Intelligent BIM-based spatial conflict simulators: A comparison with commercial 4D tools

L. Messi [a,b], B. García de Soto [b], A. Carbonari [a], and B. Naticchia [a]

[a] Polytechnic University of Marche (UNIVPM), Faculty of Engineering, DICEA Department, Ancona, Italy
[b] New York University Abu Dhabi (NYUAD), Division of Engineering, S.M.A.R.T. Construction Research Group, Abu Dhabi, United Arab Emirates

E-mail: l.messi@staff.univpm.it, garcia.de.soto@nyu.edu, alessandro.carbonari@staff.univpm.it, b.naticchia@staff.univpm.it

Abstract –

In construction projects, the space required for executing each activity is unanimously recognized as a limited but renewable resource, like workers, equipment, and materials. Overloading a given resource space, as demonstrated by statistics, leads to efficiency losses and safety threats. Despite the valuable contributions provided by academics and the construction software industry, a definitive tool for managing and resolving spatial issues is not available yet. In fact, current approaches, generally based on geometric intersection tests between main workspaces in their initial static position, do not account for not-purely-geometric spatial issues (e.g., struck-by hazards, electrical hazards, etc.) and overestimate conflicts affected by unlikely surrounding conditions.

In order to cover these gaps, a workspace management framework integrated into the preparation of the construction schedule is proposed and tested by developing a spatial conflict simulator (i.e., "Enhanced" approach). The simulator implemented using the serious gaming environment Unity3D™ was compared with Synchro Pro (i.e., "Benchmark" approach). Results show a better performance of the "Enhanced" approach, able to extend the range of detected spatial conflicts thanks to physics simulations, and filter unlikely spatial conflicts based on Bayesian inference's results.

Keywords –

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

1 Introduction

In construction projects, each activity requires a specific workspace to be executed [1]. 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 [2]. As the construction progresses, the space occupied by completed activities is released and reused by other operations [3]. Consequently, the space required by construction activities, i.e., the geometry and the location of workspaces, continuously change over time [4], leading to a sequence of workspaces associated with the project's activities [4]. As suggested by [5], the space in the construction site must be considered as a limited but renewable resource, similar to workers, equipment, and materials [3]. 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. To cite a few statistics, a study related to masonry works has reported that congested workspaces and restricted access cause efficiency losses of up to 65% [6]. In addition to the productivity impacts, a study conducted in the US found that poor workspace planning was the cause of 323 fatalities over a period of 12 years [7]. This trend can be explained by the fact that the dynamic nature of construction activities makes the management of workspaces challenging using conventional planning methods. In [8], the authors 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. As of now, workspace planning is being performed through judgment or at most by the aid of 2D sketches [2] because commercial 4D visual planning tools lack effective and holistic workspace management capabilities [4,9].

This study has developed an intelligent BIM-based spatial conflict simulator that integrates physics simulations and Bayesian inference in a serious gaming environment. The tool, aiming to enhance the range of detectable spatial conflicts and filter non-critical ones, has been tested and compared to one of the most popular 4D tools, namely Synchro Pro. The rest of this paper is structured as follows. In Section 2, the scientific background of construction workspace management and related gaps are discussed. Section 3 reports the methodology adopted for developing the proposed spatial conflict simulator. Section 4 describes the use case and the experiment design, whereas Section 5 discusses the results. Finally, Section 6 is devoted to conclusions.

2 Scientific Background

2.1 Research contributions to workspace management

Nowadays, the need to consider the spatial dimension to ensure schedule feasibility and avoid critical issues, such as safety, productivity, and constructability, is unanimously accepted by field experts. Stemming from this assumption, researchers have spent many efforts on the topic of workspace management.

