Addressing COVID-19 Spatial Restrictions on Construction Sites Using a BIM-Based Gaming Environment

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Abstract –

Spatial conflicts affect crews' productivity and workers' safety. The idea of considering workspaces as a limited resource has brought a remarkable contribution to the effectiveness of traditional scheduling techniques that generally do not consider the spatial-temporal dimension of construction activities. In previous studies, the detection of spatial interferences among main workspaces has proven to be an effective way to track down spatial issues inherent to the works schedule.

In light of recent events, this research considers spatial interferences among workspaces as occasions of COVID-19 transmission, which must be avoided. The number of spatial issues detected in previous studies must be extended by also including spatial conflicts affecting crews moving to and from main workspaces in transfer spaces (i.e., the support workspaces). A BIM-based spatial conflict simulator, integrated within the work planning process and developed using a serious game engine, is presented in this study and tested on a real work scenario. The possibility of simulating working operations in gaming environments enables investigating on how behavioral constraints, such as social distancing, can be considered during work planning. The first research outcome is that the developed prototype can read the work plan and the BIM model to provide spatial interferences due not only to the main but also to the support workspaces. The second research outcome, emerged from our preliminary simulations, is that even in a short time span (e.g., 2 days and 3 activities), interferences involving support workspaces account for 33% of the complete list of detected conflicts.

Keywords –

Construction Management; Workspace Scheduling; Spatial Conflicts; BIM; Game Engine; COVID-19.

1 Introduction

During construction projects, spatial interferences are commonly recognized as one of the main issues that can severely affect the productivity and safety of crews who share the same workspace [1]. Hence, the need to enhance traditional scheduling techniques (e.g., PERT and CPM), generally based on activities' durations and precedence relationships, by considering the space usage for each task has emerged. Since the early 1990s, a new range of planning techniques based on the management of construction site spaces has been developed [2]. Considering space as a resource, similarly to workers, equipment, and materials, the construction site layout can offer limited but renewable workspaces. Once an activity is completed, the occupied space will be released and reused by other operations [3]. On this basis, existing studies have demonstrated that detecting spatial interferences between main workspaces (i.e., associated with value-added activities) can be an effective way to tracking down spatial issues, otherwise not identifiable from the works schedule [4].

This paper contextualizes the results from existing researches in light of the coronavirus outbreak, being spatial issues a possible cause of COVID-19 transmission in constructions sites. From this perspective, spatial interferences between different crews, even occurring for a limited time within support workspaces (e.g., transfer space of workers, equipment, materials, material storage space, equipment space, temporary structure space, etc.), can be seriously dangerous. An example is a spatial issue generated by a crew that moves between two main workspaces within a transfer space and passes through the space assigned to another crew. In order to detect the biggest set of such risky scenarios, behavioral constraints (e.g., social distancing measures) must be considered regarding main workspaces and support workspaces. To this purpose, a BIM-based spatial conflict simulator has been developed using a serious game engine to validate the assumed construction work plan.

The remainder of this paper is organized as follows. In Section 2, the state-of-the-art regarding the management of the space resource in the construction field and research gaps are identified. Section 3 reports the adopted methodology to address spatial issues and COVID-19 restrictions through serious game engines. Section **Error! Reference source not found.** 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 Workspaces Definition from Literature

The idea of space as a type of resource was first introduced in project management by [11]. Workspaces are defined as renewable resources that can be occupied for activities execution; on completion, spaces currently occupied will be released and reused by other operations [3]. The authors of existing studies have defined different workspaces taxonomies. The most recurrent workspaces categories in the literature include the spaces occupied by workers [1][3][12][13][14], building elements under construction [1][3][4][12][14][15], equipment [1][12][14][13][15], temporary works [4][12][14][15], and stored materials [1][4][12][13]. Some authors define specific workspaces to protect building elements from damaging [1][15] or workers from injuries [3][4][12][14][15]. Finally, the spaces reserved for transferring equipment and material [1][4][14] and for the crews' movement between workspaces [1][4] are also defined in literature. The taxonomy proposed in [4], which has an analogy with the classification of value-added and non-value-added activities adopted in the manufacturing sector [16], is one of the most complete. According to this, the workspace occupied by a crew that directly adds tangible value to the construction process (e.g., building a wall) is classified as a "main workspace". In other words, "main workspaces" activities physically produce building elements that occupy "object workspaces". The latter are free until the corresponding building elements have not been built yet. It must be noted that value-added activities cannot be finalized without activities that, although they do not directly add any tangible value, support the construction process (e.g., transfer materials, equipment or workers, storage materials, install temporary works, etc.). These activities occupy the so-called "support workspaces".

