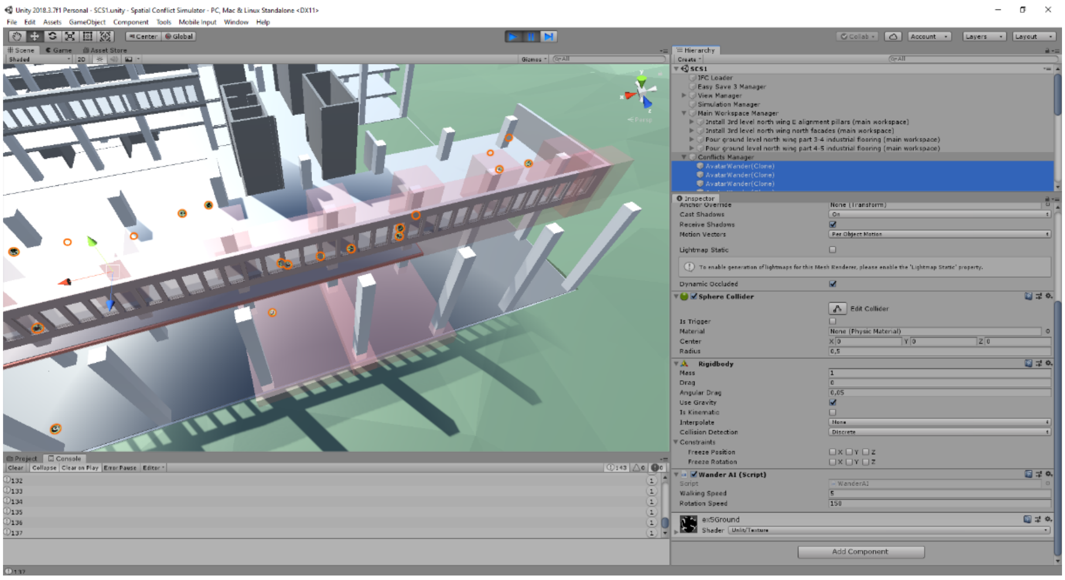


Figure 52. Instantiation of spherical random wandering avatars for checking the presence or not of any barrier protecting ETRA workspaces.

Finally, the last button of this series, namely "5. Get CORA and ETRA Walkable Surface Distance Evidence", must be clicked to fill both the "CORA_walk_surf_dist_string" and "ETRA_walk_surf_dist_string" with one of the following variable states: "0-2" and "2-inf". The first one means that the walkable surface limit is closer than 2 meters from the edge of the higher walkable element, whereas the second one farer than 2 meters. In order to get the evidence of these variables, the "5. Get CORA and ETRA Walkable Surface Distance Evidence" button triggers the geometric computation based on the walkable surfaces determined by the Recast graph provided by the A* Pathfinding tool for Unity3D™ (Granberg, 2020). In Figure 53, the green surface, provided by the Recast graph function of this tool (Granberg, 2020), is the walkable surface on the slab where the CORA workspace is placed. In the same Figure 53, 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 54, the pink surface, provided by the Recast graph function of this tool, is the walkable surface on the slab where the ETRA workspace is placed. In the same Figure 54, 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^{TM}, are reported respectively by the "CORA Walkable Surface Distance" and "ETRA Walkable Surface Distance" fields (Figure 55).

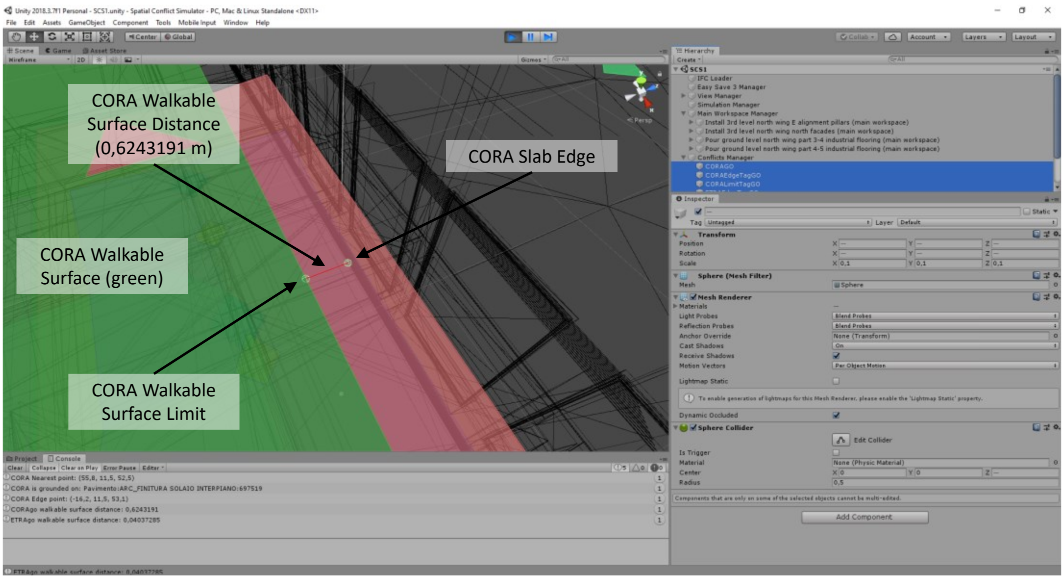


Figure 53. Automatic geometric computation of the "CORA Walkable Surface Distance" by the serious gaming tool.

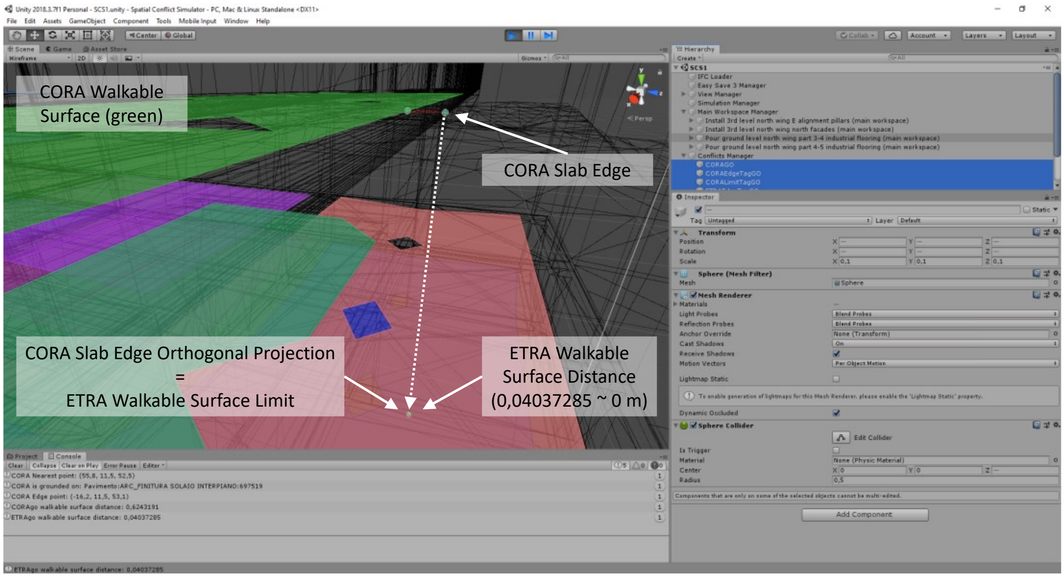


Figure 54. Automatic geometric computation of the "ETRA Walkable Surface Distance" by the serious gaming tool.

All the variables' evidence described above can be obtained, alternatively and all in one step, simply by clicking on the "Get All BN Evidences" button. Once all the evidences have been obtained, the "Run BN Inference" button must be pressed in order to obtain 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" (Figure 55). In Figure 55, the higher value has been computed for the "High_struck_by_hazard_prob" (i.e., 78,10%), indicating that, given the states of the variable, the corresponding scenario can be effectively considered as critical. As a consequence, the construction management team can benefit of the contribution given by this decision support system (DSS) during the refinement process of the work schedule.

In Figure 35, the "Struck-by hazard" entity represents the Bayesian inference. This entity is defined on the basis of the "CORA workspace" and "ETRA workspace" parameters, inherited from the "Workspace ID1" and "Workspace ID2". It must be noted that, as defined above, the CORA and ETRA workspace are assigned according to their spatial position (i.e., height). Finally, the "High probability", "Medium probability", and "Low probability" parameters corresponds to the Bayesian inference results.

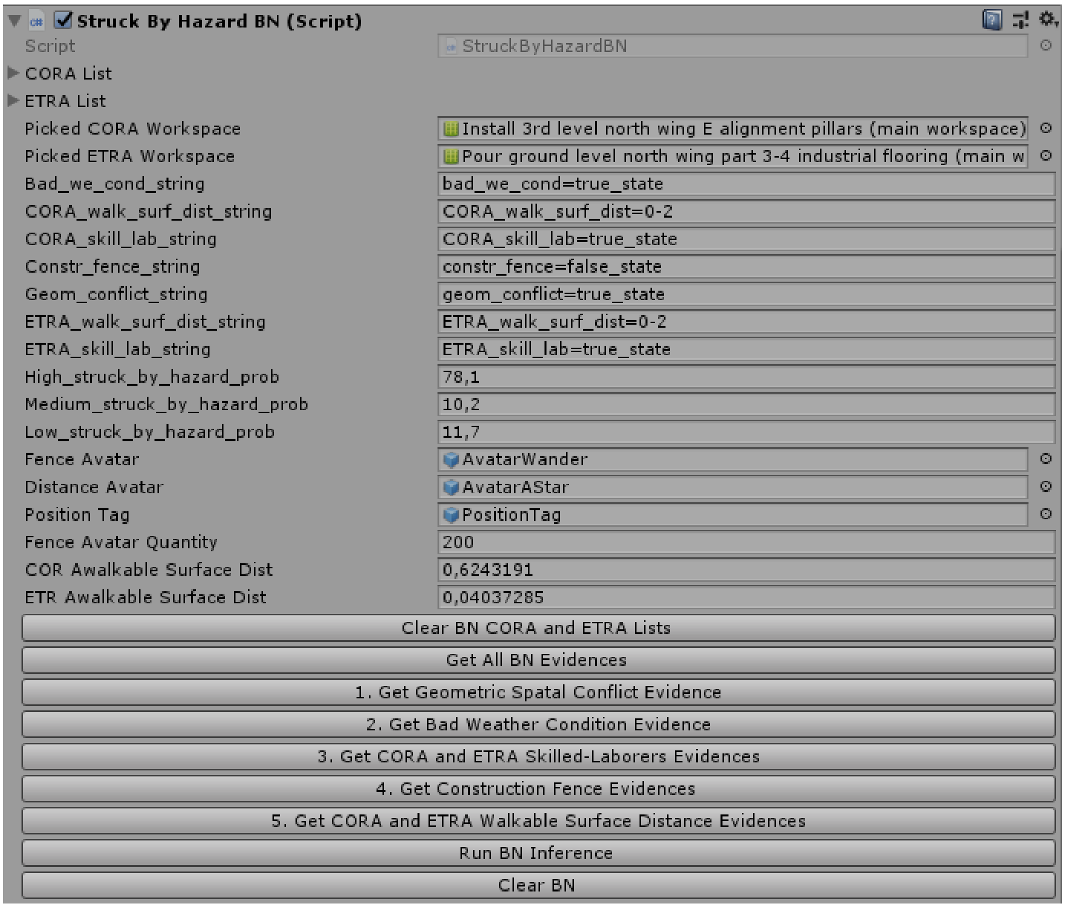


Figure 55. Front end of the “Struck by Hazard BN” component after having get the Bayesian network evidences.

5.3. Integration in the workspace management framework

In this Section, the technical solutions that has enabled the integration of the system components presented in the previous Sections 5.1 and 5.2 are illustrated. As fully described in Section 4.5, the proposed workspace management framework is defined by the integration of two main pools: the one related to the construction management team for the scheduling phase and the other one related to the developed spatial conflict simulator (Figure 34). The integration between these two, defining a cycle, requires an information flow in both directions. The information flow from the construction management team to the spatial conflict simulator and then vice versa is defined by the following tasks:

- Loading the BIM model by the "File Chooser" component.
- Loading the work schedule by the "Model Input" component.
- Generating main workspace by the "Instantiate Main Workspaces From IFC" component.
- Carrying out geometric computations and physical simulations by the "Intersection Test" component.
- Getting variables' evidence from the serious gaming simulation environment and running Bayesian inference by the "Struck by Hazard BN" component.

Each one of the above-mentioned tasks is enabled by a specific component developed in the serious gaming environment. In Figure 56, the integration of the serious gaming tool's components in the workspace management framework is graphically described. More technical details about each one of the above-mentioned steps are provided as follows, following the chronological order of application, as depicted in Figure 56.

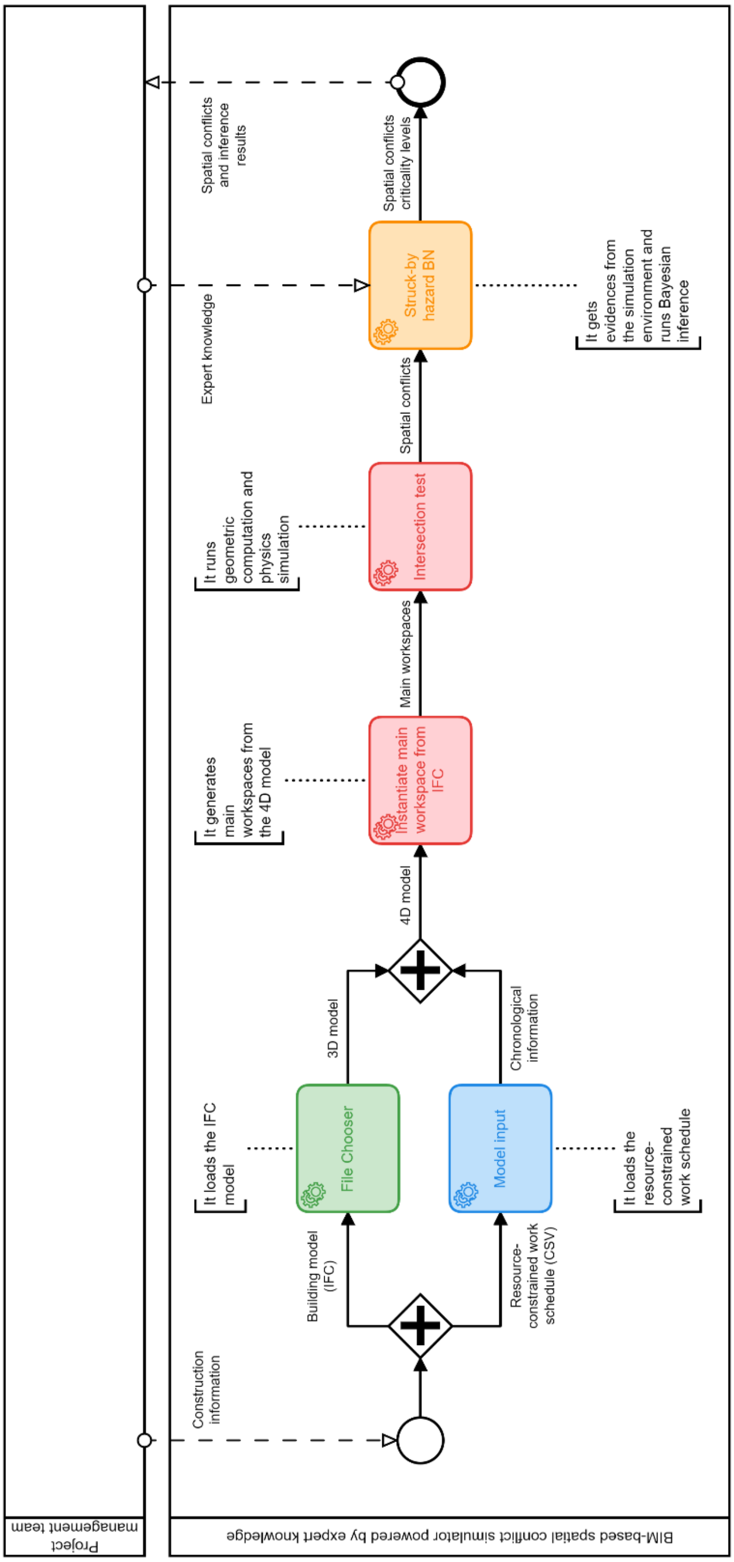


Figure 56. Integration of the serious gaming tool's components in the workspace management framework.

Loading the BIM model by the "File Chooser" component

The building model, once exported from the BIM authoring platform in IFC format, is loaded within Unity3D™ by using an IFC Loader, internally developed by the DICEA Department on the basis of the IFC Engine DLL library (RDF Ltd., 2006). The "File Chooser", enabling the user to select the IFC model and trigger its loading in Unity3D™, defines the front end of the adopted IFC Loader (Figure 56). This IFC Loader models the 3D environment using one of the most powerful techniques in solid modelling, that is 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.

Loading the resource-constrained work schedule by the "Model Input" component

In order to instantiate main workspaces within Unity3D™, 3D model must be enriched with the chronological information of the construction process. This is possible by loading the resource-constrained work schedule, in CSV format, with the serious gaming tool (Figure 56). This task is enabled by the "ModelInput.cs" C# script, whose pseudocode is reported below.

```
ReadCSV()

       GET 4DModel.csv file path

       READ 4DModel.csv file stream

       WHILE 4DModel.csv is not null

              SPLIT 4DModel.csv stream into lines

              IF line is empty THEN

                     END the loop

              ELSE

              GET activity index

              GET tags index

              GET crew index
```

```
        GET start date index
        GET end date index
        CREATE empty activity name list(string)
        CREATE empty product tag strings list(string)
        CREATE empty crew list(string)
        SPLIT line into records by “;”
        FOR i from 0 to line records count
               IF i-th record is empty THEN
                      RETURN “n/a”
               ELSE IF i-th record is equal to activity index THEN
                      ADD i-th record to activity name list
               ELSE IF i-th record is equal to tags index THEN
                      ADD i-th record to product tag strings list
               ELSE IF i-th record is equal to crew index THEN
                      ADD i-th record to crew list
               ELSE IF i-th record is equal to start date index THEN
                      ADD i-th record to start date list
               ELSE IF i-th record is equal to end date index THEN
                      ADD i-th record to end date list
               END IF
        END FOR
 END LOOP
 END
```

Generating main workspace by the "Instantiate Main Workspaces From IFC" component

The developed serious gaming tool generates the main workspaces on the basis of the information provided by the 4D model, which is obtained by the integration of the 3D model and the chronological information from previous phases. This step is enabled by the "InstantiateMainWorkspacesFromIFC.cs" C# script. In the pseudocode reported below, the "MultipleMWInstatiation()" method, calling "MWInstantiation(activity name, product tag string, main workspace offset)" method, generates a main workspace unit for each building elements produced by a given activity and, then, merges all the main workspace units into an overall main workspace for that activity.

```
MWInstantiation(activity name, product tag string, main workspace offset)

       CREATE empty main workspace parent gameobject

       SET main workspace parent gameobject name as "activity name + " (main
workspace)"

       SET main workspace parent tag equal to "Workspace"

       ADD space merger component

       CREATE empty product tags list(string)

       GET main workspace gameobject

       SPLIT product tag string into product tags by ","

       ADD product tags into product tags list(string)

       FOREACH i-th existing gameobject in the scene

              FOREACH j-th product tag in the product tags list

                     IF i-th game object name contains j-th product tag THEN

                            INSTANTIATE main workspace gameobject as main
workspace prefab with same position and rotation of the matched game object i-th
in the scene

                            SET main workspace prefab name as "product tag + "
- " + activity name + " (main workspace)""
```

```
                            SET main workspace prefab as a child of main
workspace gameobject
                            SET main workspace prefab scale as matched
gameobject i-th scale enhanced of 2 times main workspace offset
                    END IF
            END FOREACH
    END FOREACH
    END
```

```
MultipleMWInstatiation()
    GET simulation start date
    GET elapsed days
    FOR k from 0 to activity name list count
            GET k-th activity name in activity name list
            GET k-th product tag string in product tag string list
            GET k-th main workspace offset in main workspace offset array
            GET k-th crew string in crew string list
            GET k-th start date in start date list
            GET k-th end date in end date list
            IF (k-th start date, k-th end date) does not intersects (start
simulation date, elapsed days) THEN
                    SET k-th product tag string equals to "n/a"
            END IF
            IF activity name is not empty AND product tag string is different
from "n/a" THEN
                    MWInstantiation(activity name, product tag string, main
workspace offset)
```

```
                MergeMeshes(main workspace gameobject children)
        END IF
END
```

Carrying out geometric computations and physics simulations by the “Intersection Test” component

The developed serious gaming tool carries out geometric computation and physics simulations, given as an input the main workspaces of the activities scheduled for the simulated days. This task is enabled by the “IntersectionTest.cs” C# script, whose pseudocode is reported below. In details, the “FindSpatialConflict()” method carries out a geometric intersection test between main workspaces in their static initial position and provides a list of so-called “direct” spatial conflicts. The “FindAllOverlaps()” method, instead, carries out a geometric intersection test during physics simulations, based on the law of gravity. The “OnTriggerEnter(Collider other)” method, attached to each main workspace, detects the spatial conflicts between the main workspaces while the physics simulation is running. In this study, as described in Section 5.1.5, these spatial conflicts are called “indirect” or “possible”.

```
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
```

```
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
```

```
OnTriggerEnter(Collider other)

     IF other has tag equals to “Workspace” AND game object crew string is
different from the 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
```

Getting variables' evidence from the serious gaming simulation environment and running Bayesian inference by the "Struck by Hazard BN" component

```
public void RunBN()
{
    // BN Nodes
    // External factors nodes
    BayesianNode node1 = new BayesianNode("bad_we_cond", new string[] { "false_state", "true_state" }, new double[] { 0.5, 0.5 });

    // CORA organizational factors nodes
    BayesianNode node2 = new BayesianNode("CORA_walk_surf_dist", new string[] { "0-2", "2-inf" }, new double[] { 0.5, 0.5 });
    BayesianNode node3 = new BayesianNode("CORA_skill_lab", new string[] { "false_state", "true_state" }, new double[] { 0.5, 0.5 });

    // Workspace overlap node
    BayesianNode node4 = new BayesianNode("constr_fence", new string[] { "false_state", "true_state" }, new double[] { 0.5, 0.5 });
    BayesianNode node5 = new BayesianNode("geom_conflict", new string[] { "false_state", "true_state" }, new double[] { 0.5, 0.5 });

    // ETRA organizational factors nodes
    BayesianNode node6 = new BayesianNode("ETRA_walk_surf_dist", new string[] { "0-2", "2-inf" }, new double[] { 0.5, 0.5 });
    BayesianNode node7 = new BayesianNode("ETRA_skill_lab", new string[] { "false_state", "true_state" }, new double[] { 0.5, 0.5 });

    // Unsafe act/condition nodes
    BayesianNode node8 = new BayesianNode("falling_elements", new string[] { "false_state", "true_state" }, new double[] { 0.1,0.9,0.8,
    BayesianNode node9 = new BayesianNode("vulnerable_laborers", new string[] { "false_state", "true_state" }, new double[] { 0.05,0.95

    // Probability nodes
    BayesianNode node10 = new BayesianNode("struck_by_hazard", new string[] { "high", "medium", "low" }, new double[] { 0.00001,0.00001

    // BN definition and features
    BayesianNetwork network = new BayesianNetwork(node1, node2, node3, node4, node5, node6, node7, node8, node9, node10);
    VariableElimination ve = new VariableElimination(network);

    // Get BN evidences
    //GetBNevidences();

    // Run inference given evidences
    double[] struck_by_hazard_prob = ve.Infer("struck_by_hazard", bad_we_cond_string, CORA_walk_surf_dist_string, CORA_skill_lab_string

    // Process output
    high_struck_by_hazard_prob = Math.Round(struck_by_hazard_prob[0] * 100, 2);
    medium_struck_by_hazard_prob = Math.Round(struck_by_hazard_prob[1] * 100, 2);
    low_struck_by_hazard_prob = Math.Round(struck_by_hazard_prob[2] * 100, 2);
}
```

Figure 57. Excerpt of the C# script developed for implementing the proposed Bayesian network in Unity3D™ by using (Chen, 2017).

