# Development of a BIM-based spatial conflict simulator for detecting dust hazards

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**Abstract –**

**In construction management, a spatial conflict between two activities is generally identified as the intersection between related workspaces. Such assumption works well for detecting the majority of conflicts. Nevertheless, in certain dynamic scenarios, a spatial interference between two activities may occur even if the related workspaces do not intersect each other. This study, being construction sites one of the major responsible for creating particulate matter (PM), focuses on spatial interferences related to dust hazard, still representing an open issue. In fact, although the correlation between PM concentration and health diseases dates back several decades, no study has addressed yet spatial interferences caused by PM-creating activities under the effect of meteorological and seasonal factors.**

**In order to cover these gaps, this study proposes a BIM-based spatial conflict simulator that, framed within a workspace management framework, spatially checks future construction work plans according to atmospheric phenomena based on weather forecast data. The resulting prototype, developed within Unity3D™ and tested through sensitivity analysis, has been applied on a real construction site scenario. Experiments results has confirmed the possibility to virtually simulate construction activities and atmospheric phenomena in order to support project managers in adopting countermeasures against dust hazards.**

**Keywords –**

**Workspace Management; Spatial Conflict; Dust Hazard; Particulate Matter; BIM; Game Engine.**

## 1 Introduction

In construction projects, each activity requires a specific workspace to be executed, defined as the suitable occupational volume occupied by the involved crew and/or equipment [1], [2]. The space in construction sites must be considered as a limited but renewable resource, similar to workers, equipment, and materials [3]. Identifying a spatial conflict as two activities sharing the same workspace generally works well for detecting the majority of conflicts affecting construction works. Nevertheless, in certain dynamic scenarios (e.g., dust hazard dust hazard in windy conditions), a spatial interference may occur even if activities' related workspaces do not intersect each other. An example is represented by PM-creating activities (e.g., sawing and smoothing operations of wooden formworks for concrete placing) that in windy conditions may interfere with other ones, hence resulting incompatible, even if related workspaces do not interfere.

This study, being construction sites one of the major responsible for creating PM [4], [5], focuses on spatial interferences related to dust hazard. The relevance of this topic is confirmed by sector studies showing that atmospheric particle pollution may have adverse effects on human health. In fact, PM is believed to contribute to cardiovascular and cerebrovascular diseases and researches show that long term exposure is responsible for significantly high cardiovascular incident and mortality rate [4]. In order to dampen this trend, a workspace management framework, aimed to reduce dust hazards by integrating spatial analysis with the construction work planning phase, has been proposed by this study. A BIM-based spatial conflict simulator that spatially checks future working days, according to the work plan and atmospheric phenomena based on weather forecast data, has been developed in Unity3D™.

The rest of this paper is structured as follows. In Section 2, the scientific background is presented. Section 3 reports the methodology adopted for the prototype development, described in Section 4. In Section 5, experiments design on a real use case is presented, whereas obtained results are discussed in Section 6. Finally, Section 7 is devoted to conclusions.

## 2 Scientific Background

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. A 4D CAD system prototype, 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), has been developed in [6] to detect spatial interferences. Complementarily, the authors in [7] have introduced the concepts of macro-level (e.g., storage areas) and paths (e.g., equipment's and crews' paths) discretization. Macro- and micro-level discretizations have been extended in [2] by differentiating labor crew workspaces into static and dynamic ones, depending respectively on the their full or partial usage across time. In [8], a micro-level discretization plus the space for material handling path have been defined and adopted for collecting and reusing historical activity-specific workspace information for congestion identification and safety analysis in BIM. In [3], workspaces defined by aforementioned studies 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). The workspaces classification adopted in [9], inherited from the manufacturing industry, includes, in addition to workspaces occupied by building elements and reserved as safety distance, a discretization depending on the value added by 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 have applied the described taxonomy to develop a construction workspace management tool using the XNA game engine. The same workspace taxonomy has been adopted in [10]–[12] to develop, using the serious game engine Unity3D™, spatial conflict simulators able[12] to detect interferences due to moving crews[10,11] and falling objects. Numerous commercial 4D modeling software solutions are available in the market. A comparison between the two most popular ones, namely Autodesk Navisworks and Synchro Pro, has pointed out that, although both of them implements clash detection functionalities, the second one is more indicated for checking spatial interferences during the construction process [13], [14]. In addition, in order to carry out dynamic simulations, both the tools, not embedding any physics engine, require to define objects animations manually one by one.