The authors in [10] proposed a prototype system based on a micro-level discretization (i.e., building component space, labor crew space, equipment space, hazard space, protected space, and, finally, temporary structure space) to detect spatial interferences. The system, implemented using the object-oriented programming language Powermodel, displayed the list of categorized and prioritized time-space conflicts in a 4D CAD simulation environment, namely VRML 2.0 and Excel. Complementarily, the authors in [11], introduced the concepts of macro-level (e.g., storage areas) and paths (e.g., equipment's and crews' paths) discretization. They applied the critical space-time analysis (CSA) approach to model and quantify workspace congestion, developing a computerized tool called PECASO (Patterns Execution and Critical Analysis of site Space Organization) using VBA programming. A macro- and micro-level discretization has been presented in [1], where the labor crew workspaces were differentiated into static (i.e., the entire workspace is required throughout the activity duration) and dynamic (i.e., a specific portion of the workspace is occupied during each time interval). In the same study, the authors have developed a dynamic 4D BIM-based system aiming to detect time-space conflicts and quantify their impacts considering labor crew movements. The proposed system has been implemented using the C# programming language in the .NET framework in a Visual Studio environment. In [7], a micro-level discretization plus the space for material handling path were defined. In the same study, the authors proposed a novel method that collects, formalizes, and reuses historical activity-specific workspace information for congestion identification and safety analysis in BIM. In [3], the workspaces defined by the studies mentioned above have been grouped into two main categories: entity (i.e., laborers, mechanical equipment, and building components) and working spaces (i.e., spaces required to ensure smooth operation and tasks). This workspace discretization has been applied to develop a workspace conflict detection framework using the Navisworks SDK toolkit. The classification of the workspaces adopted in [4], inherited from the manufacturing industry, considers, in addition to the workspaces occupied by building elements and reserved as safety distance, a workspace discretization depending on the value added by the activities. A "main workspace" is required by activities that add tangible value to the project (e.g., building a wall), whereas a "support workspace" is required by preparatory activities (e.g., transferring materials) supporting the first category. The authors applied the described taxonomy to develop a construction workspace management tool implemented using the XNA game engine.

A gap found from the literature review is that most existing studies [1,7,10,11] consider object-based workspace taxonomies that allocate workspaces for each building element 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 authors of this study, adopting the workspace taxonomy proposed by [4], have preliminary addressed this issue by developing a spatial conflict simulator in Unity3D^{TM} to reduce threats of COVID-19 transmission related to spatial conflicts among main and support workspaces in construction projects [12]. Another limitation of existing studies [3,4,10,11] is detecting spatial conflicts by simply carrying out geometric intersection tests between defined workspaces. Although this approach has provided early valuable results and enabled process automation, it has also led to overestimating the results and missing incompatibilities that are not purely geometric (e.g., struck-by hazards, electrical hazards, etc.).

2.2 Commercial 4D software

Several 4D modeling software (e.g., Vico Schedule Planner and 4D Player, Innovaya Visual 4D Simulation, Autodesk Navisworks, Synchro Pro, Elecosoft Powerproject BIM, etc.) already provide different capabilities and toolkits [13]. The most popular ones, namely Autodesk Navisworks and Synchro Pro, have been exhaustively compared [13]. 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 to adjust the building design and avoid spatial issues, Synchro Pro is preferred for checking spatial interferences during the construction process and adjusting the construction schedule accordingly [14]. As reported in [15], Synchro Pro enables the user to create workspaces from bounding boxes [16] and check for related spatial conflicts. In addition, both software enable the creation of animation for simulating the construction site dynamics, with the not negligible limitation that they must be defined point by point by the user [17]. In other words, these software solutions do not enable to carry out automatic realistic physics simulations. This represents a significant limit, especially if we consider big construction projects where a significant number of agents moving for each time frame must be modeled one by one.

3 Methodology

3.1 Workspace management framework

In order to cover the gaps identified in Section 2, the authors have proposed a workspace management framework that integrates the construction scheduling phase (Figure 1, top lane) with the contribution given by a spatial conflict simulator (Figure 1, bottom lane). The latter, developed by adopting the serious game engine technology, can detect eventual spatial interferences based on both the geometric and semantic information provided by the Building Information Model (Figure 1, green nodes) and the construction process data included in the construction schedule (Figure 1, blue nodes). Based on this data, workspaces can be generated in the gaming environment to carry out geometric computations and physics simulations (Figure 1, red nodes). As a result, the list of detected spatial conflicts is generated and provided as an input to a Bayesian network (BN) (Figure 2) that, using expert knowledge, can be applied to find out (and filter) non-critical scenarios to avoid conflict overestimations (Figure 1, orange tasks). Afterward, the construction management team, made aware of likely future spatial conflicts, can adjust (Figure 1, blue nodes) or confirm (Figure 1, violet node) the construction schedule.