Once the Bayesian network has been fed, it was implemented in the serious game engine Unity3D™ by developing the "StruckByHazardBN.cs" C# script (Figure 57), whose pseudocode is reported below. As already mentioned in Section 5.2.2, the commercial Discrete Bayesian Network library (Chen, 2017) for Unity3D™ has been applied for the implementation of the struck-by hazard Bayesian network in the serious gaming environment.

The "RunBN()" method, developed using (Chen, 2017), defines and run the struck-by hazard Bayesian network, given the corresponding evidences retrieved by the "GetBNEvidences()" method.

```
RunBN()

      CREATE "bad_we_cond" Bayesian node {("false", "true"), (0.5, 0.5)}
```

```
        CREATE “CORA_walk_surf_dist” Bayesian node {(“0-2”, “2-inf”), (0.5, 0.5)}

        CREATE “CORA_skill_lab” Bayesian node {(“false”, “true”), (0.5, 0.5)}

        CREATE “constr_fence” Bayesian node {(“false”, “true”), (0.5, 0.5)}

        CREATE “geom_conflict” Bayesian node {(“false”, “true”), (0.5, 0.5)}

        CREATE “ETRA_walk_surf_dist” Bayesian node {(“0-2”, “2-inf”), (0.5, 0.5)}

        CREATE “ETRA_skill_lab” Bayesian node {(“false”, “true”), (0.5, 0.5)}

        CREATE “falling_elements” Bayesian node {(“false”, “true”),
(0.1,0.9,0.8,0.2,0.8,0.2,0.9,0.1,0.00001,0.99999,0.7,0.3,0.7,0.3,0.8,0.2,0.2,0.8
,0.9,0.1,0.9,0.1,0.99999,0.00001,0.2,0.8,0.8,0.2,0.8,0.2,0.9,0.1),
“CORA_skill_lab”, “bad_we_cond”, “CORA_walk_surf_dist”, “constr_fence”}

        CREATE “vulnerable_laborers” Bayesian node {(“false”, “true”),
(0.05,0.95,0.15,0.85,0.75,0.25,0.85,0.15,0.75,0.25,0.85,0.15,0.85,0.15,0.95,0.05
), “geom_conflict”, “vulnerable_laborers”, “falling_elements”}

        CREATE “struck_by_hazard” Bayesian node {(“high”, “medium”, “low”),
(0.00001,0.00001,0.99999,0.00001,0.1,0.9,0.00001,0.1,0.9,0.1,0.2,0.7,0.1,0.2,0.7
,0.33,0.33,0.33,0.33,0.33,0.33,0.99999,0.00001,0.00001), “geom_conflict”,
“vulnerable_laborers”, “falling_elements”}

        CREATE Bayesian network (“bad_we_cond”, “CORA_walk_surf_dist”,
“CORA_skill_lab”, “constr_fence”, “geom_conflict”, “ETRA_walk_surf_dist”,
“ETRA_skill_lab”, “falling_elements”, “vulnerable_laborers”, “struck_by_hazard”)

        GetBNEvidences()

        SET “struck_by_hazard_prob” as variable elimination inference on
("struck_by_hazard", bad_we_cond_string, CORA_walk_surf_dist_string,
CORA_skill_lab_string, constr_fence_string, geom_conflict_string,
ETRA_walk_surf_dist_string, ETRA_skill_lab_string)

        SET “high_struck_by_hazard_prob” as “struck_by_hazard_prob[0]” * 100

        SET “medium_struck_by_hazard_prob” as “struck_by_hazard_prob[1]” * 100

        SET “low_struck_by_hazard_prob” as “struck_by_hazard_prob[2]” * 100

END
```

```
GetBNEvidences()

       GetGeomConflictEv()

       GetWeCond()

       GetSkillLabEv()

       GetConstrFenceEv()

       GetWalkSurfDistEv()

       END
```

```
GetGeomConflictEv()

       GET pickedCORAWorkspace

       GET pickedETRAWorkspace

       CREATE geom_conflict_string

       IF pickedCORAWorkspace and pickedETRAWorkspace exists THEN

              SET geom_conflict_string equals to “geom_conflict=true”

       ELSE

              SET geom_conflict_string equals to “geom_conflict=false”

       END IF

END
```

```
GetSkillLabEv()

       CREATE CORASkillLevel

       GET pickedCORAWorkspace crew string

       GET high-skilled laborers no. from crew string

       GET medium-skilled laborers no. from crew string

       GET laborers no. from crew string

       COMPUTE CORASkillLevel as (high-skilled laborers no. + 0,5*medium-skilled
laborers no.)/laborers no.

       IF CORASkillLevel >= 0,5 THEN

              SET CORA_skill_lab_string equals to “CORA_skill_lab=true”

       ELSE
```

```
        SET CORA_skill_lab_string equals to "CORA_skill_lab=false"
    END IF


    CREATE ETRASkillLevel
    GET pickedETRAWorkspace crew string
    GET high-skilled laborers no. from crew string
    GET medium-skilled laborers no. from crew string
    GET laborers no. from crew string
    COMPUTE ETRASkillLevel as (high-skilled laborers no. + 0,5*medium-skilled
laborers no.)/laborers no.
    IF ETRASkillLevel >= 0,5 THEN
        SET ETRA_skill_lab_string equals to "ETRA_skill_lab=true"
    ELSE
        SET ETRA_skill_lab_string equals to "ETRA_skill_lab=false"
    END IF
    END
```

```
GetConstrFenceEv()
    GET pickedCORAWorkspace
    GET pickedETRAWorkspace
    INSTANTIATE random wandering avatars within the pickedCORAWorkspace
    IF at least one random wandering avatar hit the pickedETRAWorkspace THEN
        SET constr_fence_string equals to "constr_fence=false"
    ELSE
        SET constr_fence_string equals to "constr_fence=true"
    END IF
    END
```

```
GetWalkSurfDistEv()

    GET pickedCORAWorkspace

    GET pickedETRAWorkspace
```

```
        CREATE CORA_walk_surf_dist

        CREATE CORASlabEdge

        CREATE CORAWalkSurfLim

        SET CORASlabEdge as the nearest point of the CORA slab to the
pickedETRAWorkspace

        SET CORAWalkSurfLim as nearest point of the CORA walkable surface to the
CORASlabEdge

        COMPUTE CORA_walk_surf_dist as the distance between CORASlabEdge and
CORAWalkSurfLim

        IF 0 < CORA_walk_surf_dist < 2 THEN

               SET CORA_walk_surf_dist_string equals to "CORA_walk_surf_dist=0-
2"

        ELSE IF CORA_walk_surf_dist > 2 THEN

               SET CORA_walk_surf_dist_string equals to "CORA_walk_surf_dist=2-
inf"

        END IF

        END
```

CHAPTER 6

6. Prototype validation

6.1. Use case

The workspace management framework and the spatial conflict simulator, presented in the previous Sections 4 and 5, have been tested on real construction scenarios, related to the Eustachio building, venue of the Faculty of Medicine of the Polytechnic University of Marche, located in Ancona (Italy) (Figure 58).

For the purpose of this study, the technical and project documents necessary for developing the BIM model and redefine a realistic work schedule was made available. A view of the BIM model for the Eustachio building (Figure 59) and the 3rd level plant (Figure 60) are reported below.

Figure 58. Eustachio building. Venue of the Faculty of Medicine of the Polytechnic University of Marche located in Ancona (Italy).

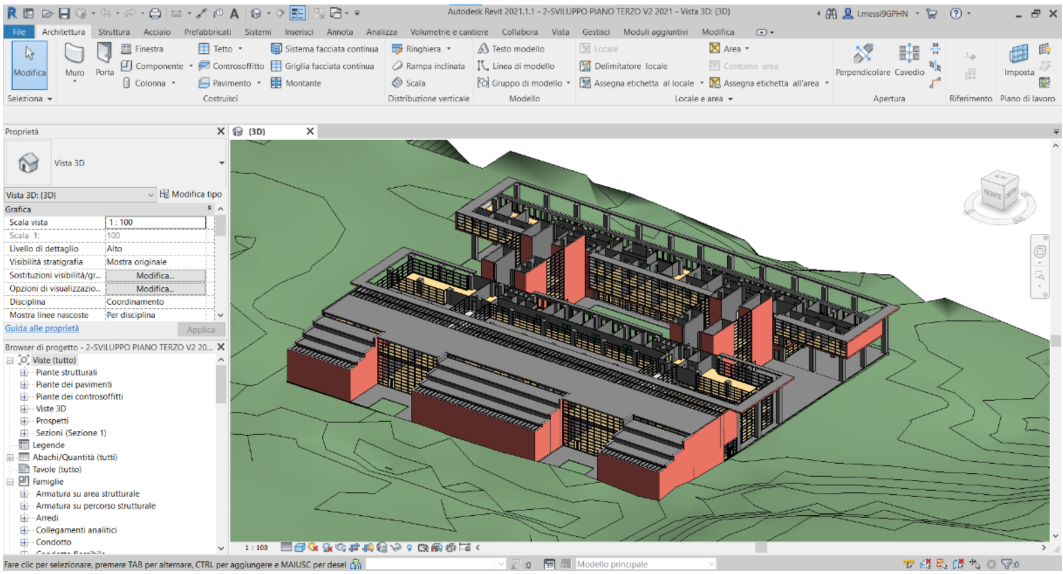


Figure 59. BIM model of the Eustachio building.

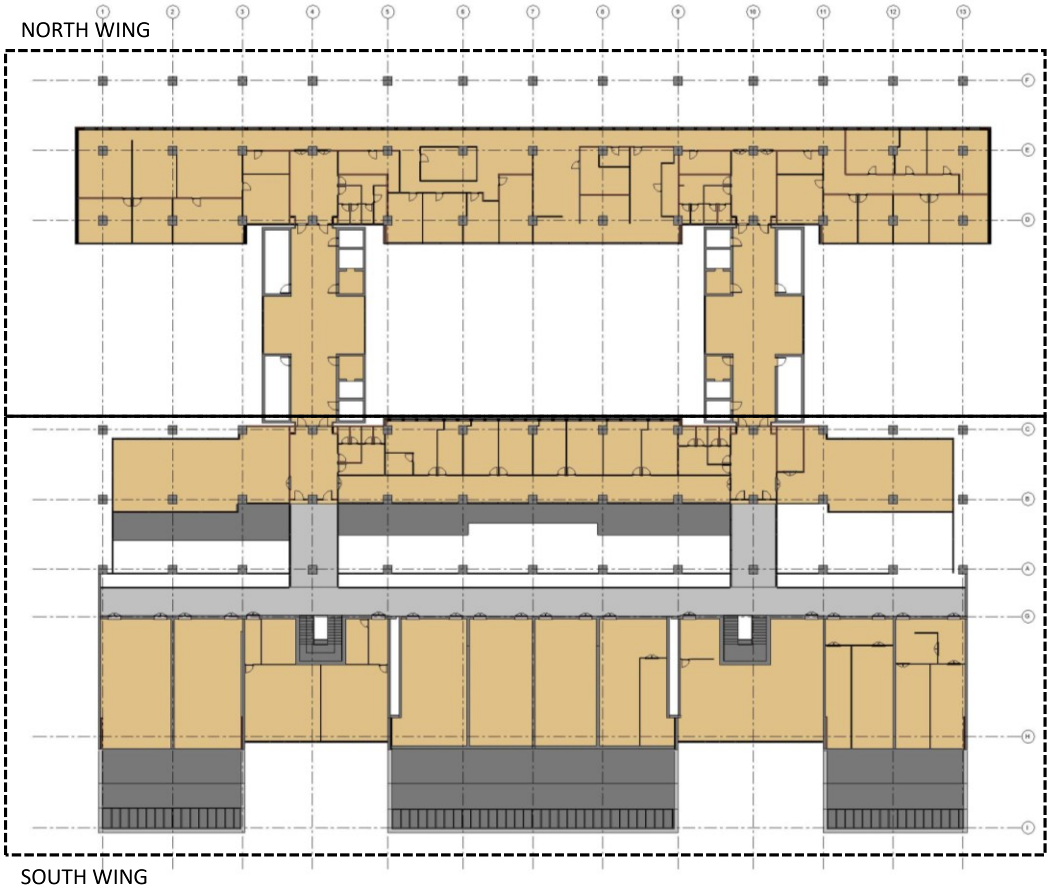


Figure 60. 3rd level plant of the Eustachio building.

6.2. Validation scenarios

In this Section, the validation scenarios, related to the use case introduced in Section 6.1, are defined to test the developed prototype (Section 5). To this purpose, an overall work schedule, depicted by Figure 61, has been defined. The following main activities related to the north wing of the Eustachio building (Figure 60) have been considered:

- Installation of precast concrete pillars.
- Installation of precast concrete facades.
- Execution of industrial flooring.

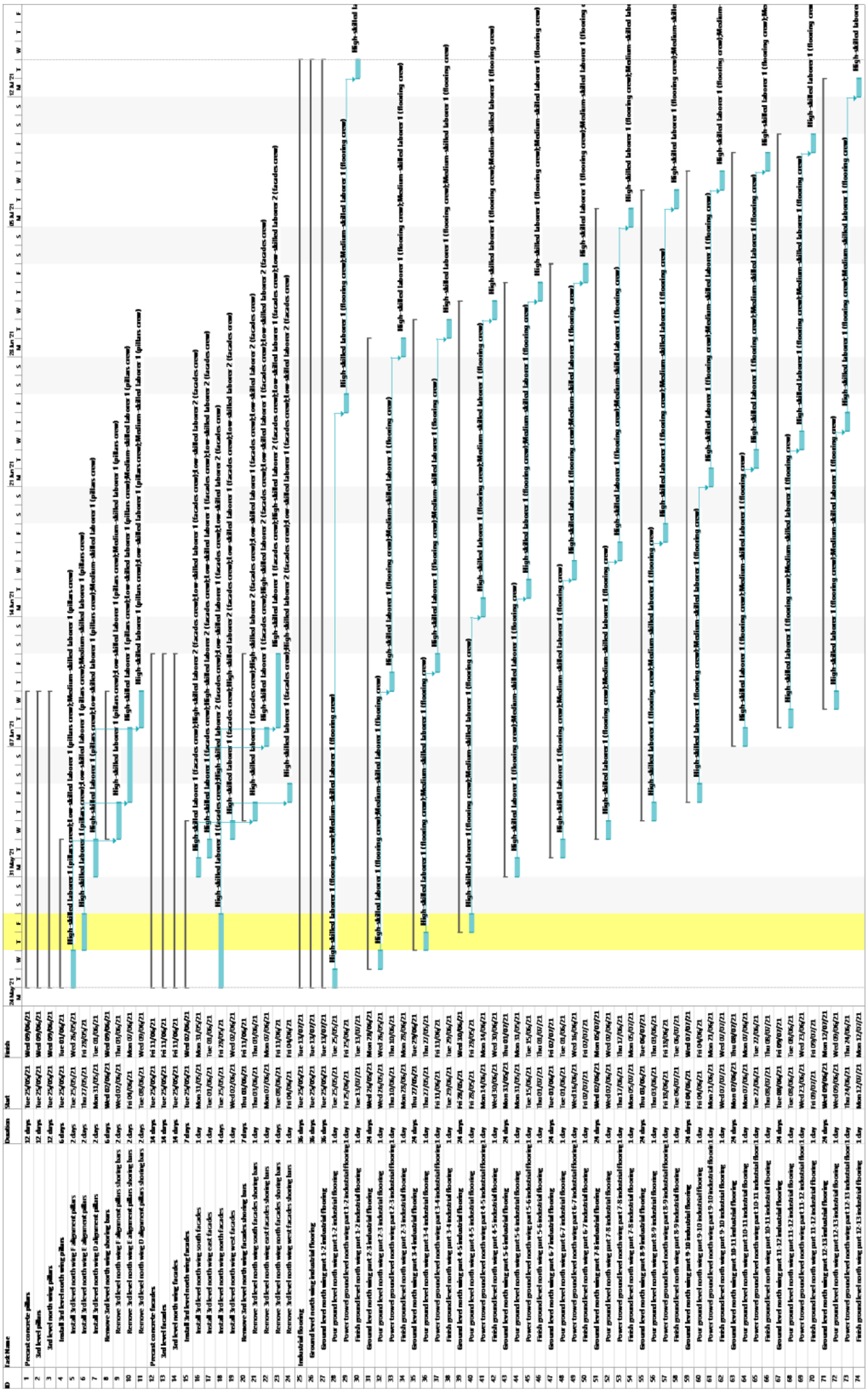


Figure 61. Overall work schedule.

Defining this work schedule (Figure 61) aims to demonstrate the tool's capability to detect spatial conflicts. Since the proposed workspace management framework adopts the Lean principles of the Last Planner System approach, a short-term simulation scenario must be defined. To this purpose, the working days May 27th and 28th, highlighted in yellow in Figure 61, have been selected from the overall work schedule. As clearly shown by Figure 62, in this time interval, the following activities are included:

- Install 3rd level north wing E alignment pillars.
- Install 3rd level north wing north facades.
- Pour ground level north wing part 3-4 industrial flooring.
- Pour ground level north wing part 4-5 industrial flooring.

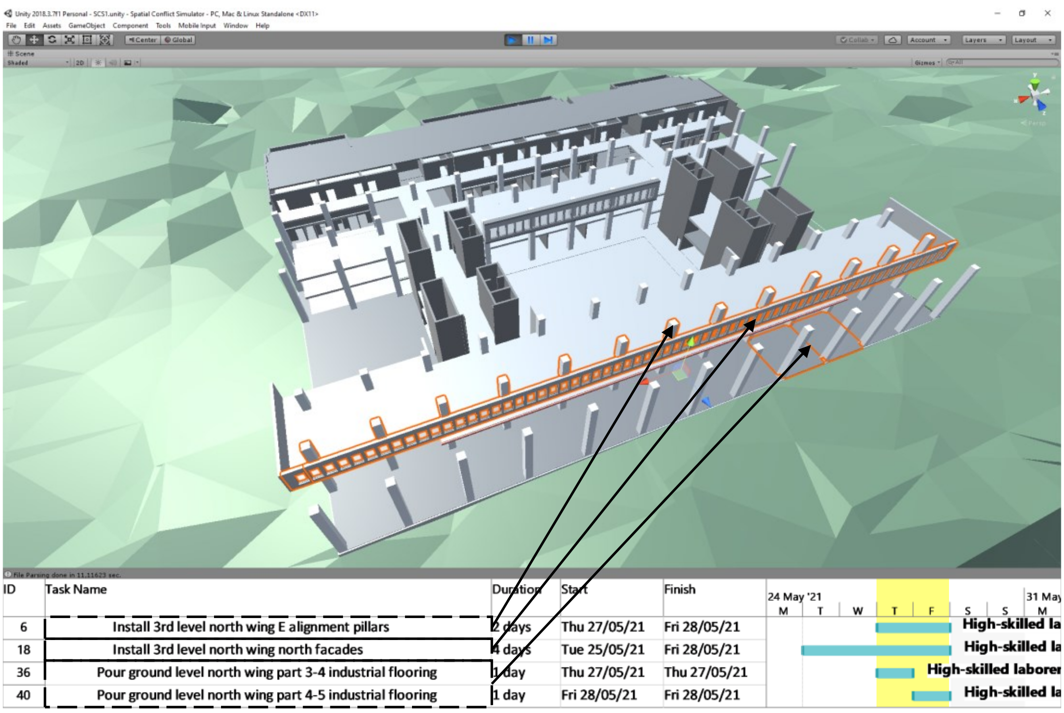


Figure 62. Excerpt of the overall work schedule reporting the activities scheduled for the selected working days May 27th and 28th (bottom) and view of the Standard model in the serious gaming environment (top).

In the following subsections, four validation scenarios are presented. The first one (Section 6.2.1) represents the state-of-the-art "Benchmark scenario" to which the second one, namely “Enhanced scenario” (Section 6.2.2), can be compared. Both are based on the BIM model of the use case, presented in Section 6.1 and called “Standard model” for simplicity. As described in the following Sections 6.2.1 and 6.2.2, the Benchmark and Enhanced scenarios differ for the different method adopted for detecting spatial conflicts. The last two scenarios (Sections 6.2.3 and 6.2.4) are defined from the Enhanced scenario by varying the Standard model into “Variation A” and “Variation B”, to stress the contribution given by the Bayesian inference. An overview of the main differences between the four scenarios is provided by Table 4.

Figure 63 depicts the concept of the Benchmark scenario. In detail, this schema illustrates, with reference to the Benchmark scenario, the state-of-the-art refinement process of the work schedule in charge to the construction manager. Figure 64, instead, depicts the concept of the Enhanced scenario. In detail, this schema illustrates, with reference to the Enhanced scenario, how the serious gaming tool’s functionalities are integrated in the refinement process of the work schedule in charge to the construction manager. The workflow is based on the workspace management framework introduced in Section 4.5.

Table 4. Overview of the main differences between the four validation scenarios.