The literature review has pointed out that existing studies, although assuming different workspace taxonomies and technological solutions, detect spatial conflicts based on – mostly static [2], [3], [6]–[9] – geometrical intersection tests among workspaces. Although this approach, stemming from detecting space resorce overloads, has provided significative contributions in automating the workspace management domain, spatial interferences strictly dependent from construction site dynamics still remain largely uncovered. An example is represented by dust-producing activities (e.g., sawing and smoothing operations of wooden formworks for concrete pouring) that in windy conditions may interfere with other ones, hence resulting incompatible, even if related workspaces do not intersect each other. Despite correlations between PM concentration and health diaseses dates back several decades [5], to the best of the authors knowledge, no past study has addressed so far spatial interferences caused by PM-creating activities. In addition, no tool supporting projects managers in managing workspaces and dust hazards during the works planning phase exists yet. Technical difficulties in implementing a similar tool are related to the need to consider also meteorological and seasonal factors affecting PM concentration in construction sites [15].

In order to cover these gaps, this study proposes a workspace management framework aimed to reduce dust hazards by integrating spatial analysis with the construction work planning phase. A BIM-based spatial conflict simulator that spatially checks future working days, according to the work plan and atmospheric phenomena based on weather forecast data, has been developed. The resulting prototype has been developed in Unity3D™ and tested on a real construction site scenario.

# 3 Methodology

## 3.1 Air quality requirements for construction activities

PM is a group of polluting agents consisting of dust, smoke, and all types of solid and liquid materials that remain suspended in the air because of their small size [16]. In general, particulate matter is identified by the wording PM plus its size in µm. For example, PM100 indicates PM particels having a diameter of 100 µm. Past studies have shown as pollutants concentration tend to exceed regulations limits in construction sites. Same studies have confirmed that PM generated by construction activities has a certain degree of impact on the air throughout the city due to meteorological (e.g., wind, rainfall, etc.) and seasonal factors [15].

In this study, wood processing (e.g., sawing and smoothing operations) to produce formworks for concrete placing has been assumed as the reference activity generating PM. Even if wood is not a carcinogenic material, its dust can be, as potential harmful effects on health are determined by the penetration and deposition of particles in the first respiratory tract [17]. This is confirmed by the European Directive 2017/2398 [18] that sets the occupational exposure limit (OEL), measured over an 8-

hour period as the inhalable fraction, equal to 2 mg/m$^3$. The inhalable fraction is defined by the UNI-EN 481/1994 standard [19] as the mass fraction of total airborne particles that can be inhaled by nose and mouth (i.e., particles having a 50 % size cut-off equal to an aerodynamic diameter of 100 μm corresponding to diameters between 10 μm and 100 μm).

### 3.2 Workspace management framework for managing dust hazards

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 (e.g., Unity3D™), can detect eventual incompatibilities between activities based on both the geometric and semantic information provided by BIM (Figure 1, green nodes) and the construction process data included in the construction schedule (Figure 1, blue nodes). To this purpose, workspaces must be generated in the gaming environment. In the state of the art of workspace management, a spatial conflict is detected between two given workspaces assigned to different crews only if their boundaries intersect each other. This study tries to go over by carrying out physics simulation of spreading dust under the effect of atmospheric phenomena based on weather forecast data. The latter must be retrieved for the desired temporal horizon and provided, along with workspaces, as an input to physics simulations and geometric computations (Figure 1, red nodes). As a result, the list of detected spatial conflicts is generated and delivered to the reasoner that, once set according to regulations in force, can be applied to filter non-critical scenarios and avoid conflict overestimations (Figure 1, orange tasks). Afterwards, the construction management team, made aware of likely future incompatible activities, can adjust (Figure 1, blue nodes) or confirm (Figure 1, violet node) the workplan.