3.2 Intelligent BIM-based spatial conflict simulator

The spatial conflict simulator proposed by this study has been developed in Unity3D™, a serious gaming environment. As shown in Figure 1 (bottom lane), the BIM model and the construction (work) schedule are provided as input to define the 4D model. BIM models are imported into the gaming environment using the in-house IFC Loader for Unity3D™, developed based on the IFC Engine DLL library [18]. Construction schedules are imported into the serious gaming tool in CSV format using a C# script developed by the authors. Based on the 4D model information, the proposed spatial conflict simulator developed by the authors in another C# script generates main workspaces and detects “direct” and “indirect” spatial conflicts between them. A spatial conflict is detected between two given workspaces assigned to different crews only if their boundaries intersect. “Direct” spatial conflicts are detected by carrying out geometric intersection tests among workspaces in their initial static position, inherited from the corresponding building elements.

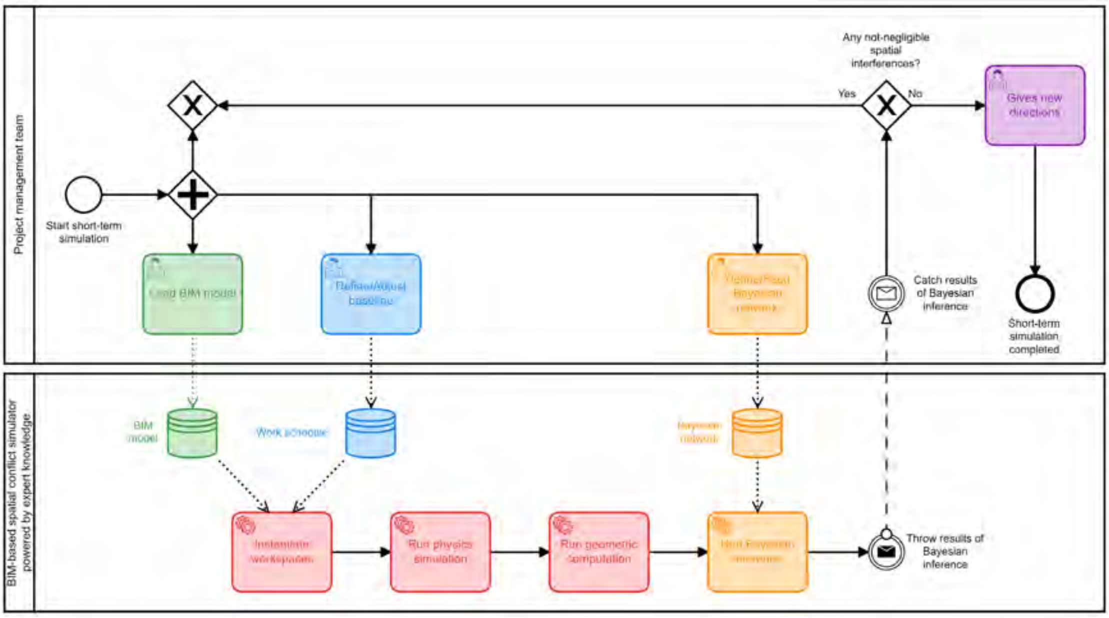

Figure 1. Proposed workspace management framework to consider spatial-temporal conflicts.

Although detecting these kinds of spatial conflicts is included in the state of the art of workspace management, it cannot cover the totality of spatial issues affecting the construction site. To make an example, a main workspace at a higher level (i.e., Cause-of-Risk-Activities or CORA workspace) than another one (i.e., Exposed-to-Risk-Activities or ETRA workspace), even if they do not intersect each other in their initial position, can be affected by spatial conflicts due to falling objects (i.e., struck-by hazards from CORA into ETRA workspaces). This kind of spatial conflict is named, here on for simplicity, as "indirect" or "possible" one. The serious gaming environment, embodying mechanical physics, enables the detection of this kind of spatial conflict, carrying out physics simulations and geometric computation (i.e., dropping down main workspaces according to the gravity law and looking for geometric intersections). The criticality level of "indirect" or "possible" spatial conflicts, being the result of a virtual simulation (e.g., dropping-down physics simulations), needs to be assessed. As indicated in Section 3.1, the criticality level is judged using Bayesian inference. The BN (Figure 2) was developed according to the factors categories (i.e., external, organizational, direct factors) presented in [19] and complemented by expert knowledge elicitation. In this study, the conditional probability tables (CPTs) have been filled according to the authors' knowledge. BNs can provide valuable support for assessing, based on surroundings conditions, the criticality level of each detected "possible" spatial conflict and filtering the ones that are not going to cause any spatial issue. The struck-by hazard BN has been implemented in Unity3D™ through a C# script based on the Discrete Bayesian Network library [20]. This enables the variables' evidence of the BN to be automatically fed by gaming simulation data.