2.2 Spatial-Temporal Conflicts Taxonomies

Many studies have recently tried to classify spatial interferences between tasks that share the same workspace. In [15], the authors have formalized one of the first time-space conflict taxonomy in construction, differentiating design conflicts, safety hazards, damage conflicts, and congestions. The first category occurs when the geometry of a building component conflicts with another building component. Since existing commercially available applications (e.g., clash detection and coordination) already solve this issue [14], design clashes are outside the scope of this research. According to [15], the second category, namely safety hazards, occurs when the space required by a hazardous activity conflicts with the space allocated to a labor crew. The third category, i.e., damage conflicts, may occur when a space that should be left available to protect a building component from getting damaged is shared with a labor crew, equipment, or a hazardous space [15]. For example, a damage conflict can occur if workers (i.e., labor crew space) walk through an area where recent concrete work was done and still has a fresh concrete slab (i.e., protected space), leaving their footprints and/or damaging that work. Similarly, a damage conflict is identified if debris falls on a surface (i.e., hazardous space) with fresh concrete (i.e., protected space). The fourth category, namely the congestion, occurs when the mutual sharing of space between labor crews, equipment, and temporary structures implies that the workspace available for a given activity is either limited or smaller than the required one [4][15]. The bigger the shared space, the higher will be the congestion level. In [12], the authors consider two types of spatial interferences, namely labor congestion and constructability issue, corresponding respectively to acceptable (ASI) and unacceptable spatial interferences (USI), introduced in [17]. Finally, in [3], a time-space conflict taxonomy, including the three available combinations between the entity spaces (ES) and working spaces (WS), is presented. The overlapping of two different entity spaces (ES-ES), similarly to the design conflict seen in [15], may cause a breakage in the building elements. When an entity crashes into a working space (ES-WS), delays and, in some cases, accidents may 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 [4][15]. The taxonomy presented in [15] has been extended, in [1], with the theoretical definition of path-related conflicts (e.g., access blockage and space obstruction).

2.3 Research Gaps and Contribution of the Paper

What emerges from the literature review reported above is that many efforts have been spent in formalizing object-related workspaces and spatial conflicts, which are defined concerning the corresponding building elements under construction. An example is provided by [4], where the authors developed a 4D tool for instantiating main workspaces and detecting related spatial conflicts. Crews moving between consecutive main workspaces, since they may interfere with each other, may result in COVID-19 transmission. Spatial conflicts must be avoided in any case to limit safety threats and constructability issues. In a sanitary emergence, where even short spatial issues occurring between different crews represent a possible threat of transmission, detecting and managing them in advance appear even more relevant. For this reason, an important step forward can be done by also considering transfer spaces (i.e., included within the wider category of support workspaces) in the search for spatial conflicts. This insight is confirmed by social distancing measures adopted by all countries after the coronavirus outbreak.

To the authors' knowledge, any tool that supports construction managers in validating work plans (i.e., construction schedules), looking to the COVID-secure requirement, does not exist nowadays. For this reason, the authors propose a prototype of a spatial conflict simulator integrated into the work planning process that implements social distancing measures for a real construction site scenario. Given its built-in computational capacity and the possibility of simulating and displaying dynamic scenarios (e.g., related to construction operations), serious game engines technology has been adopted to develop the simulation tool.