## 4 Prototype development

In this study, a prototype of spatial conflict simulator that, based on weather forecast data, carries out physics simulations in order to detect incompatible activities has been developed. The reasoner, instead, aiming to automatically discard negligible spatial conflicts related to under-threshold PM concentrations will be implemented in future studies according to PM limits [19] and fractions distributions [20] defined by regulations [18], [19].

### 4.1 Defining 4D model and workspaces

The spatial conflict simulator proposed by this study has been developed within the serious game engine Unity3D™. 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 can be imported into the gaming environment through several methods, involving different file formats (e.g., .ifc, .gltf, .fbx, etc.). In this study, the one involving

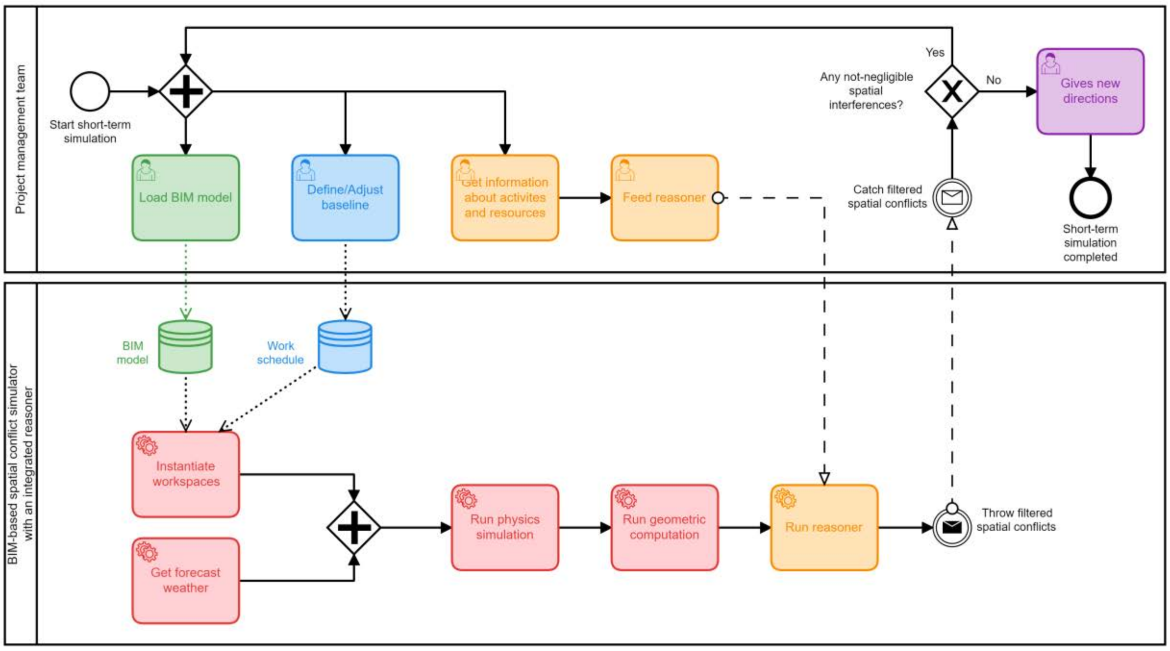


Figure 1. Proposed workspace management framework for managing dust hazards.

the .fbx (i.e., FilmBox) format has been adopted due to the smoother importing workflow, which only requires re-associating material through a computer graphics software (e.g., 3D Studio Max). In fact, contrarily to the other file formats requiring dedicated importers (e.g., "IFC importer" [20] or "Piglet: glTF Importer" [21]), an .fbx file can be directly added to the Unity3D™ scene as a prefab. Construction schedules are then imported into the serious gaming tool in .csv format using a C# script developed by the authors. Based on the 4D model information, another C# script developed by the authors generates main workspaces in the virtual gaming environment as "Cube" game objects, each one with an attached "Box collider" component enabling collision detection. The process of generating a main workspace has been fully described by the authors in [10], [12].