4 Use Case and Experiment Design

The proposed approach provides a valuable contribution to the planning phase of construction works related to medium and large projects. Falling in this category, the construction process of the Eustachio Building, a public building hosting the Faculty of Medicine of the Polytechnic University of Marche, has been selected as an example for validation purposes. The Eustachio Building is located in the extra-urban area of Ancona (Italy), close to the main regional hospital. The mixed-use building is arranged on six floors above ground and has a total area of 16,900 m^2.

The application of the spatial conflict simulator presented in this study has been defined as the "Enhanced" approach. In order to be validated, it has been compared with the "Benchmark" approach, based on the application of the most popular 4D tool for workspace management, namely Synchro Pro. Three experiments have been set up considering, for simplicity and paper length constraints, only two working days (i.e., 27th and 28th May), highlighted in yellow in Figure 3(c). The four activities shown in Figure 3(c) are the ones that have been scheduled during this time interval. One experiment (i.e., Experiment No. 1, Table 1) out of three is related to the "Benchmark" approach and considers the "Standard" BIM model of the use case (Figure 3(a)). One of the remaining two experiments (i.e., Experiment No. 2,

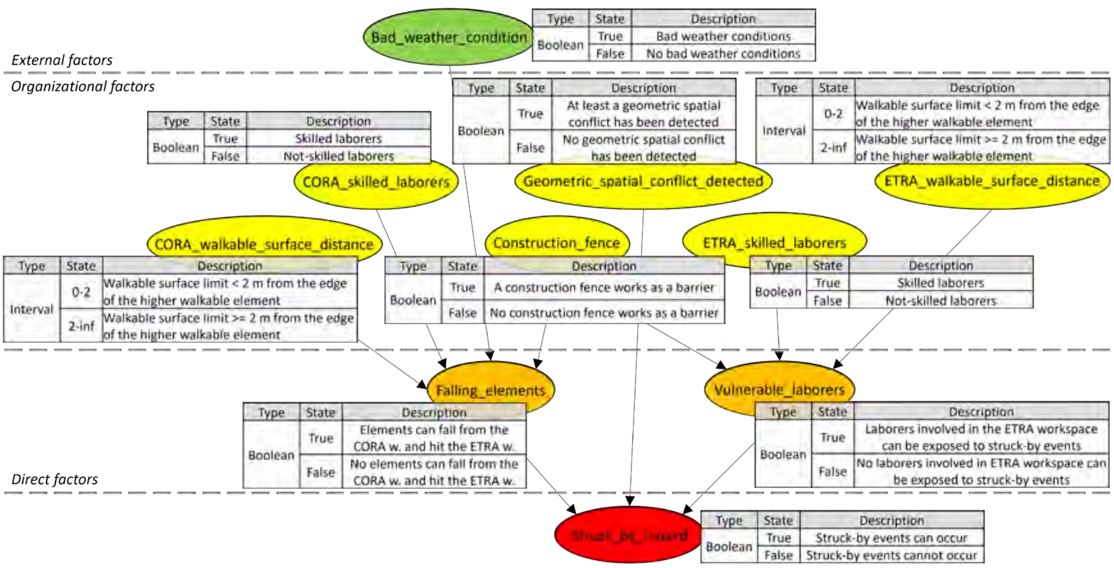

Figure 2. BN to assess the criticality level of "indirect" or "possible" spatial conflicts due to struck-by hazards.