3 Methodology

3.1 Requirements for COVID-Secure Workplaces

During the last year, the spread of the COVID-19 pandemic has led regulatory authorities worldwide to adopt specific guidelines for each field of interest. For example, sector-specific guidances adopted by European countries in the fight against COVID-19 are collected in [5]. In the construction sector, as in many others, social distancing has been recognized as the first barrier against the spread of coronavirus. Keeping workers apart can create safer working conditions during the COVID-19 pandemic. Different countries around the world adopted slightly different social distancing thresholds (e.g., 1 m in Italy [6], 6 ft (~1.8 m) in the USA [7], or 2 m in the UK [8][9] and the UAE [10]). Where it is not possible to follow the social distancing guidelines in full concerning a particular activity, a hierarchy of controls [5][9] suggests considering whether that activity needs to continue, and, if so, to take all the possible mitigating actions to reduce the risk of transmission. For example, if an activity requires workers operating within the social distancing threshold, it is highly recommended to maintain the same crew composition over time and keep it far from other crews [6][8][9].

3.2 Serious Game Engine Technology

Serious game engines are promising tools to integrate semantically rich models that can be provided in BIM and simulation engines. The first application of gaming technology can be found in the aircraft industry, using Microsoft Flight Simulator for educational purposes [18]. Later, serious game engines also became widespread in the AEC industry, demonstrating that mere entertainment is not the only feasible nor the most promising application. The success of this approach is due to the difficulty in carrying out real field experiments in some research areas, such as construction management, which usually requires quite a huge budget and time efforts to set up an experimental study. The use of game engines facilitates the deployment of virtual testbeds and tests execution. Examples of serious game engine applications in the construction industry come from education and training [19][19][21], collaboration [22], and also simulation and analysis [4][23][24][25].

In this study, the gaming technology was chosen to develop a prototypal spatial conflict simulator for validating construction work plans and creating, at the same time, the conditions for COVID-secure workplaces. For this study, Unity3D™ was adopted as the serious game engine. 3D models (e.g., for buildings, equipment, etc.) can be easily imported in various formats (e.g., FBX, COLLADA, etc.) by a built-in function, recreating a virtual replica of the construction site layout. Relying on this virtual model, walkable surfaces within the construction site can be automatically detected in Unity3D™, exploiting one of its native functions, called NavMesh Baking [28]. This is the process of creating a NavMesh from the level geometry. Once Render Meshes and Terrains of all game objects are collected, they are processed to create a navigation mesh that approximates the walkable surfaces of the level. Path search algorithms, such as Dijkstra, A*, D* or Any-angle pathfinding ones, can be used to compute the best path between two given points in Unity3D™. It is beyond the scope of this study to compare different path search algorithms. In this study, the A*, that is formulated in terms of weighted graphs, was used. Starting from a specific node of a graph, it aims to find a path to the given goal node having the smallest cost (least distance traveled, shortest time, etc.) [29]. This algorithm was implemented using the A* Pathfinding Project Pro tool [30], including an advanced function for NavMesh generation, called Recast Graph. This technology stack has been tested in [23] to develop a

BIM-based holonic management system for real-time support during fire emergencies. Gaming environments, such as Unity3D^{TM}, integrate physics engines, ensuring that the objects correctly accelerate and respond to collisions, gravity, and various other forces, making simulations closer to reality [31]. In addition, serious game engines enable implementing human and artificial sensors, known as agents, using pre-installed components or defining customized C# scripts. The sense of sight, for example, can be implemented to give human avatars awareness about what is happening around them. This can be done in Unity3D^{TM} by modeling the field of view (FOV) as a collider; a user can see an entity simply if her/his FOV collider intercepts with the entity itself. This feature has been tested by [24] to develop a twin model mock-up that implements Bayesian networks to compute collision probability during drilling operations. Finally, in [25], the authors developed C# scripts in Unity3D^{TM} to define avatars' behaviors, such as random wandering, and sensors for impacts checking to anticipate fall hazards within the construction site.