Validation scenario	BIM model	Work schedule	Tool's functionalities					
			Loading the BIM model	Loading the work schedule	Generating main workspaces	Carrying out geometric intersection tests	Carrying out physics simulations and geometric intersection tests	Getting variables' evidence and running struck-by hazard Bayesian network inference
Benchmark scenario	Standard model	Working days: May 27th, 28th	x	x	x	x		
Enhanced scenario	Standard model	Working days: May 27th, 28th	x	x	x	x	x	x
Enhanced scenario - Variation A	Variation A: some openings removed on the 3rd level north facade	Working days: May 27th, 28th	x	x	x	x	x	x
Enhanced scenario - Variation B	Variation B: a cantilever slab added on the on the 3rd level north facade	Working days: May 27th, 28th	x	x	x	x	x	x

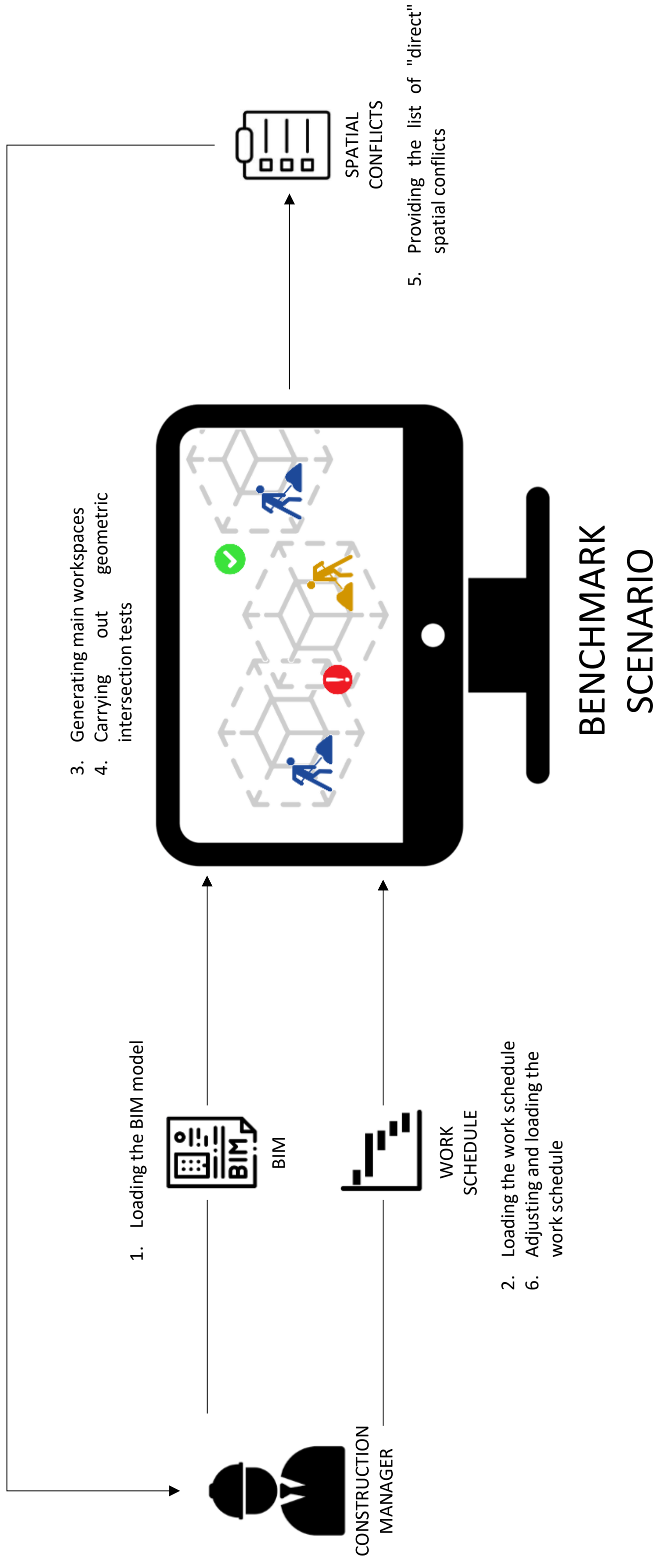


Figure 63. Concept of the Benchmark scenario.

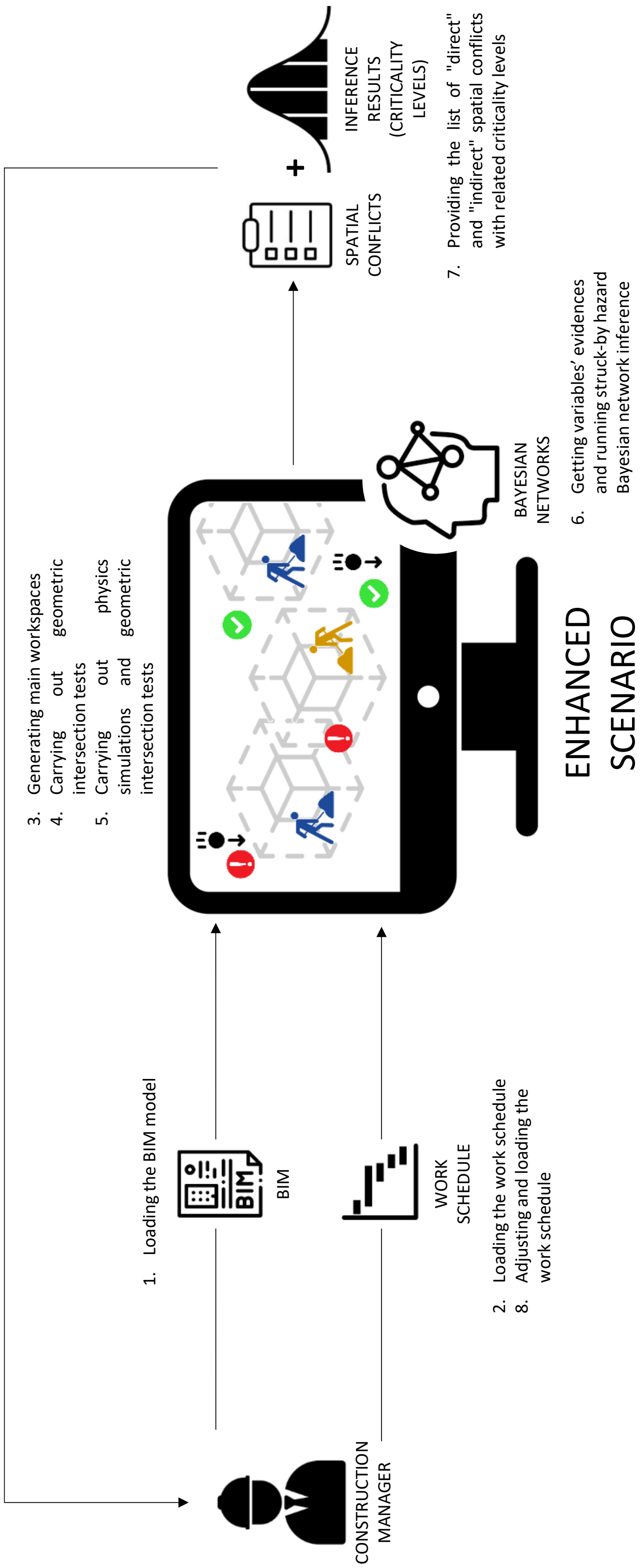


Figure 64. Concept of the Enhanced scenario.

6.2.1. Benchmark scenario

The first validation scenario, from here on referred as "Benchmark scenario" is defined to replicate the state of the art in workspace management. In the Benchmark scenario, the use of the developed serious gaming tool is limited to only detecting geometric intersection test among main workspaces during the selected working days May 27th and 28th for the adopted use case's Standard model (Figure 62). In other words, nor physics simulations neither Bayesian inference, being the real contribution of the proposed tool to the body of knowledge, have been considered in this scenario (Figure 63). Practically, in this scenario, the use of the serious gaming tool follows the description provided in Section 5.1, but stops after having clicked the "Find Geometric Spatial Conflicts" button (Section 5.1.4). The aim of this scenario is to define a benchmark whose results can be easily compared to the ones obtained by means of the added-value functionalities of the developed tool (e.g., physics simulations and Bayesian inference).

As reported in Table 4, the following tasks are carried out in the developed serious gaming tool:

- Loading the BIM model.
- Loading the work schedule.
- Generating main workspaces.
- Carrying out geometric intersection tests.

6.2.2. Enhanced scenario – Standard model

The second validation scenario, from here on referred simply as "Enhanced scenario", is defined to stress the real added values of the proposed tool as compared to the state of the art, represented by the Benchmark scenario. In the Enhanced scenario, the proposed tool's functionalities are fully tested, as described in Sections 5.1 and 5.2, to detect spatial conflicts between main workspaces during the selected working days May 27th and 28th for the adopted use case's Standard model (Figure 62). One of the aims of this scenario is to demonstrate that running also physics simulation more "possible" spatial conflicts can be detected, such as the ones related to falling objects. Secondarily, but not for importance, this scenario demonstrates that, running the developed struck-by hazard Bayesian network (Section 4.4.3), the criticality level of each “possible” spatial conflict can be assessed in order to eventually ignore the ones judged as unlikely to happen (Figure 64). In order to stress this aspect and show how different environmental conditions can be caught by the serious gaming tool, the Enhanced scenario is varied into “Variation A” and “Variation B”. As fully described in the following Subsections 6.2.3 and 6.2.4, the two variations differ each other only for slight changes in the BIM model.

As reported in Table 4, the following tasks are carried out in the developed serious gaming tool:

- Loading the BIM model.
- Loading the work schedule.
- Generating main workspaces.
- Carrying out geometric intersection tests.
- Carrying out physics simulations and geometric intersection tests.
- Getting variables' evidence and running struck-by hazard Bayesian network inference.

6.2.3. Enhanced scenario – Variation A

The “Enhanced scenario – Variation A” is defined by assuming the same work schedule than in the Enhanced one, but a slightly different BIM model (Figure 65). In fact, some of the openings on the 3rd level north facade have been removed to give it the function of a construction fence that can protect laborers below from likely falling objects. The aim of considering this scenario is demonstrating that the struck-by hazard Bayesian network 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 will be provided.

As reported in Table 4, the following tasks are carried out in the developed serious gaming tool, following the concept depicted in Figure 64:

- Loading the BIM model.

- Loading the work schedule.
- Generating main workspaces.
- Carrying out geometric intersection tests.
- Carrying out physics simulations and geometric intersection tests.
- Getting variables' evidence and running struck-by hazard Bayesian network inference.

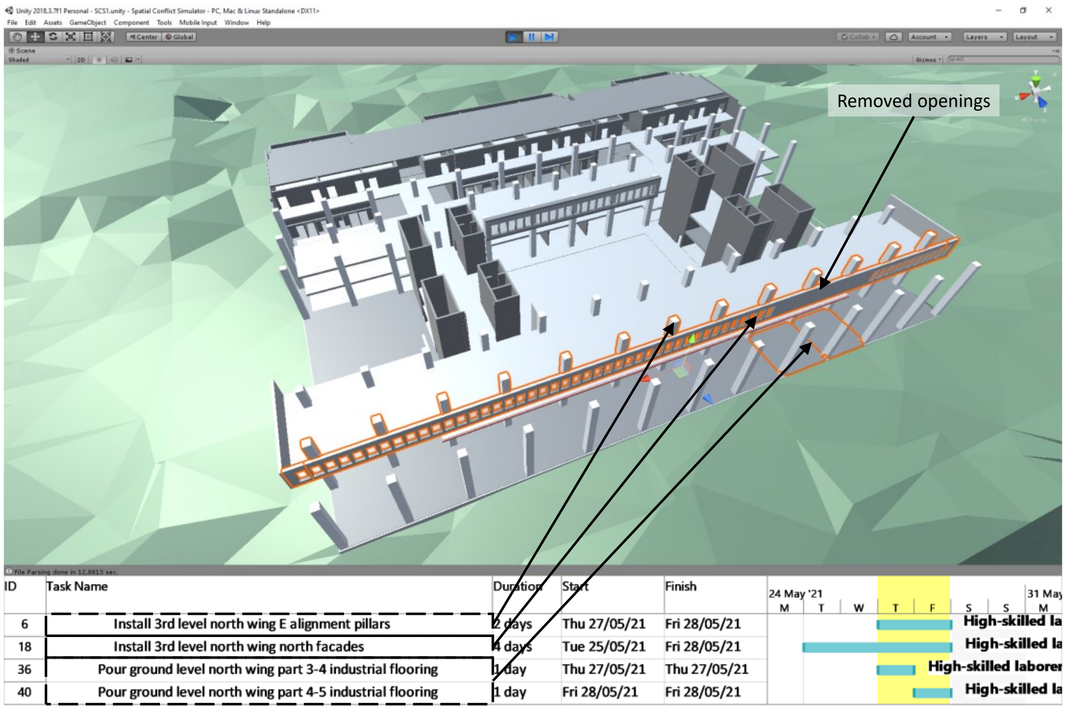


Figure 65. Excerpt of the overall work schedule reporting the activities scheduled for the selected working days May 27th and 28th (bottom) and view of the Variation A model in the serious gaming environment (top).

6.2.4. Enhanced scenario – Variation B

The "Enhanced scenario – Variation B" is defined, similarly to the "Enhanced scenario – Variation A", by assuming the same work schedule than in the Enhanced one but a slightly different BIM model (Figure 66). In this case, the upper slab has been extended to define the cantilever slab of a balcony or a solar shading. As a consequence, due to the presence of the 3rd level north facade too, the upper walkable surface backs away avoiding laborers can get closer to the edge and make accidentally let fall objects below. The aim of considering this scenario is demonstrating that the struck-by hazard Bayesian network can automatically catch this information from the serious gaming environment and fire the "CORA_walkable_surface" variable's evidence accordingly. Therefore, a different criticality level than in the Enhanced scenario will be provided.

As reported in Table 4, the following task are carried out in the developed serious gaming tool, following the concept depicted in Figure 64:

- Loading the BIM model.
- Loading the work schedule.
- Generating main workspaces.
- Carrying out geometric intersection tests.
- Carrying out physics simulations and geometric intersection tests.
- Getting variables' evidence and running struck-by hazard Bayesian network inference.

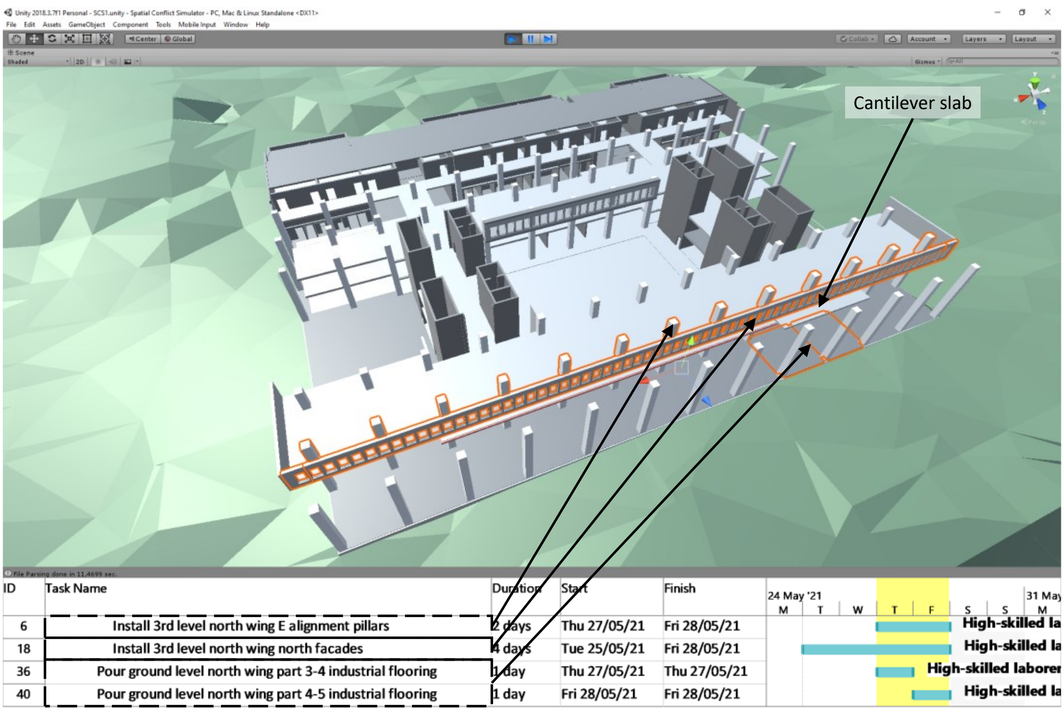


Figure 66. Excerpt of the overall work schedule reporting the activities scheduled for the selected working days May 27th and 28th (bottom) and view of the Variation B model in the serious gaming environment (top).

6.3. Experiments results

This section reports the results provided by the developed spatial conflict simulator for each one of the validation scenarios presented in the previous Section 6.2. For the sake of clarity, the tool's outputs are described for each scenario step by step with the help of figures that frame the serious game engine environment. This aspect aims to stress the fact that the adopted serious gaming environment is not only a means of simulation but also visualization.

6.3.1. Results from the Benchmark scenario

In this scenario, considering the Standard model and the working days May 27th and 28th as a work schedule (Table 4), the main workspaces depicted in Figure 67 have been generated. Clicking on the "Find Geometric Spatial Conflicts" button, as described in Section 5.1.4, a geometric intersection test between the main workspaces, generated for the considered working days, is carried out. One spatial conflict has been detected between a pair of main workspaces assigned to different crews. The serious gaming tool reports this spatial conflict by printing the following message, indicating the names of the two involved main workspaces, in the Unity3D™ Console window (Figure 67):

G.1. Spatial conflict detected! Workspaces involved: Install 3rd level north wing E alignment pillars (main workspace); Install 3rd level north wing north facades (main workspace).

In addition, as shown in Figure 66, the pair of intersecting main workspaces are displayed in red in the Unity3D™ Scene window. Table 8 reports this spatial conflict along with the ones obtained in the other validation scenarios.

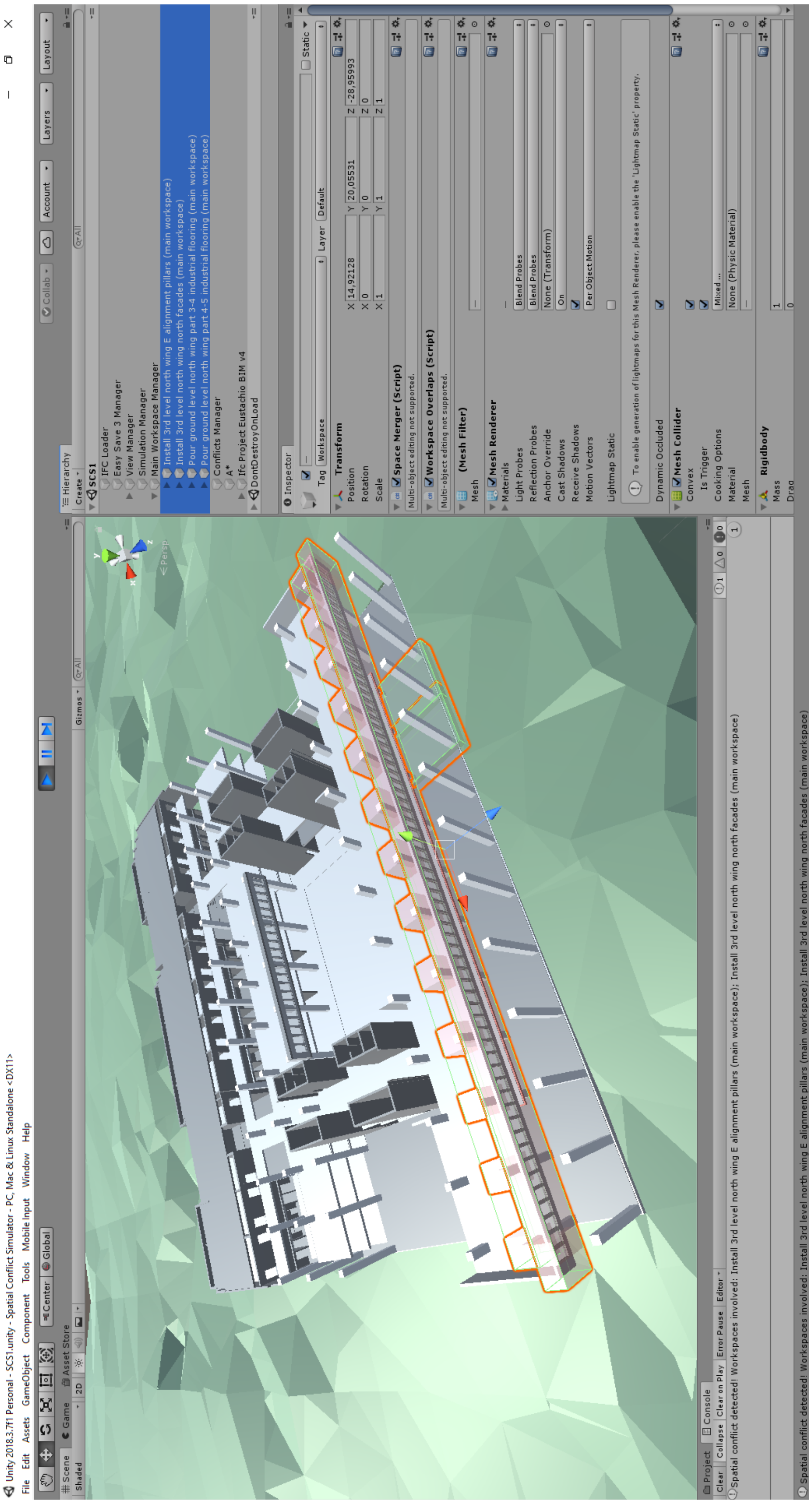


Figure 67. Results from the geometric intersection test executed for the Standard model for the working days May 27th and 28th, assumed as work schedule.

6.3.2. Results from the Enhanced scenario – Standard model

In this scenario, the first simulation output comes from the geometric intersection tests between main workspaces (Section 5.1.4). Considering the Standard model and the working days May 27th and 28th as work schedule (Table 4), as in the Benchmark scenario, the same simulation results are obtained for this step. One spatial conflict, between a pair of main workspaces assigned to different crews, is detected and reported by the following message in the Unity3D™ Console window (Figure 67):

G.1. Spatial conflict detected! Workspaces involved: Install 3rd level north wing E alignment pillars (main workspace); Install 3rd level north wing north facades (main workspace).