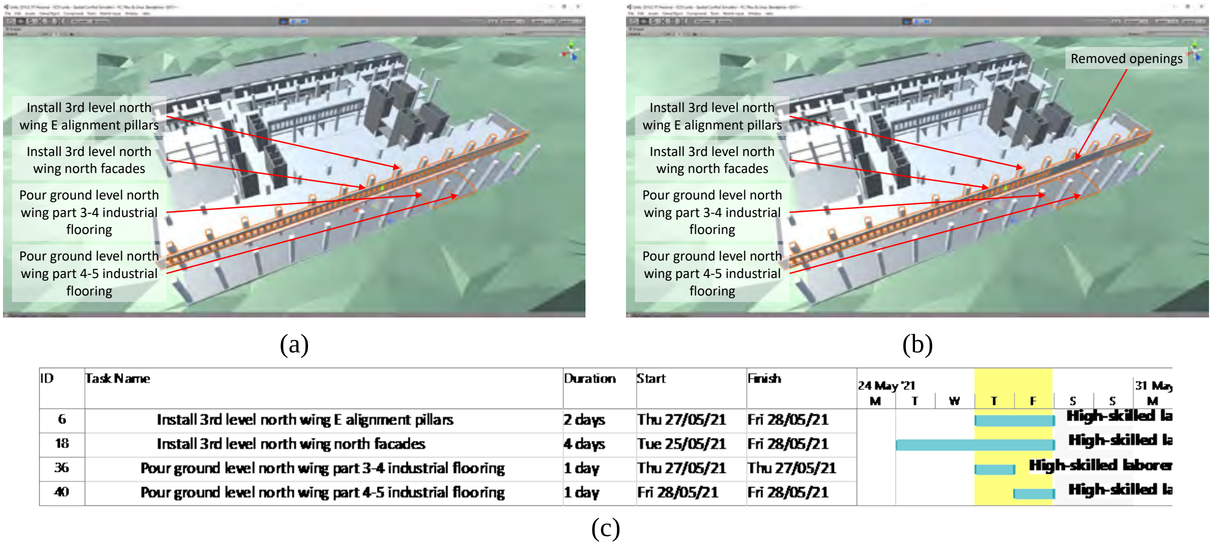

Figure 3. Views of the (a) "Standard" and (b) "Variation A" BIM models. (c) Excerpt of the overall construction schedule reporting the activities scheduled for the selected working days.

Table 1. Overview of the main differences between the three experiments.

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

Table 1), related to the "Enhanced" approach, considers the "Standard" BIM model, whereas the other one (i.e., Experiment No. 3, Table 1) considers the "Variation A" BIM model (Figure 3(b)).

The "Variation A" BIM model has been obtained from the "Standard" one by removing some of the openings on the 3rd level north façade. This was done to assess the contribution of the Bayesian inference by considering a different spatial conflict criticality level depending on the surrounding conditions. The different tool functionalities tested in the "Standard" and "Enhanced" approaches have been summarized in Table 1.

5 Results and Discussion

In the Experiment No. 1, the geometric intersection test carried out by Synchro Pro (e.g., "Benchmark" approach) has detected one spatial conflict between two workspaces at the same level (i.e., 3rd level) overlapping each other in their static position (Figure 4, Table 2). The proposed spatial conflict simulator (i.e., "Enhanced" approach) has been tested in Experiments No. 2 and 3. In both cases, one "direct" and four "indirect" or "possible" spatial conflicts have been detected (Figure 5, Table 2).

The "direct" spatial conflict detected between two workspaces overlapping in their initial static position is the same one reported in Experiment No. 1. The four "indirect" or "possible" spatial conflicts, detected between workspaces at different levels (i.e., ground level and 3rd level), resulted from the combination of the physics simulation and geometric intersection tests. In Experiment No. 2, that is when the "Standard" BIM model was considered in the Enhanced approach, the Bayesian inference has provided a "high" criticality level. In fact, as shown in Table 2, the "high" state of the "Struck_by_hazard" variable has, for each "indirect" or "possible" spatial conflict, the highest probability value