3.3 Workspace Management Framework

In this study, a workspace management framework for validating construction work plans and ensuring COVID-secure workplaces has been defined. The framework is described by the Business Process Model (BPM) depicted in Figure 1. On its basis, a prototype of a spatial conflict simulator has been developed within Unity3D^{TM}. The main tasks of the BPM, reported on the top of the same figure, are listed as follows:

1. Load BIM model.
2. Read 4D model and instantiate main workspaces.
3. Compute A* paths between main workspaces and instantiate transfer spaces (i.e., included within the wider category of support workspaces).
4. Run intersection tests among all the possible pairs of workspaces (i.e., main and support workspaces).

It must be noted that, as mentioned in Section 2.3, the main tasks 1 and 2 represent the state-of-the-art in workspace management [4], while main tasks 3 and 4 represent the contribution to the body of knowledge given by the current research work. According to the proposed framework, the user must load the BIM model (e.g., in FBX format) within the Unity3D^{TM} environment. It has been assumed that, once the BIM model (e.g., in RVT format) and the work schedule (e.g., in CSV format) are opened within a commercial software for scheduling (e.g., Navisworks), the 4D model can be defined by linking each activity to the corresponding building elements. Afterward, the data related to the association between activities and their products can be exported into a CSV-formatted file. It must be noted that these tasks are out of the scope of this research and have been assumed as input.

Afterward, the tool, thanks to the C# scripts “ModelInput.cs” and “InstantiateMainWorkspaces.cs” (pseudocodes available at [26]), developed by the authors, can read the 4D model and instantiate the main workspace for each activity. In detail, the main workspace is obtained by merging the main workspace units, instantiated for each one of the building elements (e.g., pillars) associated with the considered activity (e.g., install an alignment of pillars). The dimensions of each main workspace unit can be set for the corresponding activity by inputting an offsets vector applied to the building elements’ footprint. Using the installation of a pillar as an example, an offsets vector (X, Y, Z) = (4, 0, 4) indicates that the main workspace unit is obtained by applying a 4 m offset in both the X and Z directions and a null offset in the Y one (i.e., the same height of the pillar).

The commercial A* pathfinding tool, namely A* Pathfinding Project Pro [30], enables the tool to compute the best path between each pair of main workspaces corresponding to activities scheduled in succession. The C# script “InstantiateSupportWorkspaces.cs” (pseudocodes available at [26]) accesses the best path’s nodes and instantiates the corresponding transfer space (i.e., included within the wider category of support workspaces) in the same location. In this case, the user can set the support workspaces’ dimensions by inputting two distinct offsets vectors. The first one specifies the space required for operational purposes, whereas the second one must be set accordingly to the COVID-19 social distancing threshold in force in the considered country. Assuming to adhere to the 2 m social distance, the last offsets vector must be set as (X, Y, Z) = (2, 0, 2).

The last main task consists of detecting eventual spatial conflicts between the instantiated workspaces. To this purpose, the authors developed a C# script, called “IntersectionTest.cs” (pseudocodes available at [26]), which carries out an intersection test between all the instantiated workspaces colliders to find eventual spatial conflicts. The simulation results are provided visually, in the Unity3D’s Scene window, and as loglines, in the Console window (Figure 2). At this point, the construction manager can adjust the work plan according to the detected spatial conflicts and, then, the refinement loop continues until no spatial conflicts are detected or judged as negligible.

The data model that summarizes the main entities involved in a spatial-temporal simulation and the relationships between them can be described by an Entity Relationship Diagram (ERD) (available as extra material in [32]). Here, entities are grouped in the following domains: scheduling, resources, products, workspaces, paths, and spatial conflicts. The ERD notation expresses the cardinality of relationships between each pair of