The second simulation step consists in carrying out a physics simulation and a geometric intersection test during it (Section 5.1.5), to find out "possible" spatial conflicts between workspaces due to struck-by events. Clicking on the "Find Workspace Overlaps by Physics Simulation" button, as described in Section 5.1.5, each main workspace is dropped, according to the gravity law, in order to check if it intersects any other main workspace below. The following four "possible" spatial conflicts are detected, between pairs of main workspaces assigned to different crews, and reported by the following messages in the Unity3D™ Console window (Figure 68):

S.1. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

S.2. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

S.3. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

S.4. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

As already said in Sections 4.5 and 5.2, the spatial conflicts detected during physics simulation are labelled as “possible” ones since they may or may not happen according to surroundings conditions. These conditions, influencing the possibility to have struck-by events have been modelled by a struck-by hazard Bayesian network, introduced in Section 4.4.3. As described in Section 5.2.2, the Bayesian network variables’ evidence can be fed all in one, by “Get All BN Evidences” button, or one by one, by the dedicated buttons. The Bayesian inference has been run for each one of the “possible” spatial conflicts listed above and obtained results are respectively depicted in Figure 69, Figure 70, Figure 71, and Figure 72. As shown by Table 5, the variables’ evidence is the same for each one of the four “possible” spatial conflicts. In this scenario, the criticality levels of the “possible” spatial conflicts are judged by the Bayesian inference as high, being the “high” state of the “Struck_by_hazard” variable equal to 78,1% (Table 8).

Just for validating the Bayesian inference results provided by the serious gaming tool, Figure 73 reports the ones obtained by using Hugin Researcher 8.7, where the same Bayesian network with the same evidence has been redefined. Table 5 and Figure 73 demonstrates that the inference results computed by the two implementations are comparable.

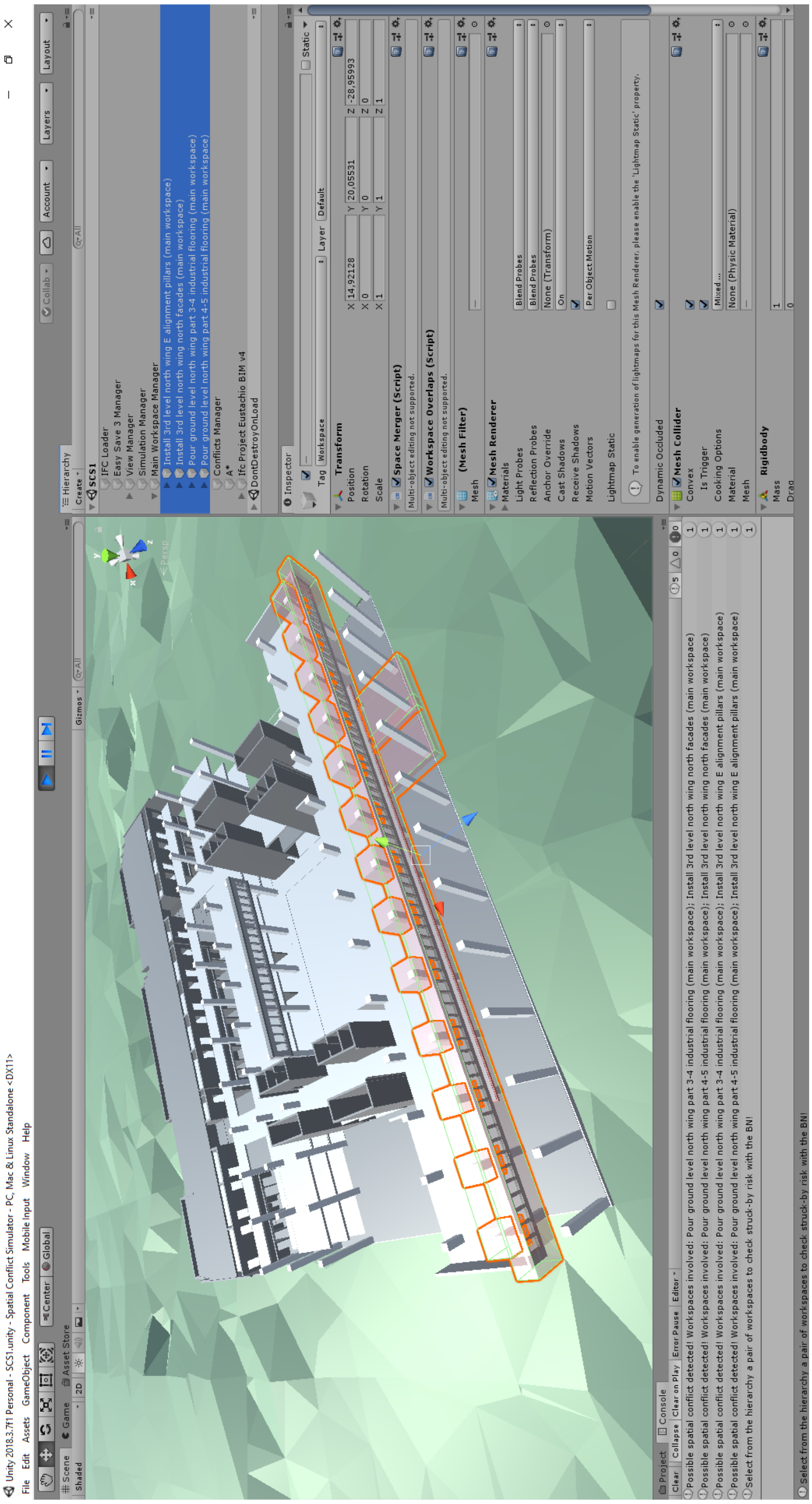


Figure 68. Results from the geometric intersection test during physics simulation executed for the Standard model for the working days May 27th and 28th, assumed as work schedule.

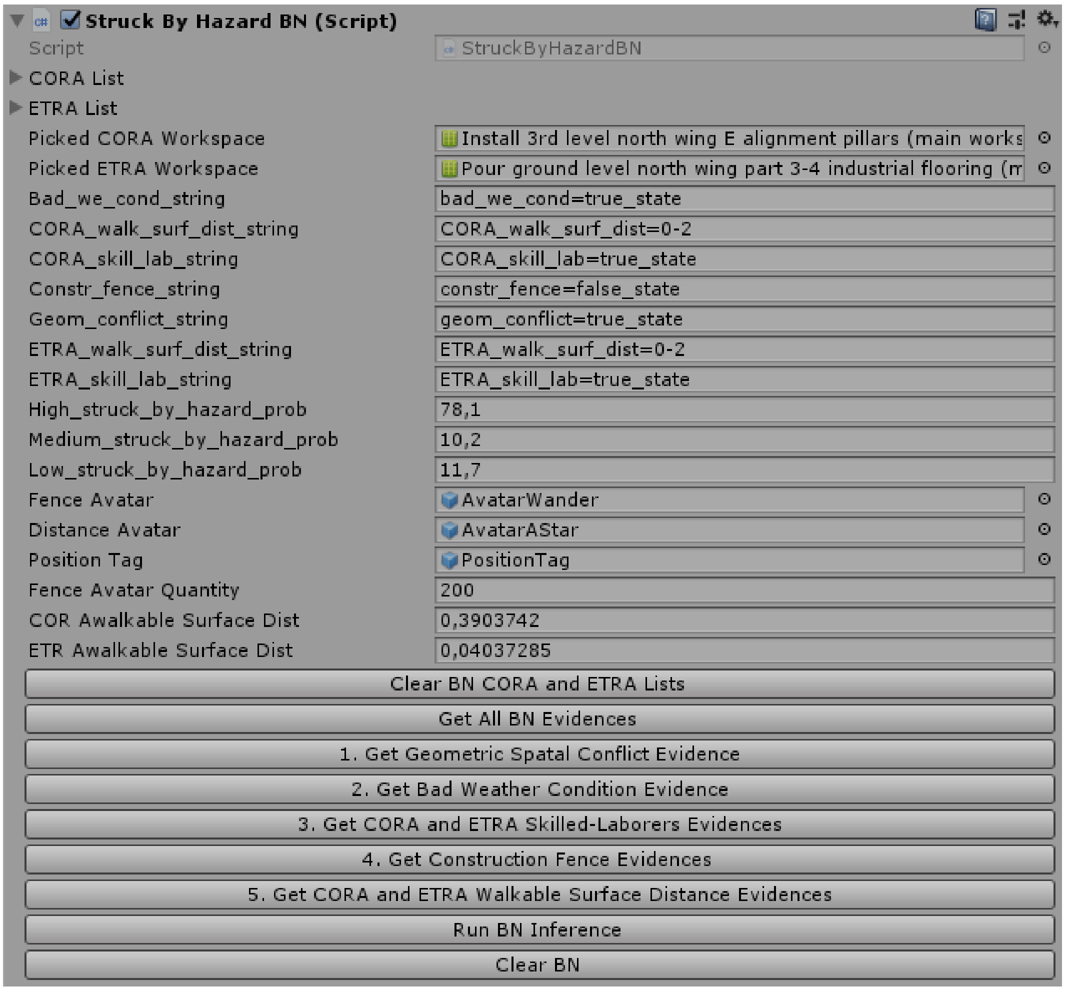


Figure 69. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict S.1.

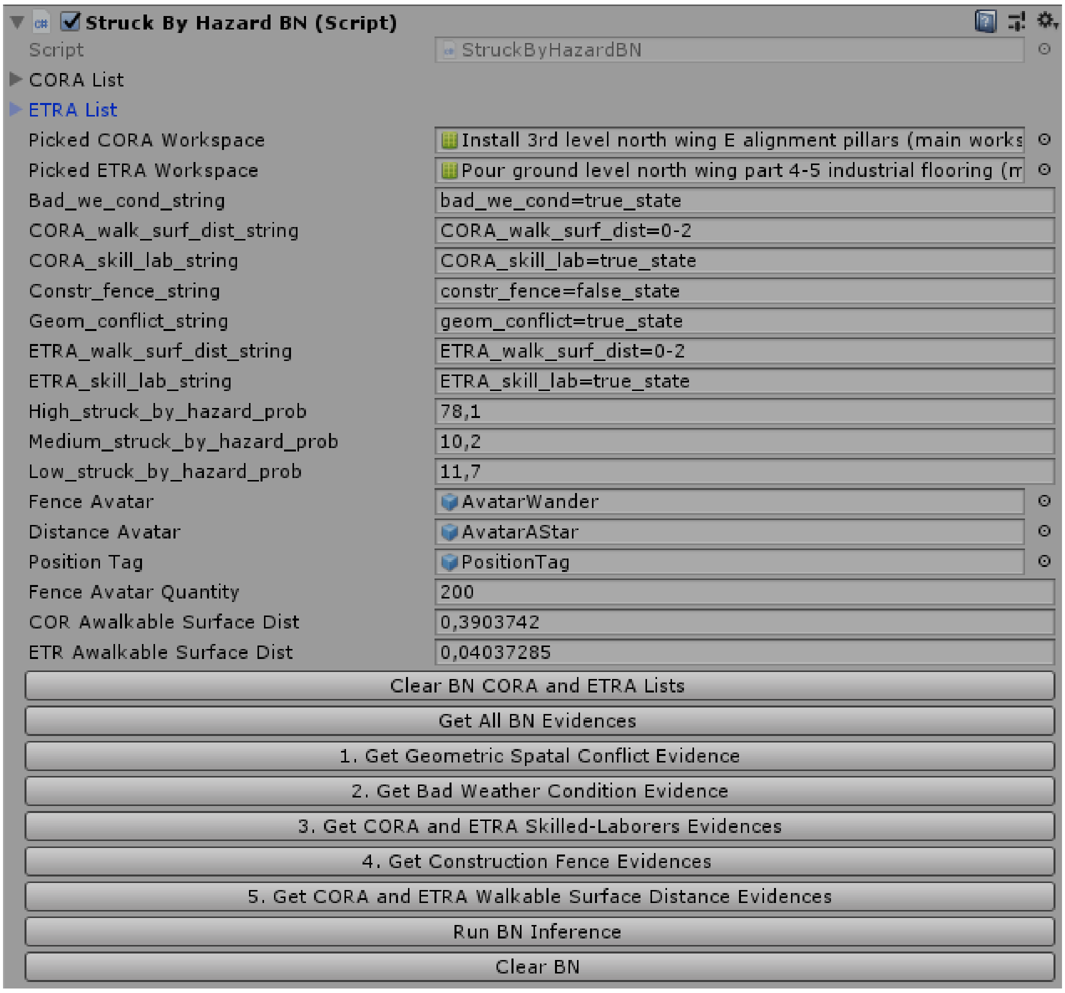


Figure 70. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict S.2.

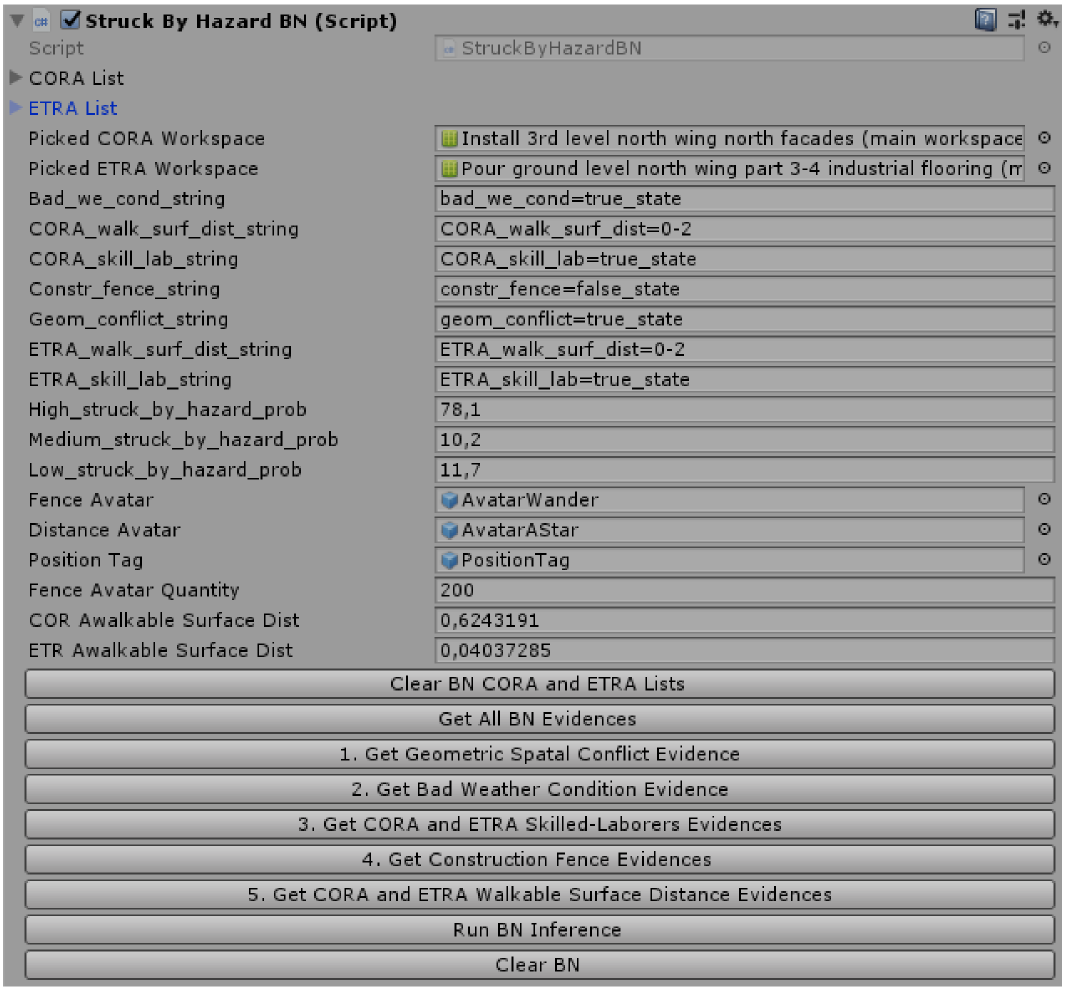


Figure 71. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict S.3.

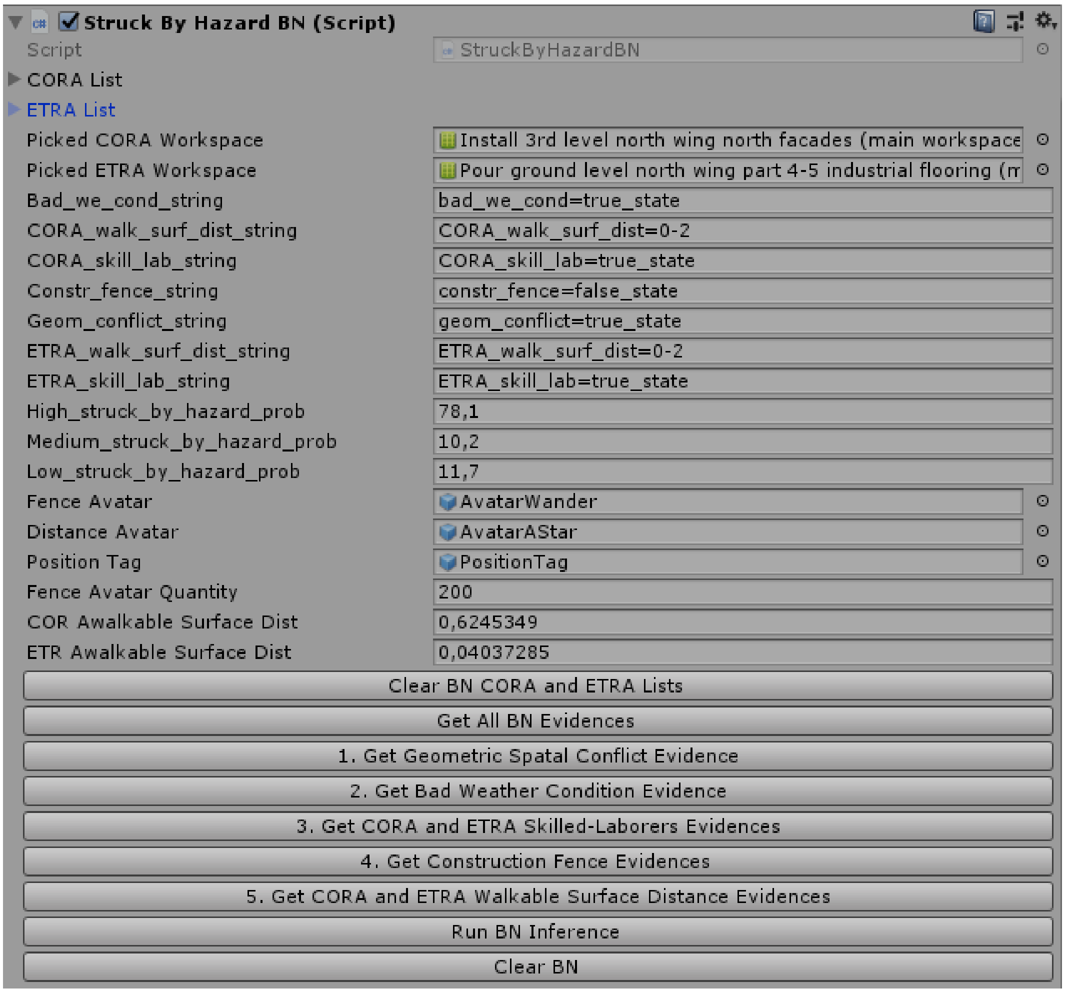


Figure 72. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict S.4.

Table 5. Summary table with the Bayesian inference results obtained for each "possible" spatial conflict detected in the Enhanced scenario.

Variable		Variables states for each "possible" spatial conflict (Enhanced scenario)			
		S.1.	S.2.	S.3.	S.4.
Bad_weather_condition		True	True	True	True
CORA_walkable_surface_distance		0-2	0-2	0-2	0-2
CORA_skilled_laborers		True	True	True	True
Construction_fence		False	False	False	False
Geometric_spatial_conflict_detected		True	True	True	True
ETRA_walkable_surface_distance		0-2	0-2	0-2	0-2
ETRA_skilled_laborers		True	True	True	True
Struck_by_hazard	High	78,10%	78,10%	78,10%	78,10%
	Medium	10,20%	10,20%	10,20%	10,20%
	Low	11,70%	11,70%	11,70%	11,70%

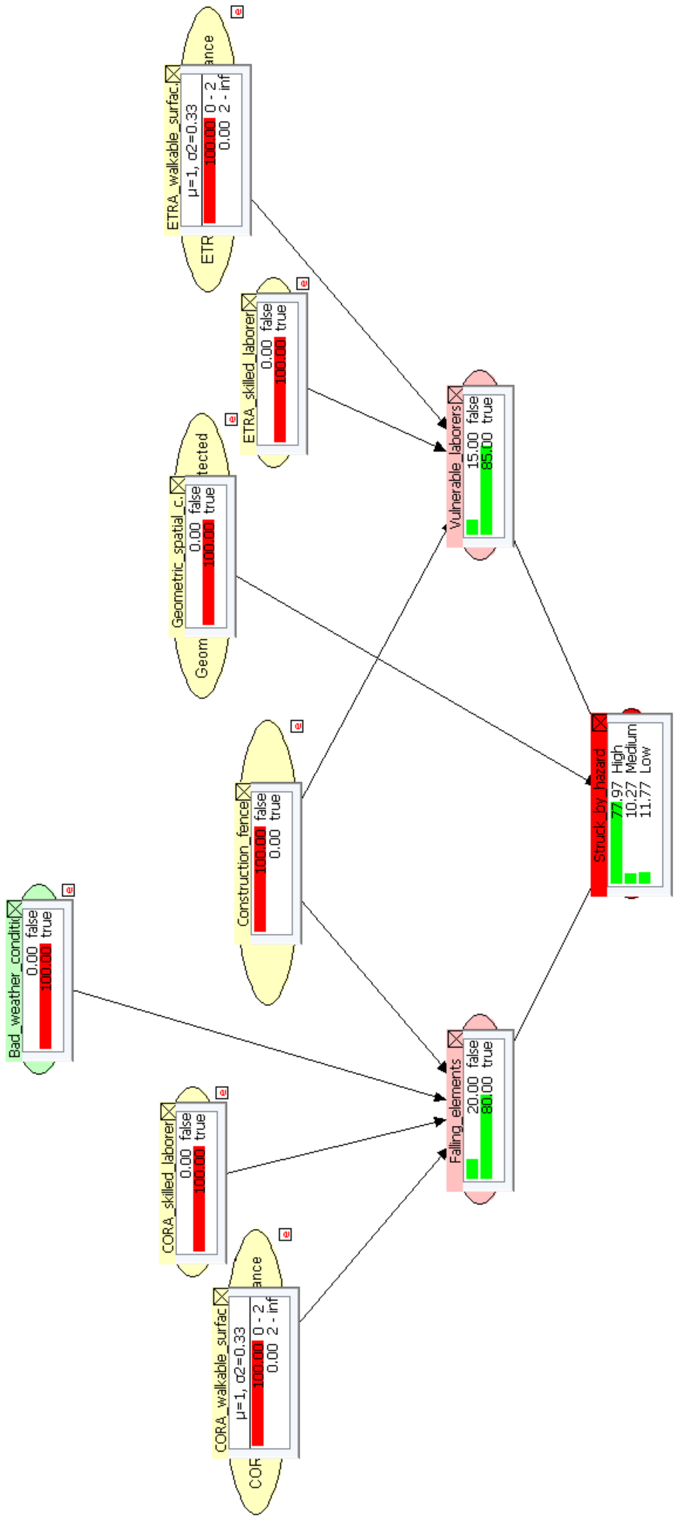


Figure 73. Bayesian inference results obtained by using Hugin Researcher 8.7 for the Enhanced scenario.