### 4.2 Retrieving forecast weather data

In order to identify any interference caused by dust-producing activities, PM spreading must be virtually simulated according to atmospheric phenomena replicated according to weather forecast data. The latter must be retrieved for the days the simulation is planned for. To this purpose, the Unity3D™ tool Real-Time Weather has been adopted. Such tool enables to retrieve weather forecast data up to several days into the future via "Tomorrow.io mode" or "OpenWeatherMap mode". The only required inputs are the geographical coordinates of the construction site and an Api Key, available on tomorrow.io [22] and OpenWeatermap.org [23] web portals, respectively.

At this point, weather forecast data (e.g., wind speed and direction), required for dynamically simulate atmospheric phenomena, have been accessed. Such data can be displayed on a 24-hours or 7-days base by clicking on the dedicated information panel of the Real-Time Weather tool. The wind speed is expressed in m/s, whereas its direction in counter-clockwise radiants from due north.

### 4.3 Running physics simulations and geometric computations

The serious game engine Unity3D™, embodying mechanical physics, enables to (i) virtually mirror likely weather conditions affecting the considered construction site and (ii) virtually simulate dust-producing activities during a specific time interval of the work plan.

About virtually mirroring likely weather conditions, this study focuses on replicating windy conditions (e.g., speed and direction) affecting PM spreading around the construction site. To this purpose, a virtual agent replicating the action of the wind spreading PM according to retrieved weather forecast data (Section 4.2) amongst construction site workspaces (Section 4.1) must be defined. To make this possible, a "Wind Zone" game object [24], defining a virtual wind agent with its speed (i.e., "Main" field, expressed in unit of space per unit of time, assumed as m/s) and direction (i.e., "Rotation" Vector3 fields, expressed in degrees) within Unity3D™, has been used. In order to apply weather forecast data to simulate wind dynamics, the following two C# scripts have been defined by the authors:

- "ProcessWindData.cs": for each simulation frame, it continuously processes wind speed and direction, provided by the Real-Time Weather tool, to make them readable by the "Wind Zone" game object. In particular, it converts the wind direction from gradiants to degrees.
- "GetWindData.cs": for each simulation frame, it continuously gets wind data, processed by the previous C# script, and update speed (i.e., "Main" field) and direction (i.e., "Rotation" fields) of the "Wind Zone" game object.

About virtually simulating PM-creating activities, this study focuses on wood processing (e.g., sawing and smoothing operations) to produce formworks for concrete placing. To determine the amount of dust emitted by each piece of equipment, a report carried out by Veneto region [25], providing samplings for the production of wooden furniture and fixtures, has been assumed as a reference. Specifically, such report collects dust concentrations emitted by various pieces of equipment, measured during 2.5-hours samplings and expressed in mg/m$^3$. In order to virtually simulate activities producing dust particles in Unity3D™, the "Particle System" effect [26] has been used. Such component requires the user to set the number of particles emitted per seconds. In order to determine such value, the following assumptions have been made:

- The particles volume has been computed by assuming diameters included between 10 μm and 100 μm, since wood particles within this range (i.e., inhalable fraction), if inhaled, produce carcinogenic effects [17]. In the absence of more detailed information, a uniform size distribution of 10 % for each 10-μm-interval between 10 μm and 100 μm has been assumed. The resulting 10 intervals exhaustively describe how the wind differently affects dust particles according to their size;
- The weight of a particle for each 10-μm-interval fraction has been computed by multiplying its volume by fir wood's specific gravity;
- The number of emitted particles for each 10-μm-interval fraction has been computed by dividing the total weight of dust aspirated during samplings, provided by [25], by the weight of each particle size.