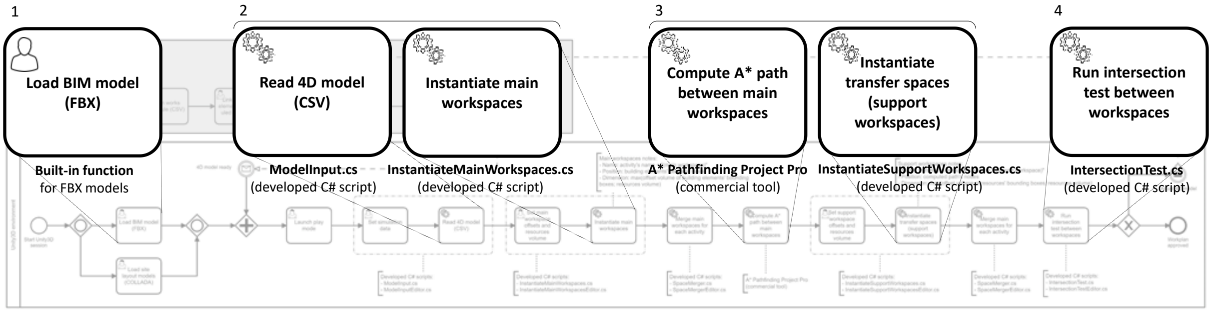
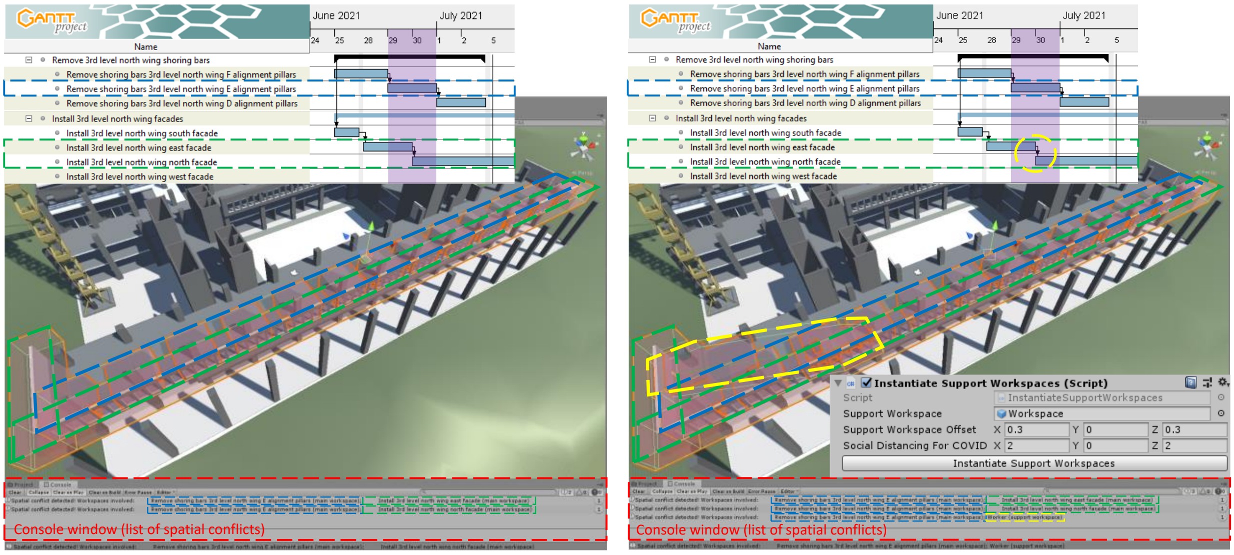


Figure 1. Business Process Model describing the logic behind the proposed workspace management framework for validating construction work plans (full-size figure available in [32]).



Instantiate Support Workspaces (Script)
Script: InstantiateSupportWorkspaces
Support Workspace: Workspace
Support Workspace Offset: X 0.3 Y 0 Z 0.3
Social Distancing For COVID: X 2 Y 0 Z 2
Instantiate Support Workspaces

(a)

(b)

Figure 2. Application of the spatial conflict simulator respectively in the first (a) and second (b) scenarios for the same working days (i.e., June 29th and 30th) (full-size figure available in [27]).

entities by the symbols at the ends of the links. To cite a few examples, the link between the entities "Activity" and "Building element" is of type "1 to 0 or many". In fact, an activity can produce no products (e.g., transfer pillars from the storage area to the installation area) or many (e.g., install an alignment of pillars). Instead, each link between the entities "Spatial conflict" and "Main/Support workspace" is of type "1 to 1" since each "Workspace ID" attribute in the first entity identifies a single main workspace.