6.3.3. Results from the Enhanced scenario – Variation A

In this scenario, although the Standard model has been replaced by the Variation A (Table 4), the results of the geometric intersection tests between main workspaces (i.e., first simulation step), for the working days May 27th and 28th, are the same than the one obtained in the previous scenarios. In fact, the same spatial conflict, between a pair of main workspaces assigned to different crews, is detected and reported by the following message in the Unity3D^{TM} Console window (Figure 74):

G.1. Spatial conflict detected! Workspaces involved: Install 3rd level north wing E alignment pillars (main workspace); Install 3rd level north wing north facades (main workspace).

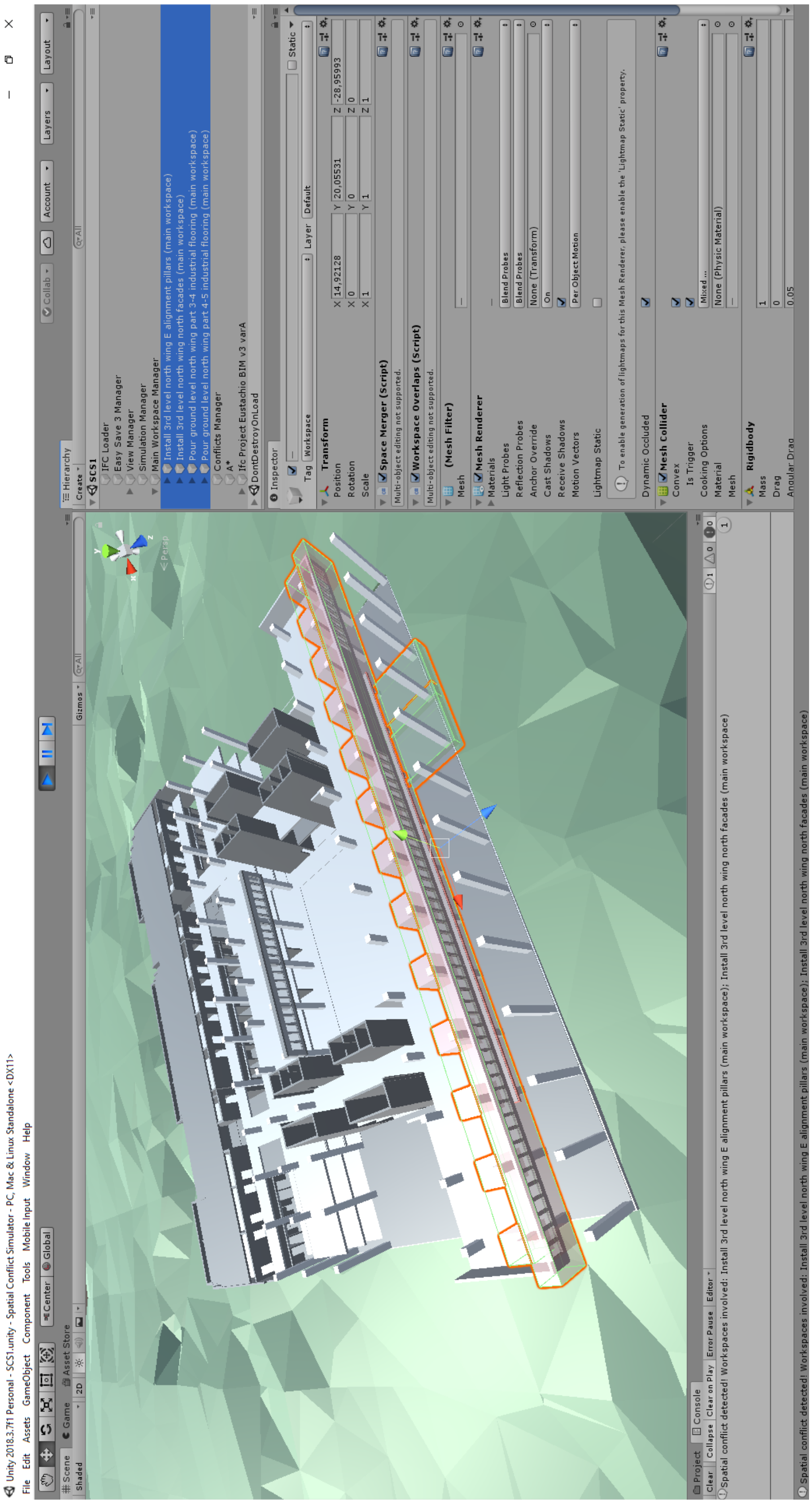


Figure 74. Results from the geometric intersection test executed for the Variation A of the Standard model for the working days May 27th and 28th, assumed as work schedule.

The results obtained by the geometric intersection tests carried out during physics simulations (i.e., second simulation step) are the same than the one obtained in the previous scenarios. In fact, the same four "possible" spatial conflicts, between pairs of main workspaces assigned to different crews, are detected and reported by the following messages in the Unity3D^{TM} Console window (Figure 75):

A.1. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

A.2. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

A.3. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

A.4. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

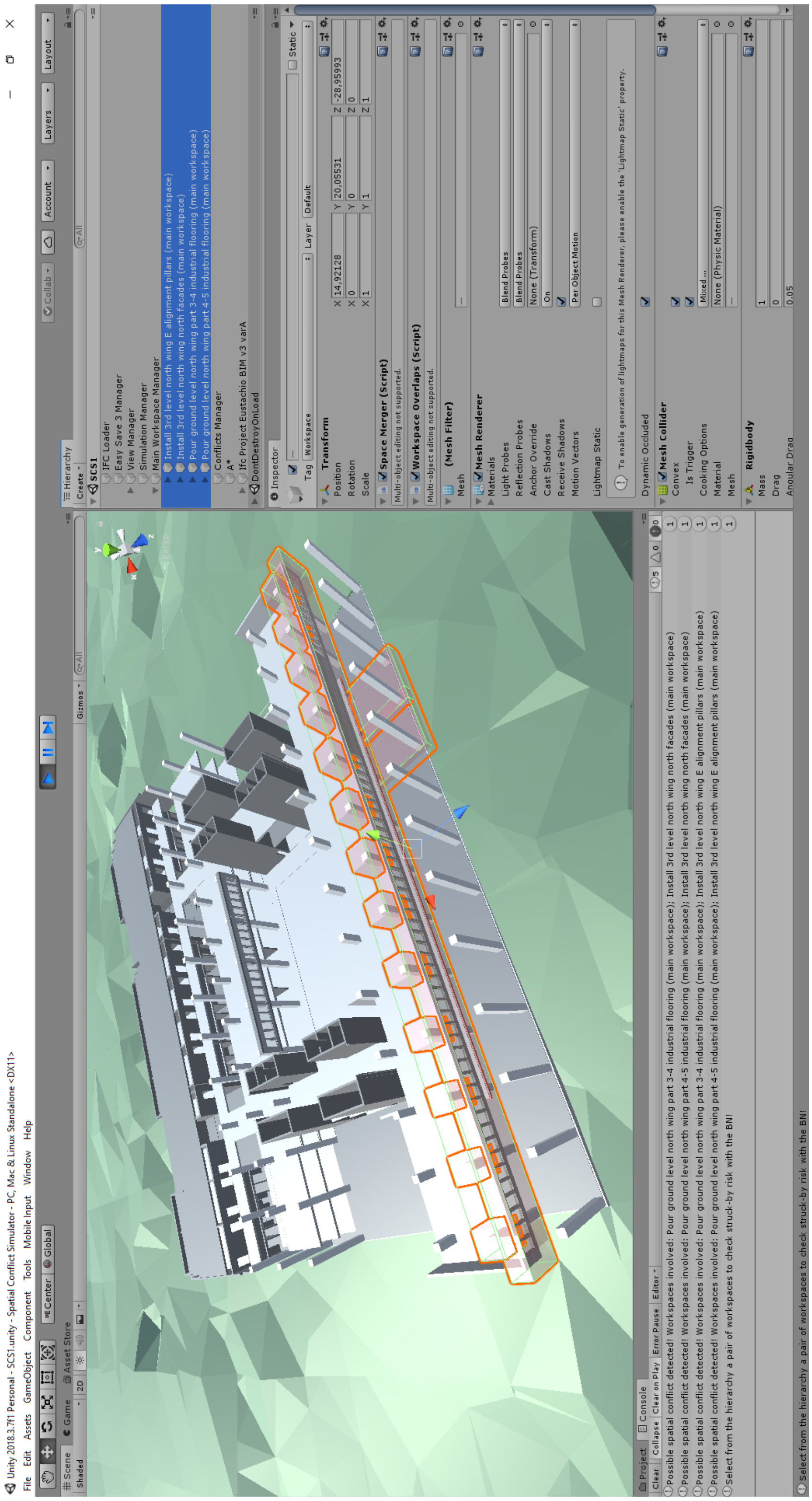


Figure 75. Results from the geometric intersection test during physics simulation executed for Variation A of the Standard model for the working days May 27th and 28th, assumed as work schedule.

As already said in the previous Section 6.3.2, the surroundings conditions may induce or not the occurrence of these “possible” spatial conflicts. For each of these ones, the Bayesian inference has been run to assess their criticality levels. The obtained results for each “possible” spatial conflict are respectively depicted in Figure 76, Figure 77, Figure 78, and Figure 79. As shown by Table 5, the variables’ evidence and the Bayesian results are the same for each one of the four “possible” spatial conflicts. In this scenario, the criticality levels of the “possible” spatial conflicts are judged by the Bayesian inference as low, being the “low” state of the “Struck_by_hazard” variable equal to 57,34% (Table 8).

Just for validating the Bayesian inference results provided by the serious gaming tool, Figure 80 reports the ones obtained by using Hugin Researcher 8.7, where the same Bayesian network with the same evidence has been redefined. Table 5 and Figure 80 demonstrate that the inference results computed by the two implementations are comparable.

In this scenario, the Standard model has been varied into the Variation A by removing some of the openings on the 3rd level north facade in order to give it the function of a construction fence that can protect laborers below from likely falling objects. The change of this building feature is caught by the serious gaming tool. In fact, randomly wandering avatars have been generated in a random initial position within the higher workspaces (e.g., “Install 3rd level north wing E alignment pillars (main workspace)” and “Install 3rd level north wing north facades (main workspace)”). Since the openings on the 3rd level north facade have been removed in correspondence of the lower main workspaces (e.g., “Pour ground level north wing part 3-4 industrial flooring (main workspace)” and “Pour ground level north wing part 4-5 industrial flooring (main workspace)”), no avatar can fall down. Therefore, the variable “Construction_fence” has been fired as “true” state. This is the reason why, in this scenario, the criticality level is changed from high (78,1%), as in the Enhanced scenario, to low (57,34%).

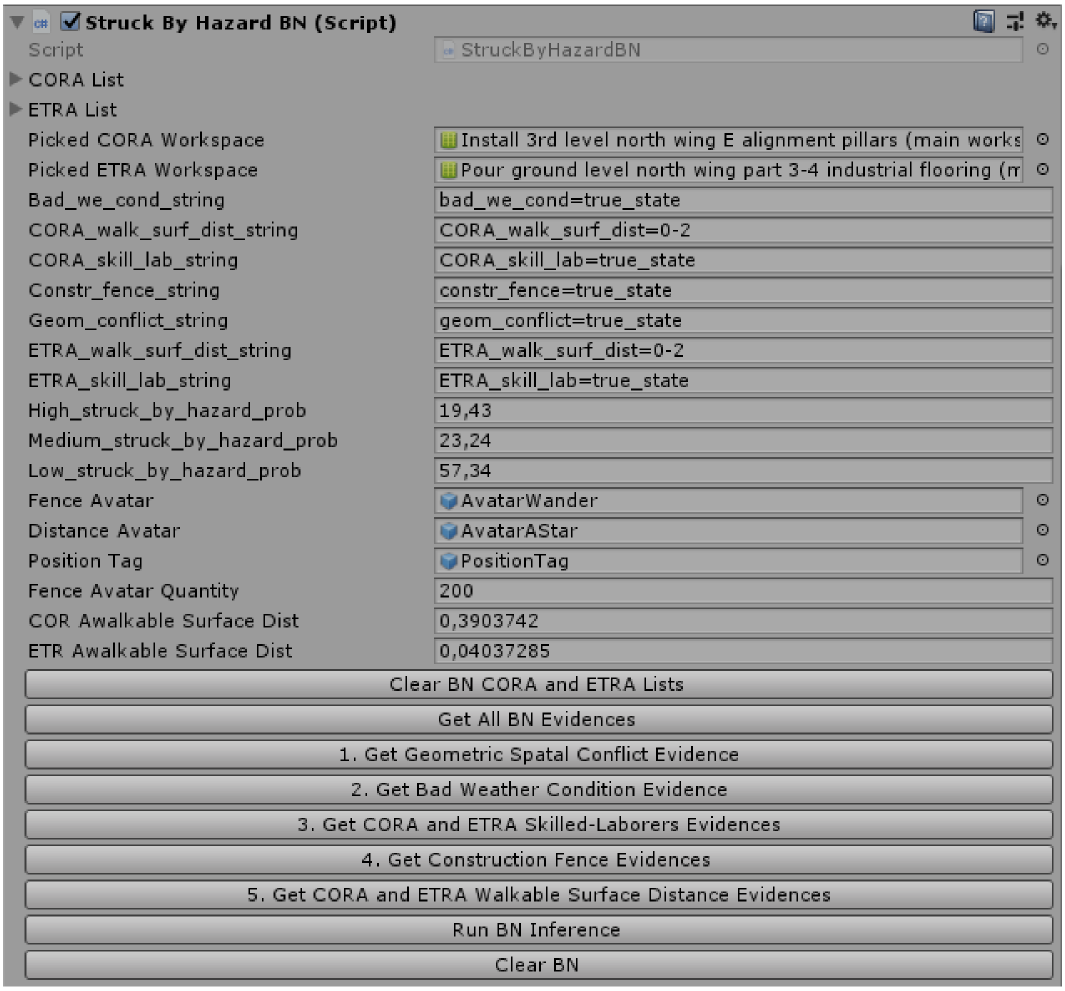


Figure 76. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict A.1.

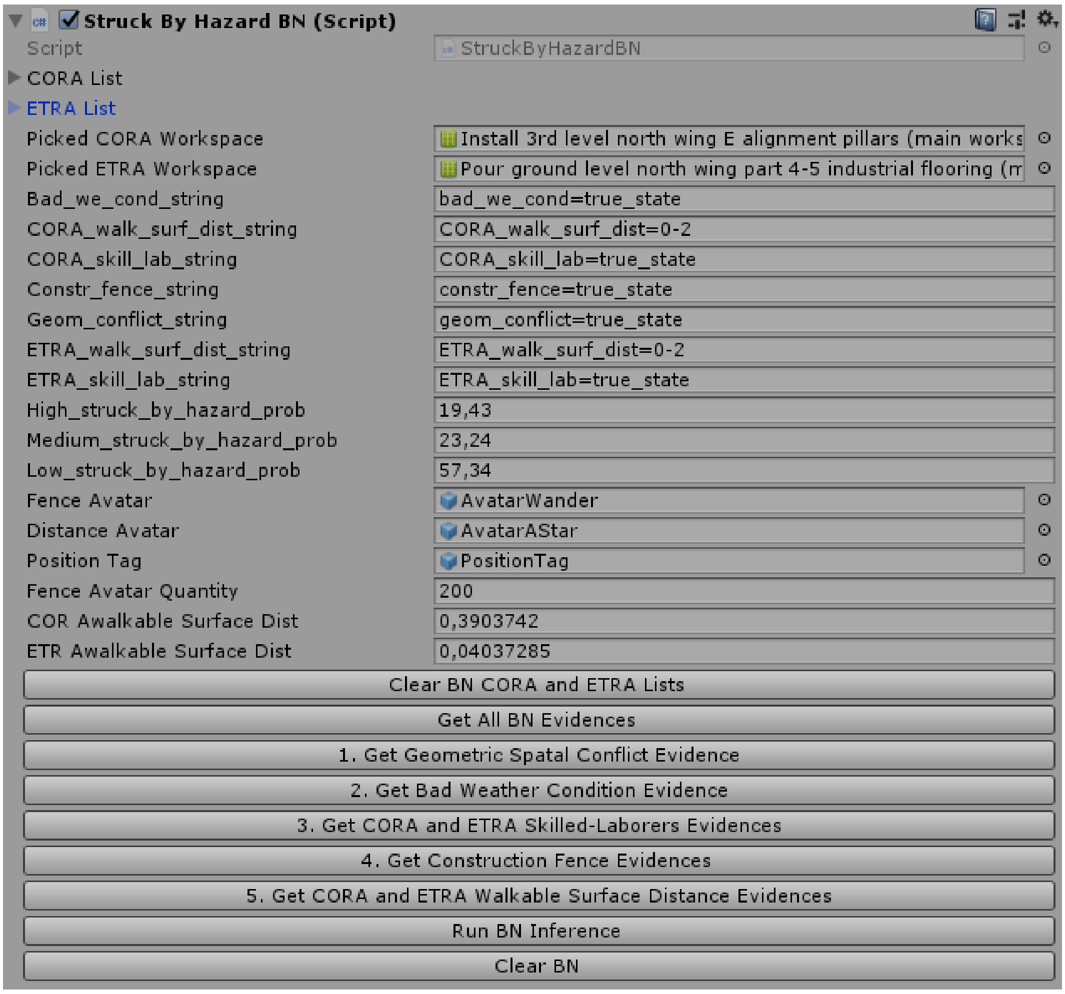


Figure 77. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict A.2.

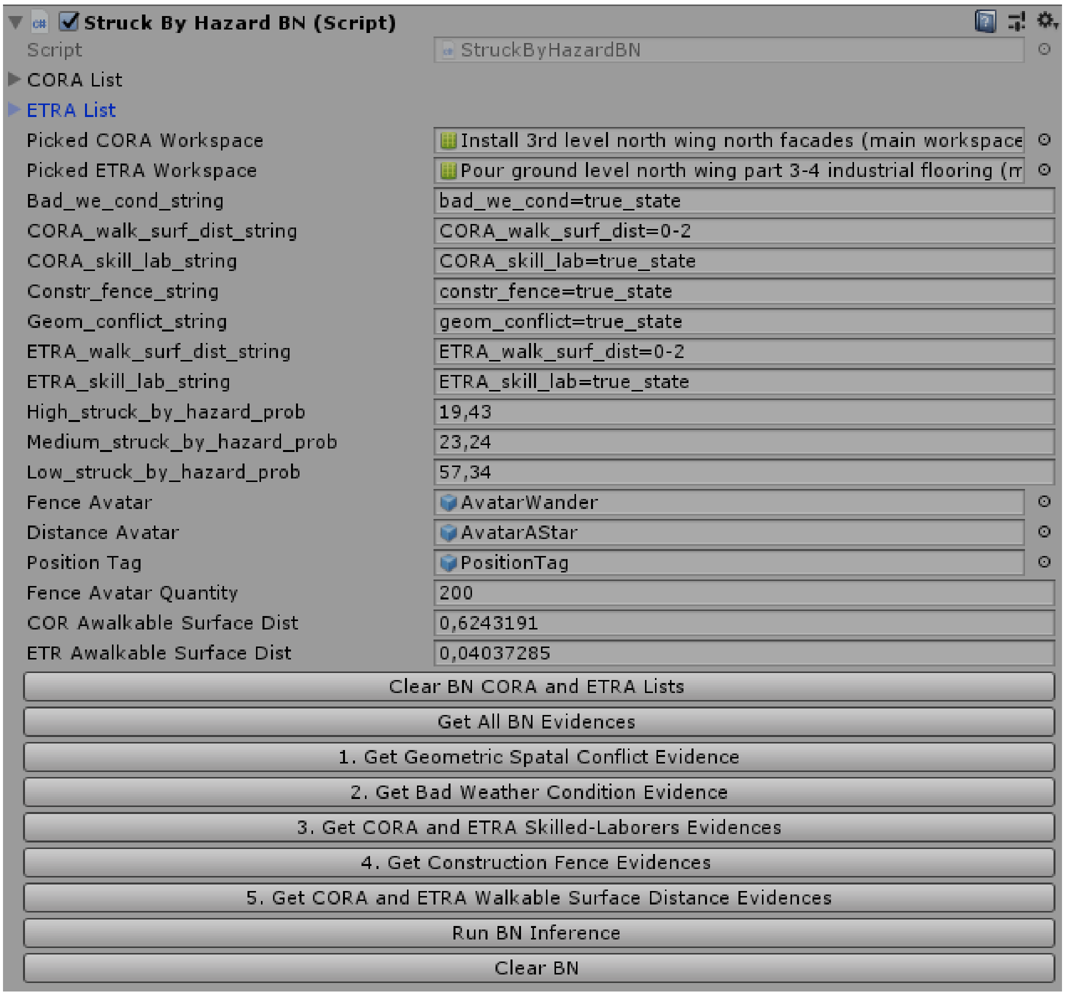


Figure 78. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict A.3.