Furthermore, the "Particle System" effect has been defined by setting a spheric shape and the related volume.

In addition, such effect has been set by checking the "External Forces" and "Collision" features. The first one enables the movement of dust particles according to the wind speed and direction. The second one enables physical collisions against whole world's game objects. This setting is required to quantify the amount of dust within a workspace, determined by monitoring the number of particles that impact against workspaces through the "OnParticleCollision" function [27]. By calling such function through a C# script assigned to each workspace game object, the number of collided particles is returned. The total weight of collided particles is computed as the sum of contributions obtained by multiplying the number of collided particles, uniformly distributed for each interval between 10 μm and 100 μm, by the weight of the corresponding particle size. Finally, the amount of dust within a workspace is computed as dust concentration by dividing the total weight of collided particles, computed assuming the same aforementioned size distribution of 10 % for each 10 μm-interval between 10 μm and 100 μm, by the workspace volume.

### 4.4 Sensitivity Analysis

The reason why a sensitivity analysis has been carried out is checking the realistic responsiveness of the developed spatial conflict simulator prototype. In fact, reasonable variations of dust in the considered workspaces should correspond to variations of dust in the amount of emitted particles and wind directions. To prove this, six different scenarios, reported by Table 1, have been defined by varying the number of emitting equipment (i.e., multiples of circular saws and orbital sanders), that produce a different amount of particles, and the wind direction (i.e., directions 1, 2, and 3). Figure 2 depicts the positions of emitters and workspaces and the assumed wind directions.

Results of sensitivity analysis, reported by Table 2, confirm what was expected. In fact, in scenario 2, which assumes the double the particles emitted in scenario 1 and wind blowing towards direction 1 like in scenario 1 (i.e., orthogonal to workspaces) (Table 1), the double the dust concentration of scenario 1 has been registered within workspaces (Table 2). In scenarios 3 and 4, as the wind direction change into direction 2 (i.e., oblique to workspaces) (Table 1), dust concentration radically decreases within workspaces (Table 2). Even further, in scenarios 5 and 6, as the wind direction change into direction 3 (i.e., parallel to workspaces) (Table 1), dust concentration becomes zero within workspaces (Table 2). It must be noted that, for all scenarios, dust concentrations registered for workspace 3 are lower than the ones registered for the other workspaces. This is due to the fact that workspace 3 is located at a lower level than dust emitters and, hence, only marginally involved in particles uptake. Finally, results of sensitivity analysis are comparable to the limit of 2 mg/m$^3$ imposed by [18]. In scenarios 1 and 2, dust concentrations registered respectively for workspace 1 and workspaces 1 and 2 exceed such limit.

Table 1. Overview of sensitivity analysis's scenarios.

| Scenario | No. of dust emitters | | Wind direction |
|---|---|---|---|
| | Circular saws | Orbital sander | |
| 1 | 2 | 1 | 1 |
| 2 | 4 | 2 | 1 |
| 3 | 2 | 1 | 2 |
| 4 | 4 | 2 | 2 |
| 5 | 2 | 1 | 3 |
| 6 | 4 | 2 | 3 |

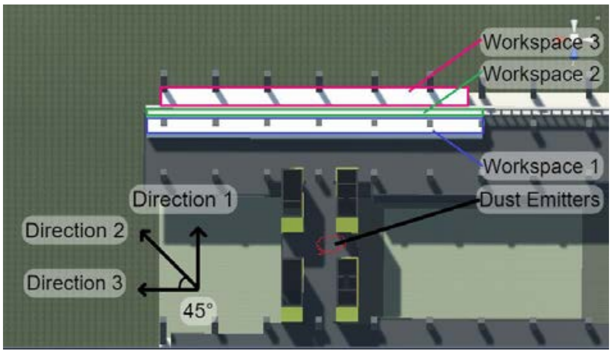


Figure 2. Sensitivity analysis's set up indicating positions of emitters and workspaces and wind directions.