4 Use Case and Experiment Design

The workspace management framework and the resulting prototypal spatial conflicts simulator, presented in Subsection 3.3, have been tested on the Eustachio building, a real construction project that currently houses the Faculty of Medicine of the Polytechnic University of Marche in Ancona, Italy. A work schedule of the construction activities for this building is considered (available as extra material in [32]).

This study considered the installation of precast elements, specifically pillars and façades on the 3rd level of the north wing. As reported in [33] and [34], the installation steps for each element are putting it into position, installing shoring bars, and placing concrete within the element's holes. Then, after having waited for concrete curing, the removal of shoring bars concludes the process. An excerpt of the work schedule related to removing the pillars' shoring bars and installing the façades on the 3rd level of the north wing is displayed in Figure 2(a) and Figure 2(b). This Section aims to demonstrate:

1. How the proposed spatial conflicts simulator can effectively contribute to detecting COVID-

spreading threats due to overlapping workspaces.

2. The relevance of transfer spaces and the wider category of support workspaces in detecting spatial conflicts and COVID-spreading threats.

To this purpose, the working days June 29th and 30th, highlighted in purple in Figure 2(a) and Figure 2(b), were considered for carrying out spatial conflicts simulations in two scenarios. In the first one, used as the benchmark, only main workspaces have been generated according to the state-of-the-art. Figure 2(a) displays the automatic instantiation of the main workspaces for the activities:

- "Remove shoring bars 3rd level north wing E alignment pillars", which lasts for the working days considered and is executed by the pillars crew (see the blue dashed rectangle in Figure 2(a)).
- "Install 3rd level north wing east façade" and, in sequence, "Install 3rd level north wing north façade", which is executed by the façades crew (see the green dashed rectangle in Figure 2(a)).

In the second scenario, both the main and support workspaces have been considered. In addition to the main workspaces for the activities listed above, the transfer spaces (i.e., included within the wider category of support workspaces) have been automatically instantiated. Since the activities "Install 3rd level north wing east façade" and "Install 3rd level north wing north façade" are in sequence, the assigned crew (i.e., façades crew) is asked to move from the first one's main workspace to the second one. The corresponding transfer space (see the yellow dashed shape in Figure 2(b)) is automatically instantiated based on the best path between the two main workspaces and the offsets vectors. The front end of the C# script for instantiating support workspaces, reported in Figure 2(b), displays that (X, Y, Z) = (0.3, 0, 0.3) and (X, Y, Z) = (2, 0, 2) are the offsets vectors assigned, respectively, for operational purposes and COVID-19 social distancing. In both scenarios, the workspaces' color, set as green as default, becomes red if the intersection test returns an overlapping (Figure 2(a) and Figure 2(b)). At the same time, the list of conflicting workspaces pairs is printed as an output (see the red dashed rectangles in Figure 2(a) and Figure 2(b)).

5 Results and Discussion

In this study, the installation process of precast elements on June 29th and 30th (highlighted in purple in Figure 2(a) and Figure 2(b)) was considered for testing the proposed spatial conflicts simulator. In the first scenario, only main workspaces were automatically generated, defining a benchmark according to the state-of-the-art. The potentialities of the proposed tool are fully tested in the second scenario by automatically generating both main and support workspaces.

In the first scenario, the intersection test between each pair of workspaces identifies the spatial conflicts between the following pairs of workspaces (Table 1):

- "Remove shoring bars 3rd level north wing E alignment pillars (main workspace)", assigned to the pillars crew, and "Install 3rd level north wing east façade (main workspace)", assigned to the façades crew.
- "Remove shoring bars 3rd level north wing E alignment pillars (main workspace)", assigned to the pillars crew, and "Install 3rd level north wing north façade (main workspace)", assigned to the façades crew.