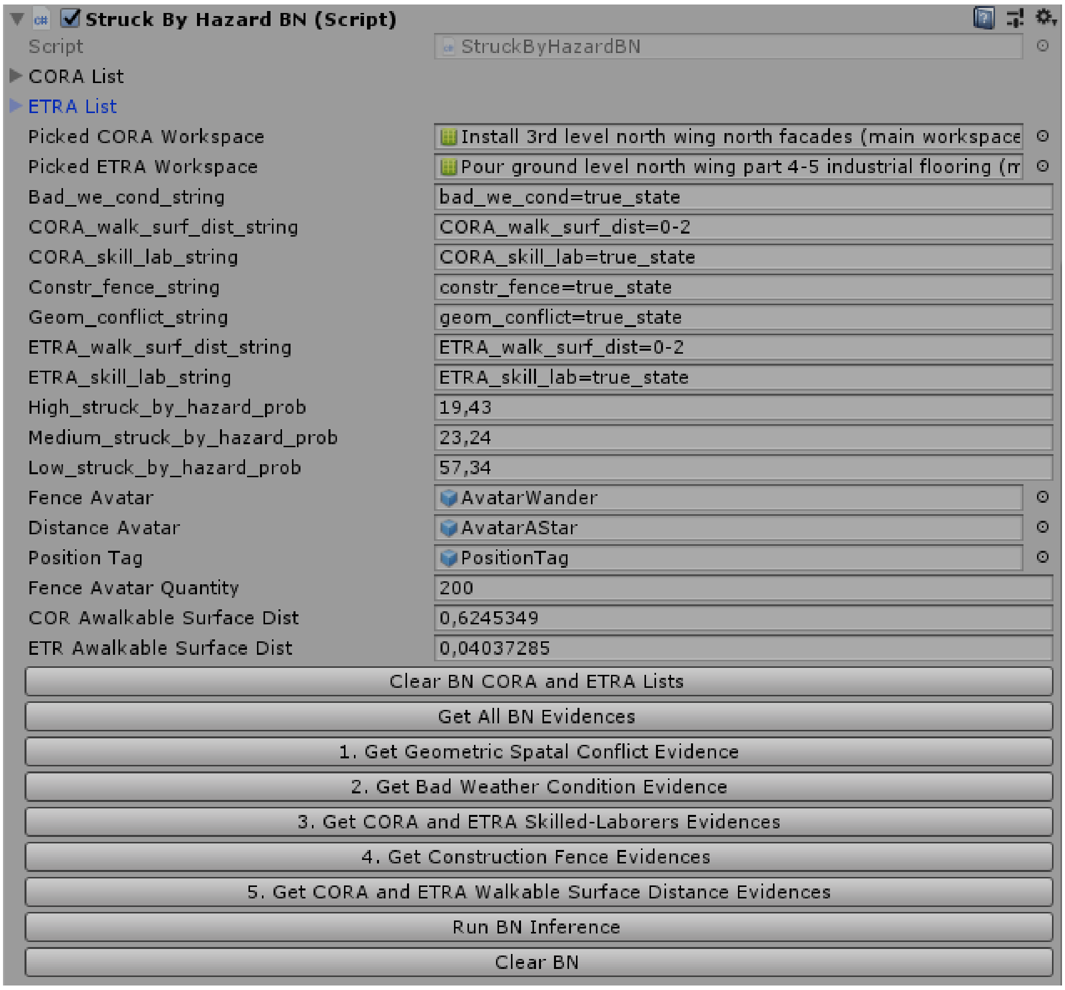


Figure 79. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict A.4.

Table 6. Summary table with the Bayesian inference results obtained for each "possible" spatial conflict detected in the Enhanced scenario – Variation A.

Variable		Variables states for each "possible" spatial conflict (Enhanced scenario - Variation A)			
		A.1.	A.2.	A.3.	A.4.
Bad_weather_condition		True	True	True	True
CORA_walkable_surface_distance		0-2	0-2	0-2	0-2
CORA_skilled_laborers		True	True	True	True
Construction_fence		True	True	True	True
Geometric_spatial_conflict_detected		True	True	True	True
ETRA_walkable_surface_distance		0-2	0-2	0-2	0-2
ETRA_skilled_laborers		True	True	True	True
Struck_by_hazard	High	19,43%	19,43%	19,43%	19,43%
	Medium	23,24%	23,24%	23,24%	23,24%
	Low	57,34%	57,34%	57,34%	57,34%

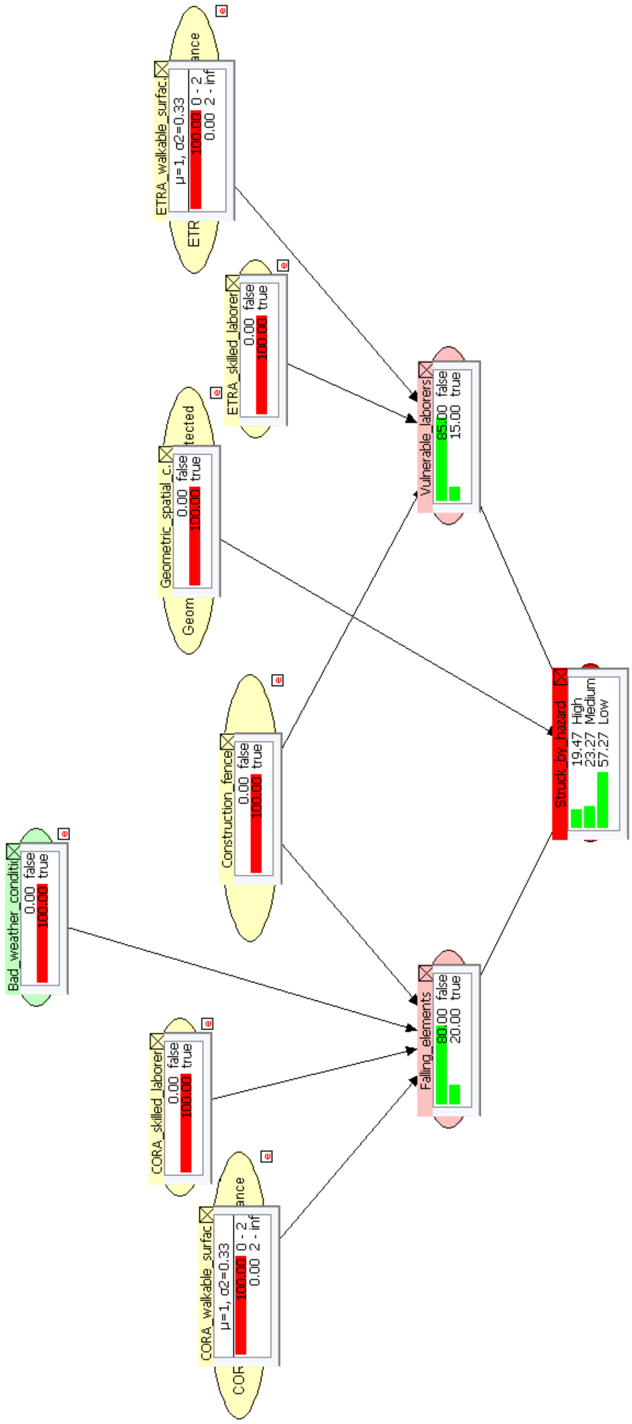


Figure 80. Bayesian inference results obtained by using Hugin Researcher 8.7 for the Enhanced scenario – Variation A.

6.3.4. Results from the Enhanced scenario – Variation B

In this scenario, although the Standard model has been replaced by the Variation B (Table 4), the results of the geometric intersection tests between main workspaces (i.e., first simulation step), for the working days May 27th and 28th, are the same than the one obtained in the previous scenarios. In fact, the same spatial conflict, between a pair of main workspaces assigned to different crews, is detected and reported by the following message in the Unity3D^{TM} Console window (Figure 81):

G.1. Spatial conflict detected! Workspaces involved: Install 3rd level north wing E alignment pillars (main workspace); Install 3rd level north wing north facades (main workspace).

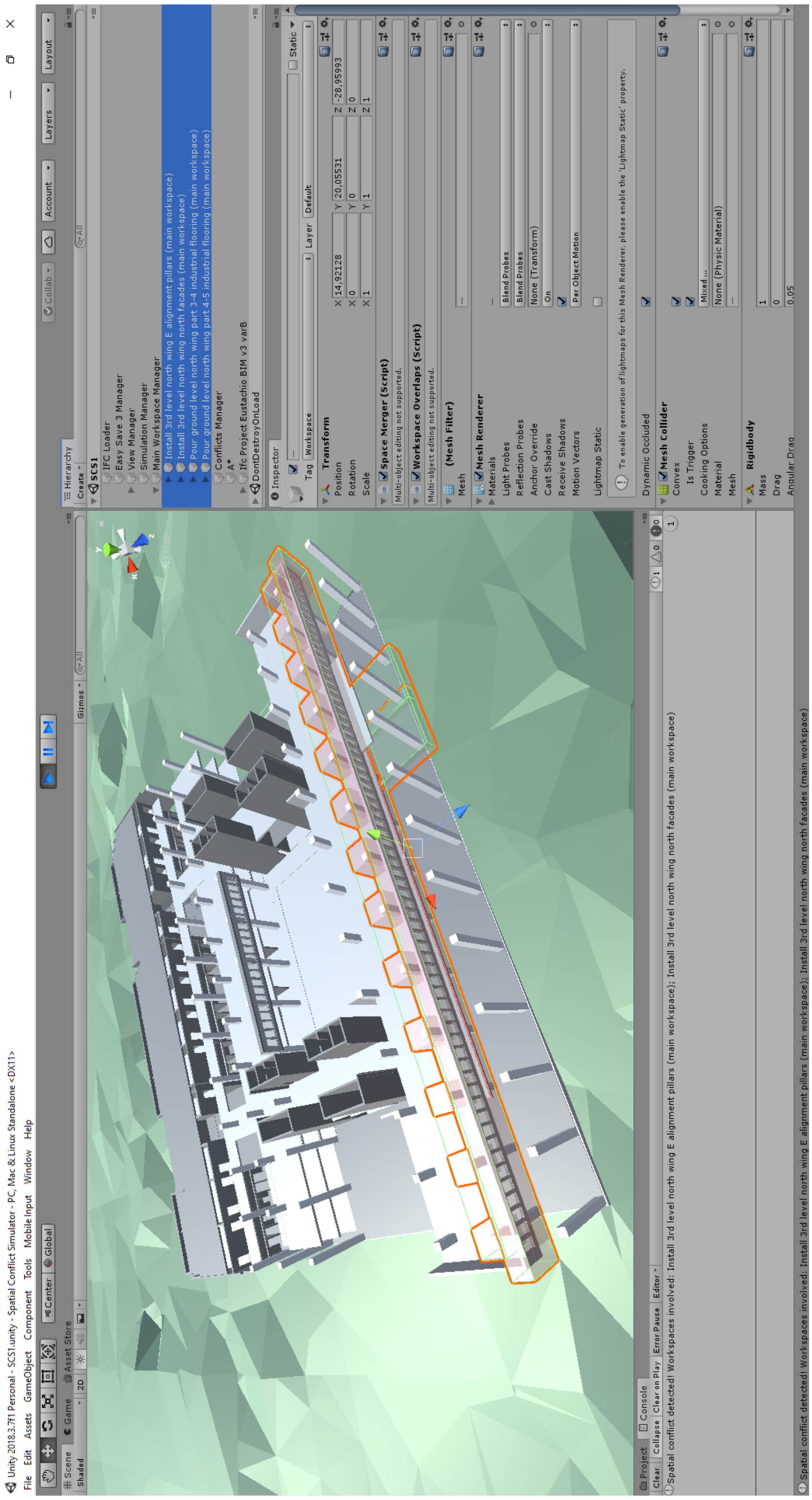


Figure 81. Results from the geometric intersection test executed for the Variation B of the Standard model for the working days May 27th and 28th, assumed as work schedule.

The results obtained by the geometric intersection tests carried out during physics simulations (i.e., second simulation step) are the same than the one obtained in the previous scenarios. In fact, the same four “possible” spatial conflicts, between pairs of main workspaces assigned to different crews, are detected and reported by the following messages in the Unity3D^{TM} Console window (Figure 75):

B.1. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

B.2. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing E alignment pillars (main workspace).

B.3. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 3-4 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

B.4. Possible spatial conflict detected! Workspaces involved: Pour ground level north wing part 4-5 industrial flooring (main workspace); Install 3rd level north wing north facades (main workspace).

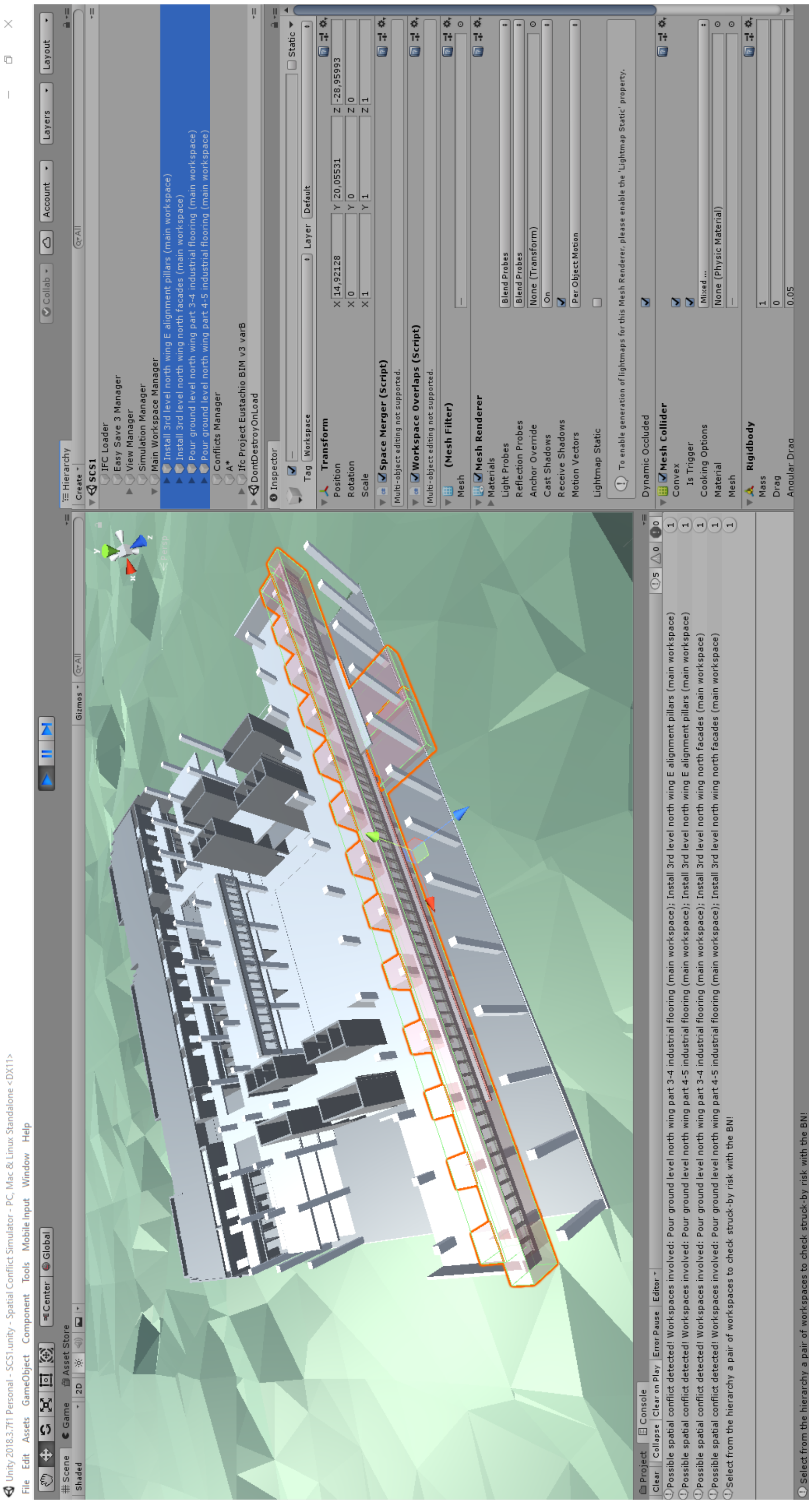


Figure 82. Results from the geometric intersection test during physics simulation executed for Variation B of the Standard model for the working days May 27th and 28th, assumed as work schedule.

As already said in the previous Section 6.3.2, the surroundings conditions may induce or not the occurrence of these “possible” spatial conflicts. For each of these ones, the Bayesian inference has been run to assess their criticality levels. The obtained results for each “possible” spatial conflicts are respectively depicted in Figure 83, Figure 84, Figure 85, and Figure 86. As shown by Table 7, the variables’ evidence and the Bayesian results are the same for each one of the four “possible” spatial conflicts. In this scenario, the criticality levels of the “possible” spatial conflicts are judged by the Bayesian inference as high, being the “high” state of the “Struck_by_hazard” variable equal to 41,93% (Table 8).

Just for validating the Bayesian inference results provided by the serious gaming tool, Figure 87 reports the ones obtained by using Hugin Researcher 8.7, where the same Bayesian network with the same evidence has been redefined. Table 7 and Figure 87 demonstrate that the inference results computed by the two implementations are comparable.

In this scenario, the Standard model has been varied into the Variation B by adding a cantilever slab (e.g., a balcony or a solar shading) that makes the upper walkable surface back away, avoiding laborers can get closer to the edge and make accidentally let fall object below. Figure 83, Figure 84, Figure 85, and Figure 86 report that the “CORA Walkable Surface Distance”, retrieved by geometric computations carried out in the serious gaming environment, is higher than 2 meters. Therefore, the “CORA_walkable_surface_distance” variable passes from the “0-2” state of the previous scenarios to the “2-inf” state. This is the reason why, in this scenario, the criticality level remained high, but decreasing its probability from 78,1%, as in the Enhanced scenario, to 41,93%.

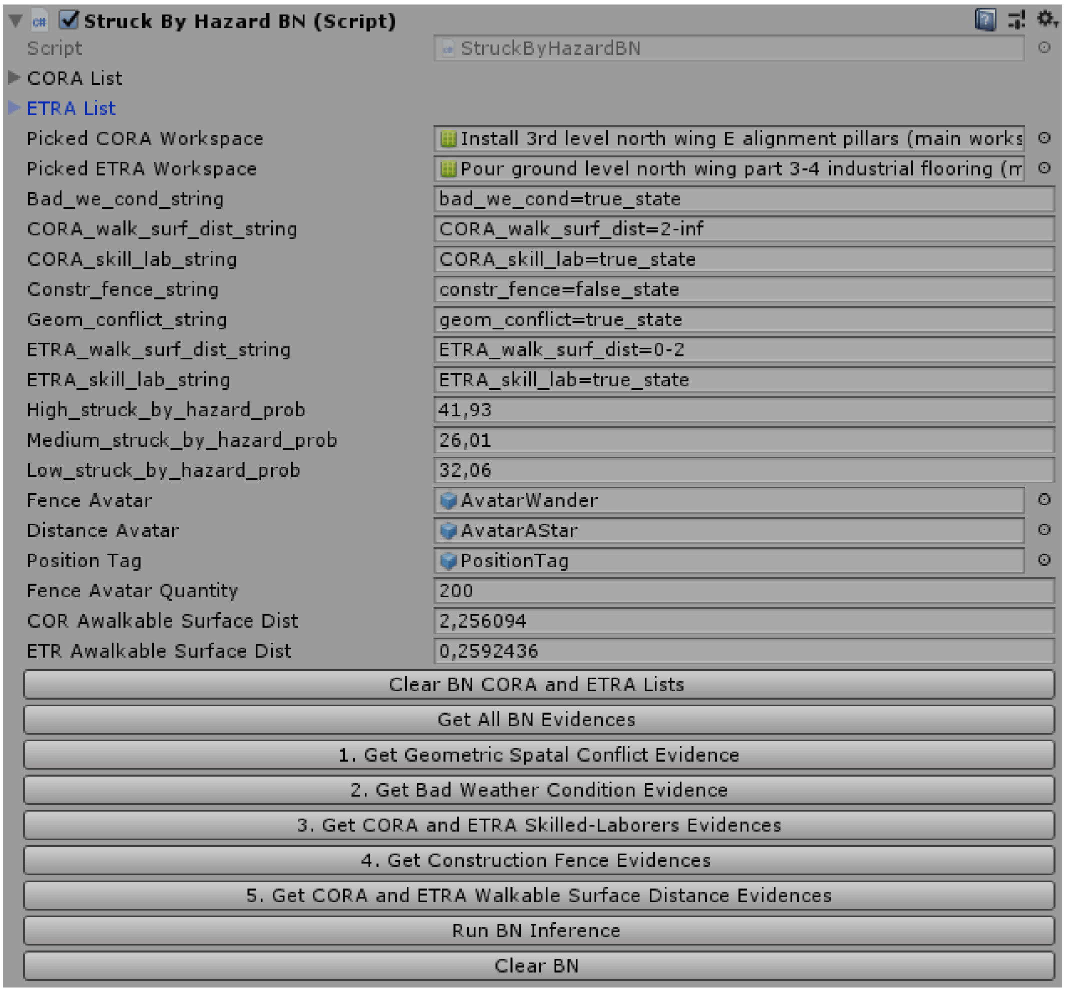


Figure 83. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict B.1.

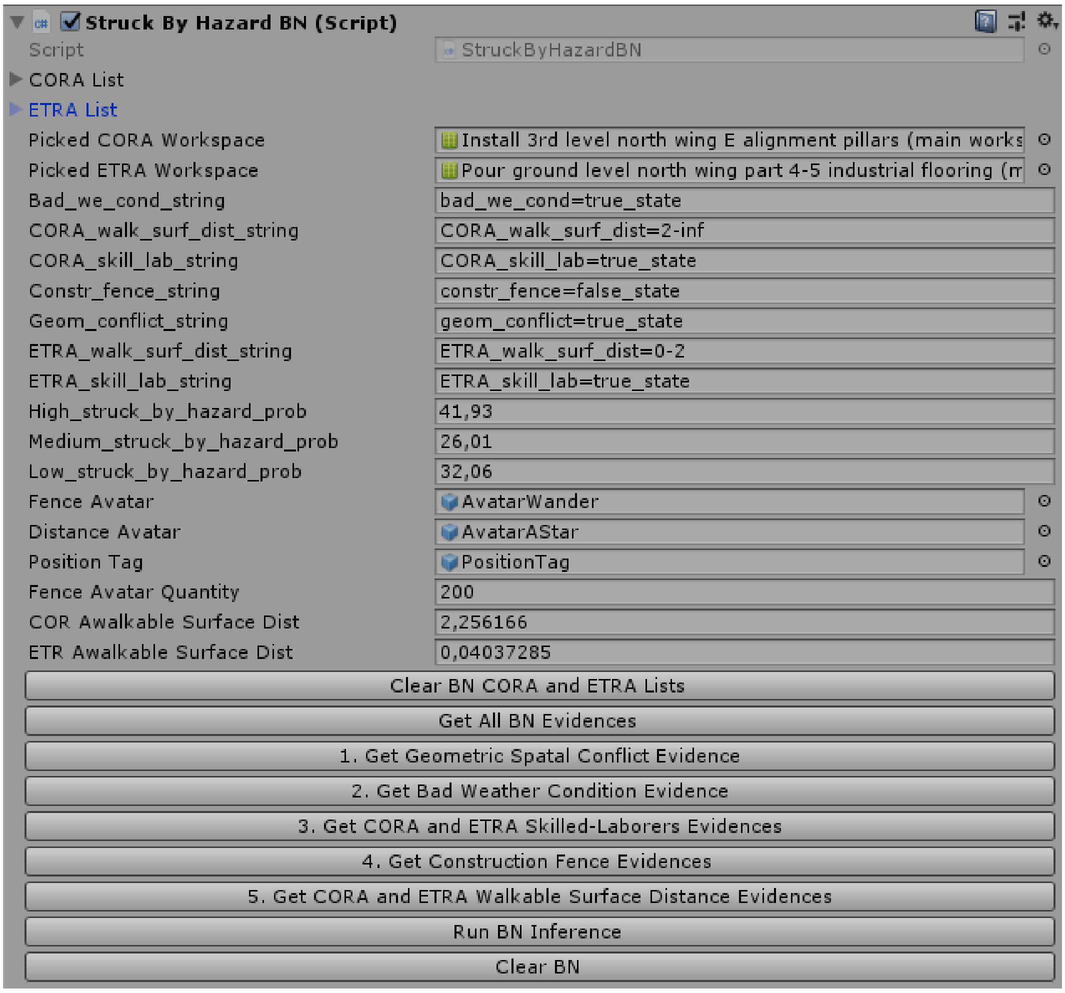


Figure 84. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict B.2.