Table 2. Results of sensitivity analysis.

| Workspaces | Volume [m$^3$] | Dust concentration [mg/m$^3$] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
| Workspace 1 | 350,63 | 1,160 | **2,320** | 0,190 | 0,380 | 0,000 | 0,000 |
| Workspace 2 | 175,31 | **2,080** | **4,170** | 0,220 | 0,430 | 0,000 | 0,000 |
| Workspace 3 | 645,00 | 0,003 | 0,006 | 0,004 | 0,009 | 0,000 | 0,000 |

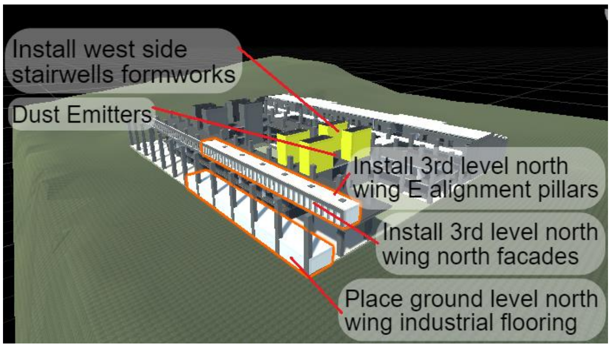


Figure 3. Construction site use case with workspaces and dust emitters.

## 5 Use Case and Experiments Design

The proposed spatial conflict simulator, once its functioning has been confirmed by sensitivity analysis, has been tested on a real construction site scenario. To this purpose, 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 (Figure 3). 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 $m^2$. For simplicity and paper length constraints, only two working days (i.e., January 30th and 31st, 2023) of the construction work schedule, highlighted by a red box in Figure 4, have been taken into account for experiments design.

The experiments, carried out in this study, consist in applying the developed spatial conflict simulator, according to the workspace management framework presented in Section 3.2, for detecting eventual spatial interferences due to dust hazard in the two considered working days. The experiments start with loading the BIM model and the work schedule within the gaming environment in order to generate workspaces (Section 4.1). Afterwards, weather forecast data will be retrieved as described in Section 4.2 and, finally, physics simulations of selected working days with related wind conditions will be carried out. Each working day has been assumed including 8 working hours, from 8 am to 4 pm.

The four activities, scheduled for these days, are shown in Figure 4. They include the installation of precast façade (3rd level, north-west wing), the installation of precast pillars (3rd level, north-west wing), the placing of the industrial flooring (ground floor, north-west wing), and the installation of stairwells formworks (3rd level, west block). The latter activity, responsible for creating and spreading PM into the environment, involves sawing and smoothing operations of the wooden formwork. They take place in the area among the four stairwells, highlighted in yellow in Figure 3. The cutting operation has been assumed to be done by using two circular table saws, while the smoothing operation by using an orbital sander. A reasonable construction site layout has been assumed in this study. Although temporary construction structures (e.g., scaffoldings) may affect dust spreading, they have not been considered in this first implementation. This is justified by the fact that this paper, presenting a proof of concept of the proposed spatial conflict simulator, focuses on the prototype development and testing.

## 6 Results and Discussion

Experiment results, obtained by carrying out spatial conflict simulations for the working days January 30th and 31st, 2023, have been reported in Table 3. Experiments results for the selected working days (i.e., January 30th and 31st, 2023).. Dust concentrations in the three workspaces are very low for both days and do not exceed the threshold of 2 $mg/m^3$ imposed by [18]. These results can be explained by considering that on January 30th, the weather forecast data indicates low wind speeds (i.e., between 3,33 m/s to 3,38 m/s) and a North-East direction, that is oblique to workspaces. Hence, workspaces have been only partially affected by dust spreading. On January 31st, the weather forecast data indicates low wind speeds (i.e., between 3,45 m/s to 4,19 m/s) and a East direction, that is parallel to workspaces. Hence, workspaces have not been affected by dust spreading. In these cases, since dust concentration complies with the aforementioned regulation limit, the reasoner would return no incompatibilities among scheduled activities, meaning that the work plan can be confirmed by the project manager and delivered as it is to the construction site. Contrarily,