In the second scenario, in addition to the spatial conflicts reported above for the first one, the one between "Remove shoring bars 3rd level north wing E alignment pillars (main workspace)", assigned to the pillars crew, and "Worker (support workspace)", assigned to the façades crew, is also detected (Table 1).

In both scenarios, the detected spatial conflicts are related to workspaces assigned to different crews (Table 1). Such interferences can cause not only productivity loss but also health and safety hazards, including COVID-spreading threats. Hence, the proposed spatial conflicts simulator can effectively support the construction manager in keeping different teams apart, as recommended by the COVID-19 guidances (Section 3.1). To sum up, the first main research outcome is an integrated spatial conflict simulator that reads the updated work plan and the BIM model of the site to provide as output the number of conflicts generated by interferences due not only to the main but also to the support workspaces. The second main outcome emerging from our preliminary simulations is that even in a short time span, limited to 2 days with 3 activities, interferences involving support workspaces account for 33% of the complete list of detected conflicts (Table 1). This demonstrates the relevance of transfer spaces and the wider category of support workspaces in detecting spatial conflicts and COVID-spreading threats.

6 Conclusions

The motivation of this research originated from the need to minimize congested construction sites which can contribute to COVID-19 transmission among construction workers. Hence, a better spatial awareness and consideration is required during the planning phase. Spatial interferences among different crews, even for a limited time, can create a potential scenario for coronavirus transmission; therefore, they must be avoided. To the authors' knowledge, any tool that supports project engineers in validating work plans, looking to the COVID-secure requirement, does not exist nowadays. For this reason, the authors have proposed a

Table 1. Overview of the pairs of detected conflicting workspaces respectively in the first and the second scenarios.

	First scenario (main workspaces only)		Second Scenario (main and support workspaces)	
Pairs of detected conflicting workspaces	Remove shoring bars 3rd level north wing E alignment pillars (main workspace) – Pillars crew	Install 3rd level north wing east façade (main workspace) – Façades crew	Remove shoring bars 3rd level north wing E alignment pillars (main workspace) – Pillars crew	Install 3rd level north wing east façade (main workspace) – Façades crew
	Remove shoring bars 3rd level north wing E alignment pillars (main workspace) – Pillars crew	Install 3rd level north wing north façade (main workspace) – Façades crew	Remove shoring bars 3rd level north wing E alignment pillars (main workspace) – Pillars crew	Install 3rd level north wing north façade (main workspace) – Façades crew
			Remove shoring bars 3rd level north wing E alignment pillars (main workspace) – Pillars crew	Worker (support workspace) – Façades crew

workspace management framework and the prototype of a spatial conflict simulator for the validation of work plans. Serious game engines technology was used to develop the simulation tool, given its built-in computational capacity and the possibility of simulating and displaying dynamic scenarios (e.g., related to construction operations). A proof-of-concept of the spatial conflict simulator has been tested on a real construction scenario. This aims to demonstrate its contribution in minimizing COVID-spreading threats related to overlapping workspaces. In addition, the authors want to prove the relevance of transfer spaces (i.e., included within the wider category of support workspaces) for extending the number of detected spatial conflicts that could be a source of potential coronavirus transmission.

The prototype presented in this paper has limitations. For example, it cannot compute the severity of the detected conflicts and the delay caused by the work plan refinement. In addition, future work includes an improved version of the proposed tool that can be applied to create the conditions for on-site applicability of proximity tracing devices [35], able to send, in real-time, an alert if social distancing measures are not met during the execution of different construction activities. The validation of work plans is required to detect and resolve eventual spatial interferences inherent to the work schedule. In this way, proximity tracing devices will detect only misbehaving workers in close proximity, avoiding alert overloads not related to unfeasible work plans. In addition, in future works, several activities (e.g., more than 3) and progressively increasing can be considered to quantify the contribution of support workspaces under different complexity conditions of the construction scenarios.

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