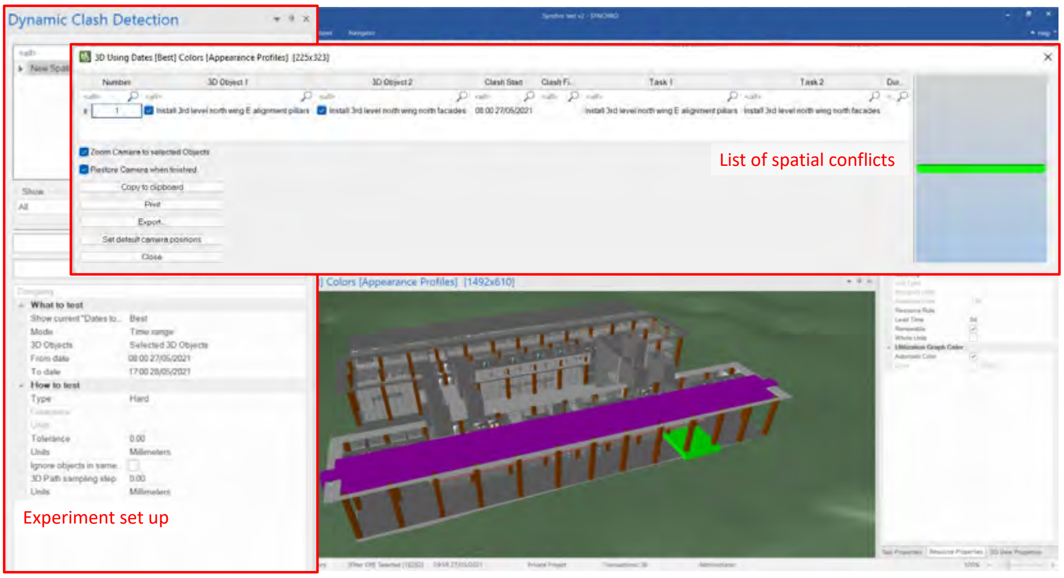

Figure 4. View of Synchro Pro after executing the "Benchmark" approach experiment.

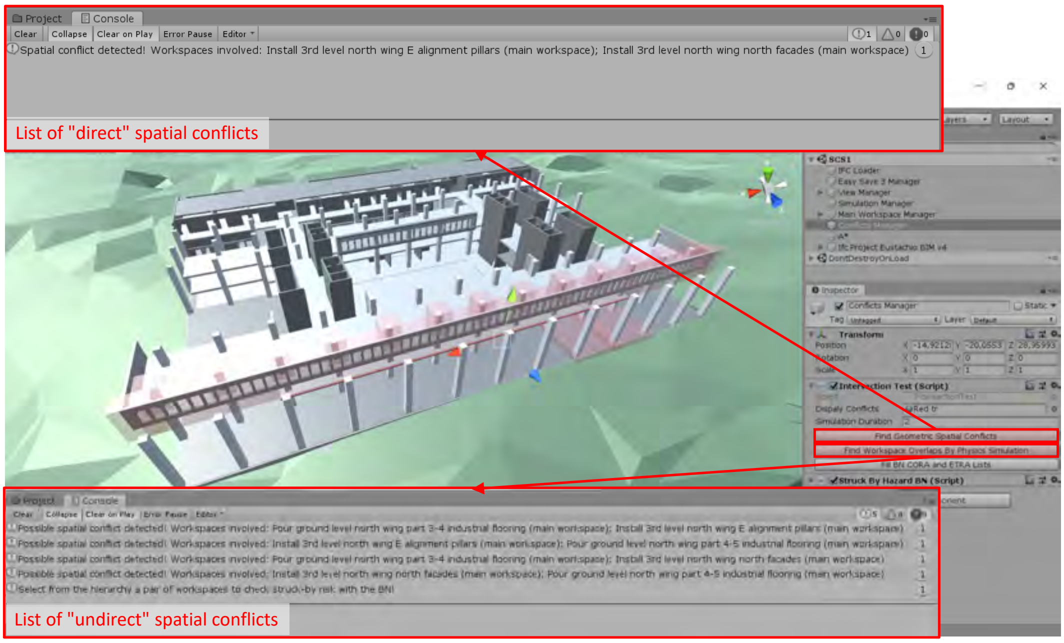

Figure 5. View of the gaming environment after executing the "Enhanced" approach experiments.