| Task name | Duration | Start | Finish |
|---|---|---|---|
| Install west side stairwells formworks | 2 days | Mon 30/01/23 | Tue 31/01/23 |
| Install 3rd level north wing E alignment pillars | 2 days | Mon 30/01/23 | Tue 31/01/23 |
| Install 3rd level north wing north facades | 4 days | Mon 30/01/23 | Thu 02/02/23 |
| Place ground level north wing part ovest industrial flooring | 2 days | Mon 30/01/23 | Tue 31/01/23 |

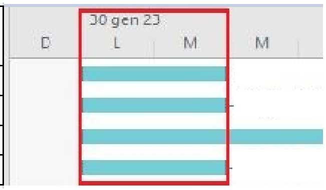


Figure 4. Excerpt of the overall construction schedule reporting the activities scheduled for the selected working days (i.e., January 30th and 31st, 2023).

Table 3. Experiments results for the selected working days (i.e., January 30th and 31st, 2023).

| Workspaces | Vol-ume [$m^3$] | Dust concentration [$mg/m^3$] 30th Jan | Dust concentration [$mg/m^3$] 31th Jan |
|---|---|---|---|
| Install 3rd level north wing E alignment pillars | 350,63 | 0,024 | 0,000 |
| Install 3rd level north wing north facades | 175,31 | 0,020 | 0,000 |
| Placing ground level north wing west part industrial flooring | 645,00 | 0,000 | 0,000 |

in case registered dust concentrations exceed the regulation limit [18], the application of mitigation actions to the workplan should be evaluated by the project manager. An example of mitigation action could be giving directions to wear PPE (e.g., face masks) to who is working in workspaces close to the emitters and affected by above-threshold dust concentrations. Another example of mitigation action could be moving backward or forward the PM-emitter and/or the PM-receiving activities.

# 7 Conclusions and outlook

This study, being construction sites one of the major responsible for emitting PM whose long exposure may cause health diseases, has focused on spatial interferences related to dust hazard, still representing an open issue. In fact, to the best of the authors knowledge, no study has addressed yet spatial interferences caused by dust-producing activities under the effect of meteorological and seasonal factors. In addition, no tool supporting projects managers in managing workspaces and dust hazards during the works planning phase exists yet. In order to cover these gaps, this study proposes a workspace management framework aimed to reduce dust hazards by integrating spatial analysis with the planning phase. A BIM-based spatial conflict simulator that spatially checks future construction work plans according to atmospheric phenomena based on weather forecast data has been developed. The resulting prototype has been implemented in Unity3D™ and its functioning confirmed through sensitivity analysis before to be applied on a real construction site scenario. Experiments results confirmed the possibility to virtually simulate construction activities and atmospheric phenomena in order to support project managers in adopting countermeasures against interferences due to dust hazards.

Limitations of this study can be summarized as follows. First, in this study, the reasoner has not been implemented yet. Hence, the compliance of dust concentrations, registered during spatial conflict simulations carried out by the developed prototype, to the regulation limit has been assessed manually. In addition, dust spreading has been simulated within the gaming environment under the effect of only wind speed and direction. In future implementation, more atmospheric phenomena (e.g., rainfall), seasonal factors, and particles size distributions will be considered. Sensitivity analysis, virtually carried out within the gaming environment, will be extended with real world experiments in order to assess the consistency of simulation results to reality. Finally, future studies will investigate on the possibility to integrate (e.g., through a Functional Mock-up Unit) the proposed spatial conflict simulator with an external co-simulator, supporting advanced fluid dynamics simulations of dust spreading.

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