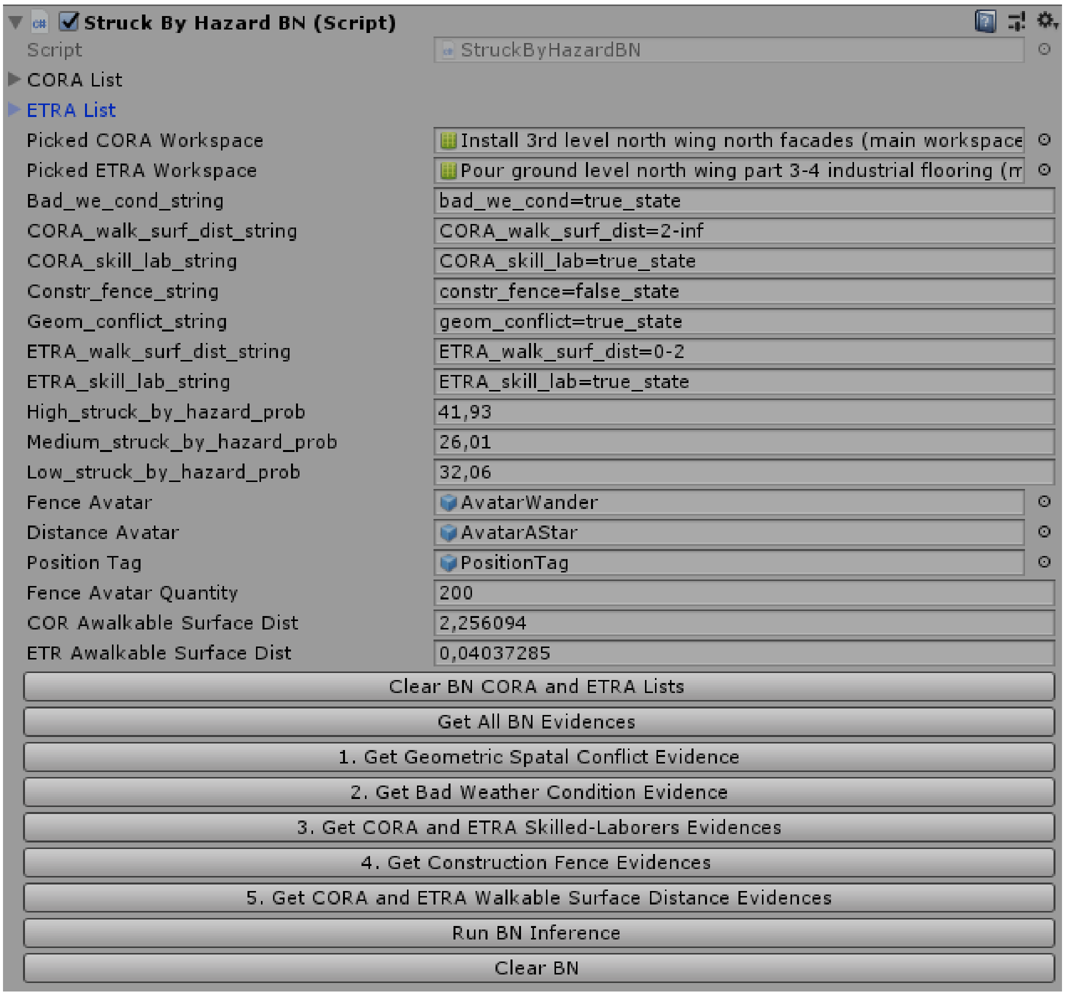


Figure 85. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict B.3.

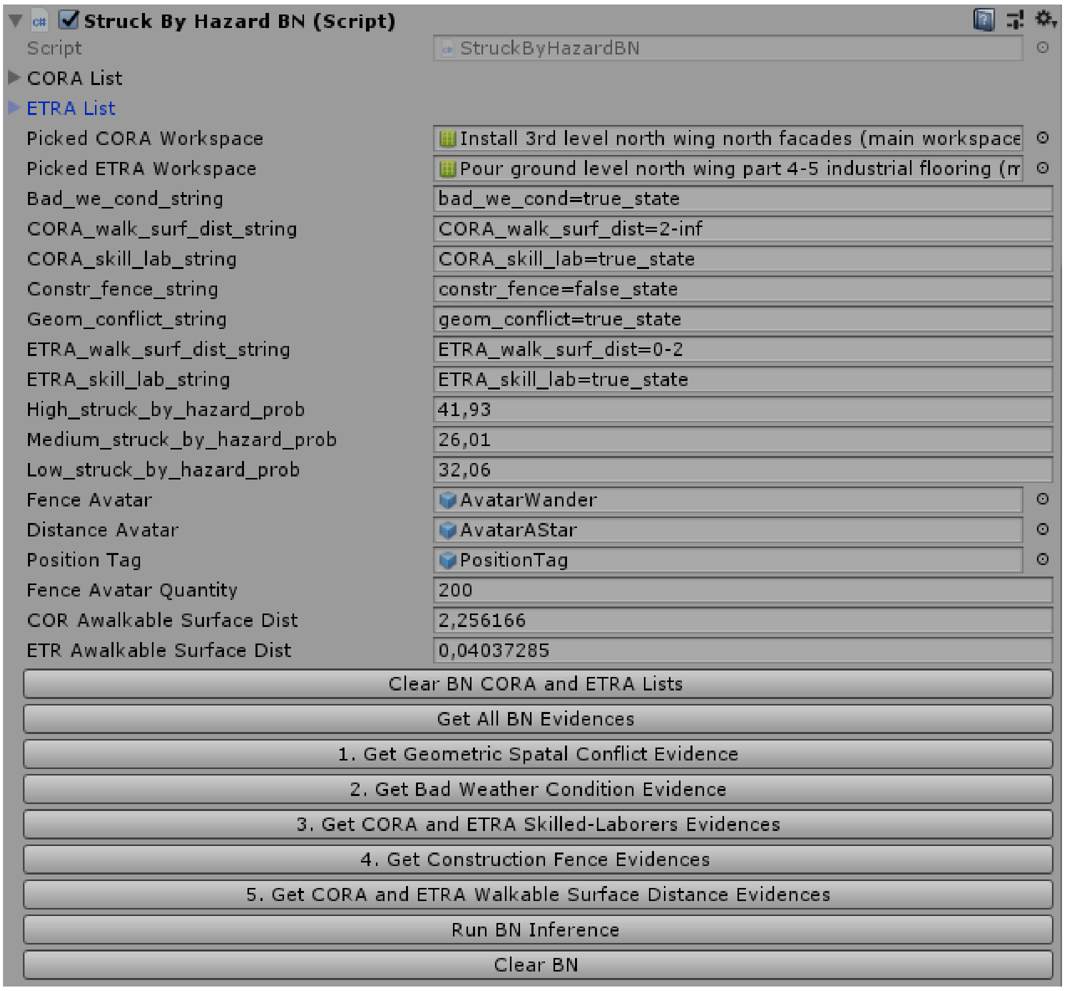


Figure 86. "Struck by Hazard BN" component reporting the Bayesian inference results for the "possible" spatial conflict B.4.

Table 7. Summary table with the Bayesian inference results obtained for each "possible" spatial conflict detected in the Enhanced scenario – Variation B.

Variable		Variables states for each "possible" spatial conflict (Enhanced scenario - Variation B)			
		B.1.	B.2.	B.3.	B.4.
Bad_weather_condition		True	True	True	True
CORA_walkable_surface_distance		2-inf	2-inf	2-inf	2-inf
CORA_skilled_laborers		True	True	True	True
Construction_fence		True	True	True	True
Geometric_spatial_conflict_detected		True	True	True	True
ETRA_walkable_surface_distance		0-2	0-2	0-2	0-2
ETRA_skilled_laborers		True	True	True	True
Struck_by_hazard	High	41,93%	41,93%	41,93%	41,93%
	Medium	26,01%	26,01%	26,01%	26,01%
	Low	32,06%	32,06%	32,06%	32,06%

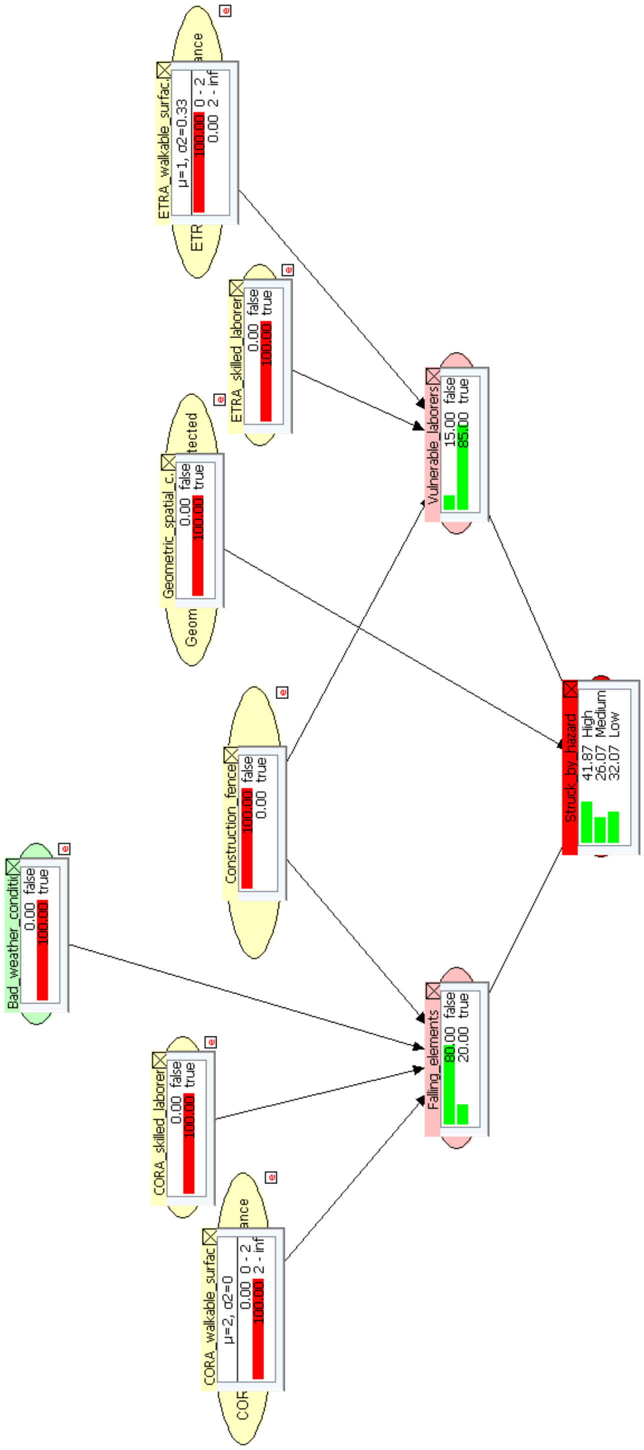


Figure 87. Bayesian inference results obtained by using Hugin Researcher 8.7 for the Enhanced scenario – Variation B.

6.4. Discussion

In this Section, the results obtained by applying the developed serious gaming tool in the different validations scenarios (Section 6.2) are discussed by comparing first the Benchmark scenario (Section 6.3.1) with the Enhanced one (Section 6.3.2) and, then, the Enhanced scenarios with the ones based on Variation A (Section 6.3.3) and Variation B (Section 6.3.4).

Benchmark scenario vs. Enhanced scenario

As described in Sections 6.2.1 and 6.2.2, whereas the Benchmark scenario replicates the state of the art in workspace management, the Enhanced one is defined to stress the added values provided by the serious gaming tool presented in this study. The difference between them is that in the Enhanced scenario, spatial conflicts among main workspaces are detected not only by carrying out geometric intersection tests, as in the Benchmark one, but also physics simulations (Table 4, Figure 63, and Figure 64). In this way, spatial interferences between different crews' workspaces can be detected also if they do not interfere in their first static configuration. Carrying out physics simulations enables to consider eventual spatial issues due to struck-by events. As a result, four more spatial conflicts of struck-by type are detected in the Enhanced scenario as compared to the Benchmark one (Table 8).

The promising results of the Enhanced scenario, described above in this Section, demonstrate the relevance of carrying out geometric intersection tests during physics simulations to enhance the range of detected spatial conflicts (e.g., including those ones due to objects falling from heights). This kind of integration, described by the proposed workspace management framework (Section 4.5) and implemented in the developed serious gaming tool (Section 5), provides the answer to the research question No. 1 (Section 3).

Enhanced scenario vs. Variation A vs. Variation B

Detecting spatial conflicts on the basis of geometric intersection tests, despite combined with physics simulations, may lead to overestimations. In fact, the detected "possible" spatial conflicts may be or may not be critical one, according to the surroundings conditions. In order to assess the criticality levels of the detected "possible" spatial conflicts and avoid any overestimation, the expert knowledge formalized in a Bayesian network has been applied in this study. This represents one of the added values to the body of knowledge by the developed tool. The contribution given by the Bayesian inference to detect spatial conflicts related to struck-by events, is stressed by varying the BIM model adopted in the Enhanced scenarios, referred to as the Standard one, into Variation A and Variation B.

In the Enhanced scenario – Standard model, the surroundings conditions lead to a high criticality level of all the detected "possible" spatial conflicts (Table 8). In fact, having the "high" state of the Bayesian network "Struck_by_hazard" variable a probability equals to 78,10%, the detected "possible" spatial conflicts must be reasonably confirmed. Therefore, according to the proposed workspace management framework (Section 4.5), the construction management team must adjust the work schedule in order to resolve all the 5 detected spatial conflicts reported in Table 8 (i.e., G.1., S.1., S.2., S.3., S.4.).

On the contrary, in the Enhanced scenario – Variation A, the surroundings conditions lead to a low criticality level of the detected "possible" spatial conflicts (Table 8). In fact, having the "low" state of the Bayesian network "Struck_by_hazard" variables a probability equals to 57,34%, the detected "possible" spatial conflicts can be reasonably ignored. Therefore, according to the workspace management framework (Section 4.5), the construction management team must adjust the work schedule in order to resolve only the spatial conflict, reported in Table 8, detected by the simple geometric intersection test (i.e., G.1.).

Finally, in the Enhanced scenario – Variation B, the surroundings conditions lead to a high criticality level of the detected "possible" spatial conflicts (Table 8). In fact, having the "high" state of the Bayesian network "Struck_by_hazard" variable a probability equals to 41,93%, the detected "possible" spatial conflicts should be confirmed, although it does not go over the 50,00%. Therefore, according to the workspace management framework (Section 4.5), the construction management team must adjust the work schedule in order to resolve all the 5 detected spatial conflicts reported in Table 8 (i.e., G.1., S.1., S.2., S.3., S.4.).

The promising results of the Enhanced scenario, described above in this Section, demonstrate the relevance of integrating expert knowledge, in the form of Bayesian networks, with site geometric information and work schedule data to avoid spatial issues overestimation. This kind of integration, described by the proposed workspace management framework (Section 4.5) and implemented in the developed serious gaming tool (Section 5), provides the answer to the research question No. 2 (Section 3).

Table 8. Summary table of the results obtained for each validation scenario.

Validation scenario	Pair ID	Pairs of workspaces involved in spatial conflicts detected by geometric intersection tests		Pair ID	Pairs of workspaces involved in possible spatial conflicts detected by physics simulations and geometric intersection tests		Criticality levesl of the possible spatial conflicts provided by Bayesian inference
Benchmark scenario	G.1.	Install 3rd level north wing E alignment pillars (main workspace)	Install 3rd level north wing north facades (main workspace)	-	-	-	-
Enhanced scenario	G.1.	Install 3rd level north wing E alignment pillars (main workspace)	Install 3rd level north wing north facades (main workspace)	S.1.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	High (78,1%)
				S.2.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	High (78,1%)
				S.3.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	High (78,1%)
				S.4.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	High (78,1%)
Enhanced scenario - Variation A	G.1.	Install 3rd level north wing E alignment pillars (main workspace)	Install 3rd level north wing north facades (main workspace)	A.1.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	Low (57,34%)
				A.2.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	Low (57,34%)
				A.3.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	Low (57,34%)
				A.4.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	Low (57,34%)
Enhanced scenario - Variation B	G.1.	Install 3rd level north wing E alignment pillars (main workspace)	Install 3rd level north wing north facades (main workspace)	B.1.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	High (41,93%)
				B.2.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing E alignment pillars (main workspace)	High (41,93%)
				B.3.	Pour ground level north wing part 3-4 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	High (41,93%)
				B.4.	Pour ground level north wing part 4-5 industrial flooring (main workspace)	Install 3rd level north wing north facades (main workspace)	High (41,93%)

CHAPTER 7

7. Conclusions and outlook

In the AEC industry, construction sites can be described as very dynamic operating environments. As a consequence, safety and constructability issues are most of the times contextual, that is to say they depend on complex geometries, spatial-temporal dependencies, and ever-changing site conditions. In this context activities workspace demand continuously change across space demanding and time, stressing the need to consider space as a limited and renewable resource in the construction site.

This issue has not been fully handled yet, neither by traditional scheduling techniques (e.g., Gantt charts) nor by more advanced 4D tools (e.g., Navisworks, Synchro). In fact, the first category can for their nature only represent temporal relationships between activities and not the space required for their execution. The second category, instead, cannot handle neither workspace dynamics nor any kind of simulation. In addition, the results of spatial analysis carried out in Navisworks show that, although it is one of the best advanced tools for clashes detection, it is not adequate for checking interferences between workspaces (Appendix A.1).

For all these reasons, construction management teams carry out spatial consideration manually with the help of 2D sketches. It is fully agreed that, especially in big construction projects having thousands of activities executed in parallel, this approach not only is highly time-demanding but also error-prone. This is fully demonstrated by statistics about losses, injuries, and productivity slowdowns.

Many efforts have been spent to date by researchers in the fields of workspace management. As reported in the Section 2.4, the main gaps existing in literature point out the need to consider the construction site dynamics and filter non-critical scenarios among pure geometric spatial conflicts.

To cover these gaps, this study proposes a workspace management framework that integrates the work scheduling phase with the contribution given by a spatial conflict simulator. The latter has been developed adopting the serious game engine technology, namely Unity3D™. Thanks to this technological solution, the proposed spatial conflict simulator can detect eventual spatial interferences on the basis of given geometric and semantic information, stored in the BIM model, and construction process data, included in the work schedule. This tool, framed within a Last Planner System (LPS) framework, is intended for simulating the work schedule in the short-term ahead and supporting the construction management team during the continuous refinement of the work schedule itself. In the serious game engine Unity3D™, geometric and physics simulations can be carried to anticipate likely future scenarios. In fact, 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 between the involved agents. Hence, in this study, not only spatial interferences between static workspaces can be detected. As described in Section 5.1.5, also "possible" spatial conflicts due to struck-by events can be detected by simulating the corresponding workspaces dropping down, according to the law of gravity, and retrieving intersections between them. The integration of physics simulations and geometric intersection tests, as described by the proposed workspace management framework (Section 4.5) and implemented in the developed serious gaming tool (Section 5), provides the answer to the research question No. 1 (Section 3).

In addition, to avoid overestimations, the criticality levels of "possible" spatial conflicts are judged by running a Bayesian network, whose variables' states are automatically fed by the simulation data provided by the serious gaming tool. As demonstrated in Section 6.3.2, the presence of a construction fence, protecting the lower workspace from falling objects, would lead to infer a low criticality level. To this regard, the standard approach would infer the presence of a barrier comparing the dimensions of existing building components to some given thresholds required to an element to be classified as a barrier.

This approach would not discern any difference between a concrete barrier and a light curtain if they have the same dimensions. The approach adopted by the proposed spatial conflict simulator, instead, infers the protective role of a barrier simulating the heavier equipment on-site hurting it and assessing its capability to resist. The integration of expert knowledge, in the form of Bayesian networks, with site geometric information and work schedule data, as described by the proposed workspace management framework (Section 4.5) and implemented in the developed serious gaming tool (Section 5), provides the answer to the research question No. 2 (Section 3).

According to the proposed workspace management framework, the construction management team, informed about likely future spatial conflicts and their criticality levels, can make more aware decisions during the refinement process of the work schedule.

The validation of the proposed workspace management framework and the resulting spatial conflict simulator has been carried out by testing them on real construction scenarios, related to the Eustachio building, venue of the Faculty of Medicine of the Polytechnic University of Marche (Ancona, Italy). The experiments results, widely described and discussed in Section 6.3 and 6.4, clearly demonstrate the potential of detecting spatial conflicts during physics simulations and the contribution given by Bayesian inference for avoiding overestimations, answering respectively to research questions No. 1 and 2 (Section 3).

The approach proposed in this study, being in its very first implementation, has some limitations. In fact, in this study, “indirect” or “possible” spatial conflicts have been detected by carrying out a very specific kind of physics simulation (i.e., dropping-down workspaces). This class of spatial conflicts, which includes all not-purely-geometric clashes among workspaces (e.g., struck-by risk from falling objects, electrical risk, etc.), must be defined according to several types of physics simulations. First, a literature review is highly recommended to define all the categories of “indirect” or “possible” spatial conflicts. On this basis, other types of physics simulations to be carried out in the spatial conflict simulator can be defined.

In addition, the application of expert knowledge for workspace management purposes has been tested only in the field of spatial conflicts among working areas. In the early future, the approach described in this study can be validated by the application on other use cases to address similar spatial-temporal issues. An example can be defined with reference to the planning phase of construction site layout. In this phase, equipment logistics operations, related to the earthmoving works, must be considered to define a safe site layout. A minimum safety distance of any moving equipment from excavation faces must be guaranteed during the entire earthmoving works phase to avoid equipment falls due to ground collapses. In this scenario, the integration of the serious gaming technology and the Bayesian inference can provide valuable contributions in assessing the risk related to the most likely paths followed by equipment during operations. The most likely path, which can be reasonably assumed as the shortest one between two given points, can be easily computed in the serious gaming environment by applying the same pathfinding tool used in this study (Granberg, 2020). Then, a Bayesian network defined for this application domain can be implemented in the serious gaming platform to detect risky site layout configurations and filter the non-critical ones. On this basis, the construction manager can make aware decision during the planning phase of construction site layout.