(e.g., 78%). The Bayesian inference provided a "low" criticality level when the "Variation A" BIM model was considered. In fact, as reported in Table 2, the "low" state of the "Struck_by_hazard" variable has, for each "possible" spatial conflict, the highest probability value (e.g., 57%). This is because in Experiment No. 3, the 3^{rd} level north façade, in correspondence to the part in which some openings have been removed, works as a barrier protecting workers in the ETRA workspace from eventual objects falling from the CORA workspace. This scenario is modeled by the "Construction_fence" variable of the BN (Figure 2) that, in Experiment No. 3, contrarily to Experiment No. 2, assumes the "True" state.

The three experiments demonstrate the proposed spatial conflict simulator's added value in detecting not-purely-geometric spatial issues and filtering the not critical ones to avoid overestimations.

6 Conclusions and outlook

In construction projects, spatial interferences lead to significant problems such as labor safety hazards, construction delays, and loss of productivity. Although researchers and 4D software developers have spent many valuable efforts in the field of workspace management, several issues have not been addressed yet. One of the main gaps in past studies is the assumption that spatial conflicts can happen only around specific building elements under construction; that is, between their static object-based workspaces. In addition, spatial conflicts have been detected simply by carrying out geometric intersection tests between workspaces. What has emerged from academic and industry sectors is the need to enhance the range of detected spatial conflicts and avoid overestimations.

The proposed tool combines physics simulations and geometric computations to replicate the construction site dynamics and detect resulting conflicts. Then, an integrated BN fed by expert knowledge and simulation results filters non-critical scenarios. The serious gaming tool has been validated by comparing the results with the ones provided by Synchro Pro for the same scenario. Promising results come from the proposed approach. In fact, combining physics simulations and Bayesian inference enhances the range of detected spatial conflicts (e.g., including the ones between workspaces at different levels affected by struck-by hazards) and filters out unlikely spatial conflicts.

Table 2. Results from the "Benchmark" and "Enhanced" approaches.

<table>
<tr><th>Experiment No.</th><th colspan="2">Pairs of conflicting workspaces detected by geometric intersection tests</th><th colspan="2">Pairs of conflicting workspaces detected by physics simulation and geometric intersection tests</th><th>Criticality levels by Bayesian inference</th></tr>
<tr><td>1
(Figure 3(a) and Figure 4)</td><td rowspan="9">Install 3^{rd} level north wing E alignment pillars</td><td rowspan="9">Install 3^{rd} level north wing north facades</td><td>(Functionality not available)</td><td>(Functionality not available)</td><td>(Functionality not available)</td></tr>
<tr><td rowspan="4">2
(Figure 3(a) and Figure 5)</td><td>Pour ground level north wing part 3-4 industrial flooring</td><td>Install 3^{rd} level north wing E alignment pillars</td><td>High (78%)</td></tr>
<tr><td>Pour ground level north wing part 4-5 industrial flooring</td><td>Install 3^{rd} level north wing E alignment pillars</td><td>High (78%)</td></tr>
<tr><td>Pour ground level north wing part 3-4 industrial flooring</td><td>Install 3^{rd} level north wing north facades</td><td>High (78%)</td></tr>
<tr><td>Pour ground level north wing part 4-5 industrial flooring</td><td>Install 3^{rd} level north wing north facades</td><td>High (78%)</td></tr>
<tr><td rowspan="4">3
(Figure 3(b) and Figure 5)</td><td>Pour ground level north wing part 3-4 industrial flooring</td><td>Install 3^{rd} level north wing E alignment pillars</td><td>Low (57%)</td></tr>
<tr><td>Pour ground level north wing part 4-5 industrial flooring</td><td>Install 3^{rd} level north wing E alignment pillars</td><td>Low (57%)</td></tr>
<tr><td>Pour ground level north wing part 3-4 industrial flooring</td><td>Install 3^{rd} level north wing north facades</td><td>Low (57%)</td></tr>
<tr><td>Pour ground level north wing part 4-5 industrial flooring</td><td>Install 3^{rd} level north wing north facades</td><td>Low (57%)</td></tr>
</table>

In the future, the proposed BN can be extended by adding variables for all the factors presented in [19]. Then, the tool can be applied to other scenarios in which physical simulations provide valuable contributions (e.g., tower cranes lifting heavy loads in windy conditions). Finally, the tool can be improved to address different scenarios. For example, modeling detailed materials properties and implementing electromagnetism rules in the gaming environment would enable addressing electrical hazards.

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