Another limitation of the proposed workspace management framework and the spatial conflict simulator is represented by their offline application. In the long term, the Decision Support System (DSS), resulting from this study and based on the proposed spatial conflict simulator, paves the way to the future development of a digital twin that can access the full data of the construction site, grasp the holistic context, and return valuable insights. The added value that comes from digital twins is not just the abundance of dynamic data it would manage, but its semantics and constant accrual of knowledge about the physical world. In future research, the proposed workspace management framework can be scaled on a near-real-time dimension in order to define a powerful instrument to support the construction management team directly on the field during the construction process. This shift would require the definition of a data source channel, able to constantly update the

BIM shell with real-time sensor data, ensuring the reliability of the look-ahead simulation results.

APPENDIX A

Appendix A

A.1. Spatial analysis in Navisworks

In this Section, the spatial analysis carried out by using one of the most popular 4D tool, namely Navisworks, is described in its main steps and the related results are reported. The aim of this analysis is replicating the same geometric intersection test executed by using the proposed serious gaming tool in the Benchmark scenario (Section 6.2.1). In fact, same use case (Section 6.1) and working days (Section 6.2.1) of the Benchmark scenario are considered.

In order to simulate the same working days of the Benchmark scenario (e.g., May 27^{th} and 28^{th}), the following time interval has been selected in the "Simulate" tab of the TimeLiner: from May 27^{th} 0 am to May 29^{th} 0 am (Figure 88).

In the Clash Detective window, a new test is added selecting all the available sets (each set correspond to an activity of work schedule) both in "Selection A" and "Selection B". This enables to check for conflicts by considering all the possible pairs of sets (i.e., activities) (Figure 89). Then, a "Clearance" type with 2 meters "Tolerance" is set to apply the equivalent offset value of 1 meter used in the serious gaming tool (Section 5.1.3). A "Clearance" clash, in Navisworks, is 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" (Autodesk, no date). On the contrary, in the developed serious gaming tool, the offset is applied to the border of each element. Finally, the TimeLiner "Link" is selected to carry out a spatial analysis within the TimeLiner interval set above.

The test has been launched by clicking on the “Run Test” button and 58 conflicts have been detected (Figure 89). The results have been exported as a report in the HTML format and then converted into the figure reported below (Figure 90, Figure 91, Figure 92, Figure 93, Figure 94, Figure 95, Figure 96, Figure 97, Figure 98, and Figure 99). Comparing these results with the ones obtained for the Benchmark scenario (Section 6.3.1), it is clear how Navisworks tends to overestimate number of detected spatial conflicts. This fact can be explained by the following considerations:

1. Navisworks reports spatial conflicts between each pair of building elements and not between activities’ workspaces.
2. Nevertheless, only 15 clashes out of 58 (clashes no. 44-58, reported in Figure 97, Figure 98, and Figure 99), correspond to the one detected in the Benchmark scenario (Section 6.3.1). Hence, only about the 25% of the detected spatial conflicts are “true positive”.
3. The rest of the clashes (i.e., 43 out of 58), that corresponds to the 75% of the detected spatial conflicts, are “false positive”. This is due to the fact that the Clearance clash test reports a clash for any building element, executed during the simulated time interval, if it is closer than the tolerance value to any other building element. This demonstrates that Navisworks, whereas can effectively check clashes between building element, is not indicated for checking spatial interferences between activities’ workspaces.

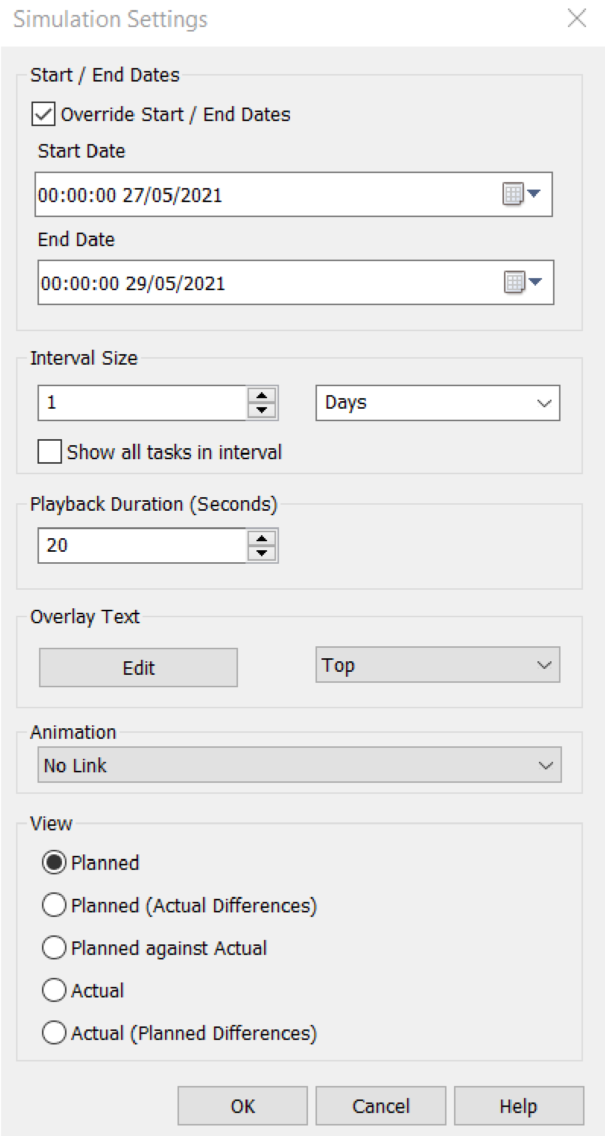


Figure 88. Setting the TimeLiner start/end dates: from May 27th 0 am to May 29th 0 am.

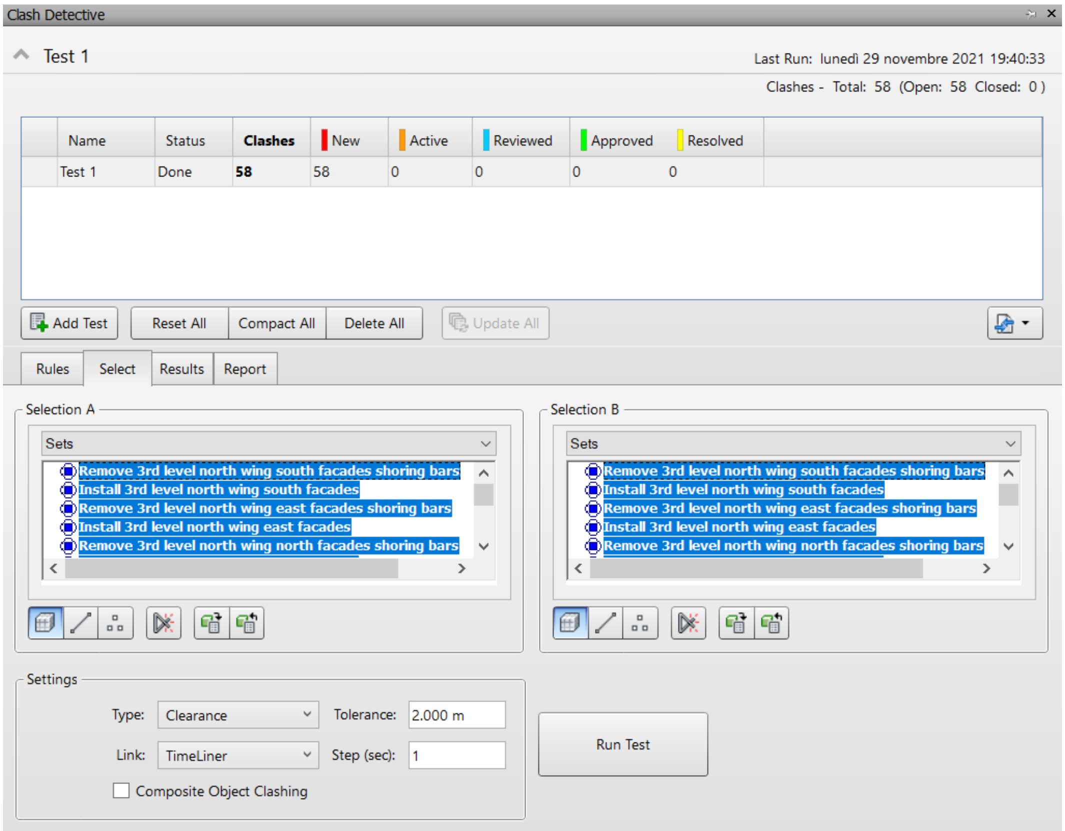


Figure 89. Setting the Clearance clash test parameters.

AUTODESK® NAVISWORKS®

Clash Report

Test 1	Tolerance	Clashes	New	Active	Reviewed	Approved	Resolved	Type	Status
	2.000m	58	58	0	0	0	0	Clearance	OK

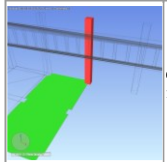
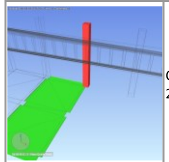
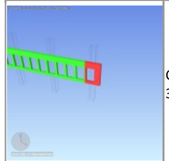
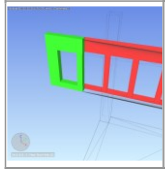
								Item 1				Item 2				Task		
Image	Clash Name	Status	Distance	Grid Location	Description	Date Found	Clash Point	Item ID	Layer	Item Name	Item Type	Item ID	Layer	Item Name	Item Type	Name	Start	End
	Clash 1	New	-0.043	F-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-5.179, y:112.290, z:29.080	*ID elemento* : 195809	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash 2	New	-0.000000232	F-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-5.556, y:113.100, z:29.080	*ID elemento* : 195809	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash 3	New	-0.0000000000000173	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:64.757, y:139.785, z:36.000	*ID elemento* : 759850	2 - Piano Secondo	Default - Calcestruzzo	Solido	*ID elemento* : 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash 4	New	-0.0000000000000173	E-1 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:-16.409, y:102.301, z:36.370	*ID elemento* : 760059	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento* : 639149	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 90. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 1-4.

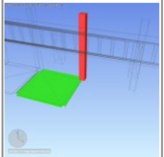
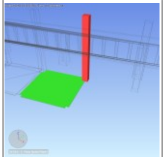
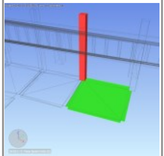
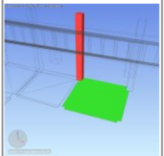
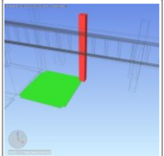
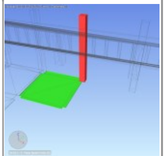
	Clash5	New	-0.0000000000000173	F-5 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:8.759, y:118.782, z:29.080	*ID elemento*: 195927	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash6	New	-0.0000000000000173	F-5 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:8.351, y:118.591, z:29.080	*ID elemento*: 195927	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash7	New	-0.0000000000000173	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.080	*ID elemento*: 195821	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash8	New	-0.0000000000000173	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:2.159, y:115.704, z:29.080	*ID elemento*: 195821	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash9	New	-0.0000000000000173	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.080	*ID elemento*: 195821	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash10	New	-0.0000000000000173	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.080	*ID elemento*: 195821	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 91. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 5-10.

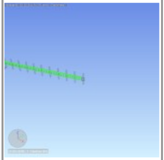
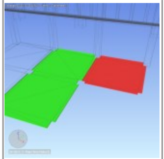
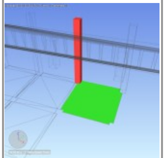
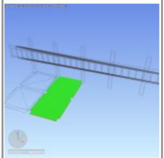
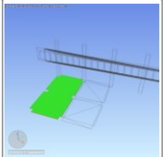
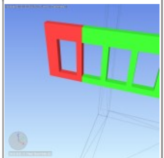
	Clash11	New	-0.000	E-13 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:64.506, y:140.032, z:36.370	*ID elemento*: 760059	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash12	New	-0.000	E-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-2.106, y:106.764, z:29.080	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash13	New	-0.000	F-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-4.738, y:113.474, z:29.080	*ID elemento*: 195809	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash14	New	0.000	F-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-5.518, y:113.118, z:29.080	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash15	New	0.000	F-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-11.701, y:109.241, z:29.080	*ID elemento*: 1227080	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento*: 1227080	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash16	New	0.000	E-1 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-16.270, y:102.002, z:36.000	*ID elemento*: 639149	2 - Piano Secondo	Default - Calcestruzzo	Solido	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 92. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 11-16.

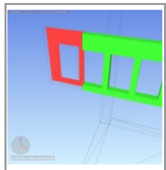
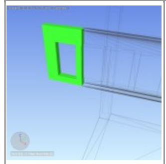
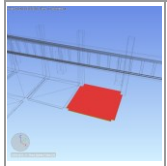
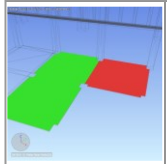
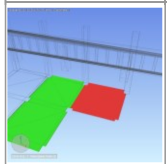
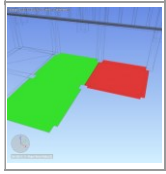
	Clash17	New	0.000	E-1 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-16.409, y:102.301, z:36.000	*ID elemento*: 639149	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash18	New	0.000	E-1 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-16.409, y:102.301, z:36.000	*ID elemento*: 639149	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento*: 639149	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash19	New	0.000	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.785, y:116.523, z:29.080	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento*: 1224989	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash20	New	0.000	E-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-2.106, y:106.764, z:29.080	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash21	New	-0.000	F-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-4.768, y:112.474, z:29.080	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash22	New	-0.000	E-3 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-2.106, y:106.764, z:29.080	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 93. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 17-22.

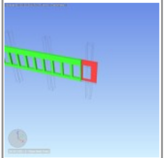
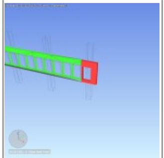
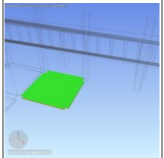
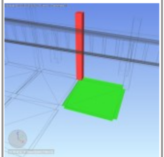
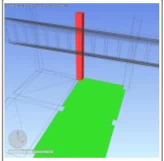
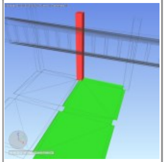
	Clash23	New	0.000	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:64.617, y:140.084, z:36.000	*ID elemento*: 759850	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash24	New	0.000	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:64.617, y:140.084, z:36.000	*ID elemento*: 759850	2 - Piano Secondo	Default - Calcestruzzo	Solido	*ID elemento*: 760059	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash25	New	0.000	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.350, y:115.327, z:29.080	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash26	New	0.000	F-3 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:-4.360, y:112.664, z:29.000	*ID elemento*: 195809	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 3-4 industrial flooring	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash27	New	0.000	F-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-10.886, y:109.621, z:29.080	*ID elemento*: 195797	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash28	New	0.000	F-2 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:-10.886, y:109.621, z:29.000	*ID elemento*: 195797	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 94. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 23-28.

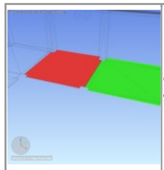
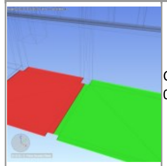
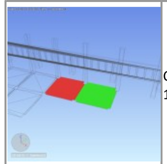
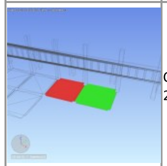
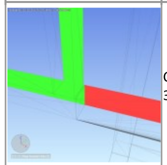
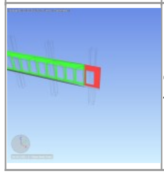
	Clash29	New	0.000	E-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:4.420, y:109.807, z:29.080	*ID elemento* : 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento* : 1224989	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash30	New	0.000	F-4 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.000	*ID elemento* : 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento* : 1224989	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash31	New	0.000	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.080	*ID elemento* : 1225516	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento* : 1224989	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash32	New	0.000	F-4 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:1.757, y:115.517, z:29.080	*ID elemento* : 1225516	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento* : 1224989	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	Pour ground level north wing part 4-5 industrial flooring	2021/5/28 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash33	New	0.0000000000000173	E-1 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:-16.409, y:102.301, z:36.370	*ID elemento* : 760059	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento* : 639149	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash34	New	0.0000000000000173	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:64.617, y:140.084, z:36.000	*ID elemento* : 759850	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido	*ID elemento* : 760059	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 95. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 29-34.

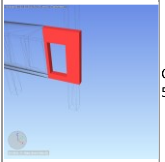
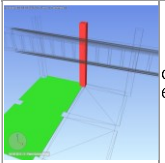
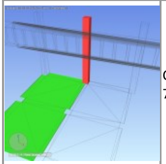
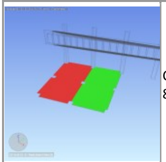
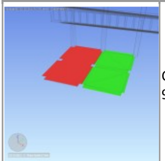
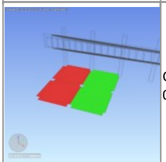
	Clash35	New	0.0000000000000173	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:66.491, y:140.958, z:36.000	*ID elemento* : 759850	2 - Piano Secondo	Default - Calcestruzzo	Solido	*ID elemento* : 759850	2 - Piano Secondo	ARC_PITTURA ESTERNA	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648
	Clash36	New	0.0000000727	F-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-12.082, y:110.057, z:29.080	*ID elemento* : 195797	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648
	Clash37	New	0.0000000727	F-2 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:-11.701, y:109.241, z:29.000	*ID elemento* : 195797	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648
	Clash38	New	0.0000000727	E-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-8.251, y:102.906, z:29.080	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648
	Clash39	New	0.0000000727	D-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-5.588, y:97.196, z:29.080	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648
	Clash40	New	0.0000000727	E-2 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-8.631, y:103.721, z:29.080	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0 -2147483648:-2147483648:-2147483648	2021/5/29 0:0 -2147483648:-2147483648:-2147483648

Figure 96. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no.35-40.

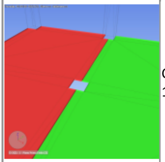
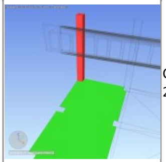
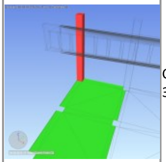
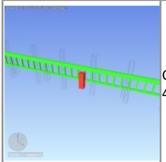
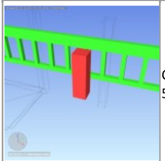
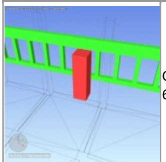
	Clash41	New	0.0000000727	E-2 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:-8.631, y:103.721, z:29.000	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido	*ID elemento* : 1226040	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash42	New	0.0000000727	F-1 : 0 - Piano Terra	Clearance	2021/11/29 15:40	x:-17.411, y:106.579, z:29.080	*ID elemento* : 195785	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_PAVIMENTAZIONE IN CERAMICA	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash43	New	0.0000000727	F-1 : 0 - Piano Interrato Pilastri	Clearance	2021/11/29 15:40	x:-17.411, y:106.579, z:29.000	*ID elemento* : 195785	0 - Piano Terra	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 1227080	0 - Piano Terra Finito	ARC_POLIURETANO ESPANSO	Solido		2021/5/27 0:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash44	New	1.670	E-8 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:30.712, y:122.989, z:36.000	*ID elemento* : 213613	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash45	New	1.670	E-5 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:10.660, y:113.639, z:36.000	*ID elemento* : 213681	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash46	New	1.670	E-3 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-2.866, y:107.331, z:36.000	*ID elemento* : 213565	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento* : 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 97. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 41-46.

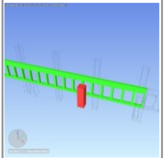
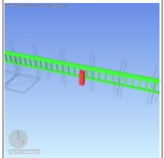
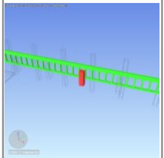
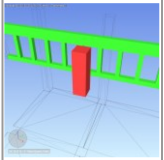
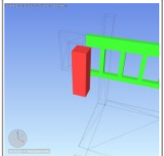
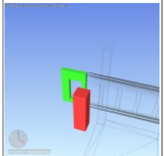
	Clash47	New	1.670	E-12 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:57.766, y:135.604, z:39.190	*ID elemento*: 213649	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash48	New	1.670	E-6 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:17.662, y:116.903, z:36.000	*ID elemento*: 213589	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash49	New	1.670	E-7 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:24.187, y:119.946, z:36.000	*ID elemento*: 213601	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash50	New	1.670	E-2 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-9.392, y:104.288, z:36.000	*ID elemento*: 213553	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash51	New	1.670	E-1 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:-15.917, y:101.245, z:36.000	*ID elemento*: 213541	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash52	New	1.670	E-1 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:-15.917, y:101.245, z:39.190	*ID elemento*: 213541	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 639149	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 98. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 47-52.

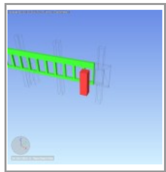
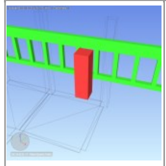
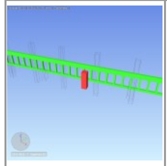
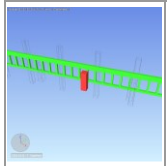
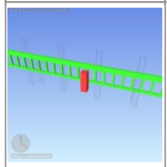
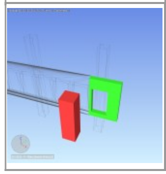
	Clash53	New	1.670	E-13 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:64.291, y:138.647, z:36.000	*ID elemento*: 213661	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash54	New	1.670	E-4 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:3.659, y:110.374, z:36.000	*ID elemento*: 213577	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash55	New	1.670	E-9 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:37.714, y:126.254, z:36.000	*ID elemento*: 213683	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash56	New	1.670	E-10 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:44.715, y:129.518, z:36.000	*ID elemento*: 213625	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash57	New	1.670	E-11 : 2 - Piano Secondo	Clearance	2021/11/29 15:40	x:51.240, y:132.561, z:36.000	*ID elemento*: 213637	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 760059	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648
	Clash58	New	1.670	E-13 : 2 - Piano Secondo Finito	Clearance	2021/11/29 15:40	x:65.108, y:139.028, z:39.190	*ID elemento*: 213661	2 - Piano Secondo	Pilastro in calcestruzzo - Rettangolare	Pilastri strutturali: Pilastro in calcestruzzo - Rettangolare: ARC_PILASTRO 90x90 cm	*ID elemento*: 759850	2 - Piano Secondo	Default - Calcestruzzo	Solido	Install 3rd level north wing E alignment pillars	2021/5/27 08:0-2147483648:-2147483648:-2147483648	2021/5/29 0:0-2147483648:-2147483648:-2147483648

Figure 99. Results of the clearance clash test executed for the working days May 27th and 28th using Navisworks. Clash no. 53-58.

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