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TECHNOLOGY FRAMEWORK FOR REAL-TIME ASSESSMENT OF SPATIAL CONFLICTS IN BUILDING RETROFITTING

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ABSTRACT

In the field of construction works planning, workspaces must be considered as limited resources, in the same way as labour crews and equipment. Being the work-related spatial information both contextual and affected by construction site's dynamics, a real-time management approach based on lean principles must be adopted. In this paper, a BIM-based serious game engine, framed within a high-level system architecture, is presented to enhance work progress management. The generation of a geometric model to perform look-ahead simulations for predicting spatial conflicts is showcased relatively to a retrofitted residential building.

INTRODUCTION

In construction projects, workspaces related to simultaneous activities may overlap generating spatial conflicts. This can be explained with the fact that 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. In addition, the dynamic nature of construction sites does not facilitate the manual detection of this types of interference. Spatial conflicts and congestions, generating productivity loss and safety hazards, represent a relevant issue which must be urgently addressed. Recent research efforts in this field have been spent considering workspaces as a construction resource, similarly to humans and equipment.

This paper proposes a dynamic management approach based on lean principles that is able to deal with workspace interference management by performing continuous site monitoring and work-plan revision. The research contributes to the body of knowledge enabling the prediction of spatial conflicts and congestions which emerge from non-linear interactions between all the actors involved within the construction site. The remainder of this paper is organized as follows. In the next section Scientific Background, the state of the art regarding the management of the space resource in the construction field is summarized and discussed. The methodology of the paper, concerning the integration of a game simulation engine within construction management for look-ahead simulation and prediction of spatial conflicts is presented in the section Technology Framework. The section Simulations and Results reports a preliminary prototype and outcomes of the look-ahead spatial simulation tool implemented for the use case provided by the EU funded project "Encore", that concerns a cost-effective residential building retrofit. Finally, the last two sections are devoted to Conclusions and Acknowledgements.

SCIENTIFIC BACKGROUND

Construction projects involve several types of limited resources such as labour, equipment and space (Tao et al., 2020). The idea of space as a type of resource in project management was first introduced by Boer (1998). Workspace was defined as a renewable resource that can be occupied for activities execution; on completion, the space currently occupied will be released and reused by other operations (Ma, Zhang and Chang, 2020). As a consequence, the space required by construction activities is dynamic, i.e., the geometry and the location of workspaces continuously change over time, leading to a sequence of workspaces that are associated with the project's tasks (Kassem, Dawood and Chavada, 2015). When the same workspace is occupied simultaneously by two or more activities, workspace interference occurs, leading to significant problems such as labor safety hazards, construction delay and loss in productivity. These kinds of interference have recorded impacts as significant as up to 65% productivity loss and a 30% delay to the entire project (Hosny, Nik-Bakht and Moselhi, 2020). A survey conducted by the Occupational Safety and Health Branch of the Labor Department of Hong Kong demonstrated that 79% of the fatalities that occurred in the construction industry during 2011 were related to workspace interference (Tao et al., 2020). Spatial collisions that occur on construction jobsites are usually the result of poor workspace management and may pose several threats to the project performance (Hosny, Nik-Bakht and Moselhi, 2020). The widely used approaches are unable to avoid space conflicts. 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). For the aforementioned reasons, incorporating workspace consideration from the spatio-temporal perspective in construction planning plays a pivotal role. 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), since commercial 4D visual planning tools (e.g. Autodesk Navisworks, Synchro) lack workspace management capabilities (Kassem, Dawood and Chavada, 2015).

The relevance of workspace management emerges from a great variety of studies. As pointed out by Ma, Zhang and Chang (2020), an entire line of research has analyzed how tower cranes' dynamics affects both site layouts and tasks scheduling. To cite a few, the authors Wu, García de Soto and Zhang (2020) and Wu and García de Soto (2020) have studied the spatio-temporal planning models of tower cranes' tasks; the proposed mathematical models can find the optimal solution based on three-dimensional project data, i.e. quantity, place and time. The research proposed by Tao et al. (2020) aims to schedule construction activities considering workspace interferences classified as unacceptable (USI), which must be avoided, and acceptable (ASI), which must be at least controlled. To this end, a two-stage meta-heuristic algorithm has been developed and implemented in Matlab. A limitation of this research, recognised by the authors, is the fact that it does not include uncertainty, which inevitably affects construction activities. Towards this direction, the authors in (Hosny, Nik-Bakht and Moselhi, 2020) have developed an IFC-based software tool, using Blender game engine, in order to model workspaces probabilistically and to detect interferences from 4D models. The authors demonstrated that compounding effects of uncertainties may significantly affect the frequency and volume of overlapped workspaces in a project. The paper by Ma, Zhang and Chang (2020) proposed a BIM-based framework which, given the Microsoft Project schedule, detects time-space conflicts using Navisworks SDK toolkit. A similar approach was proposed by Tran and Pham (2020), where Synchro Pro was used to define a 4D BIM model and check workspace conflicts. The authors in (Kassem, Dawood and Chavada, 2015) developed, within XNA game engine, a 4D IFC-compliant tool able to support the whole workspace management process through the following tasks: the allocation of workspaces to site activities, the detection of congestion, spatial and temporal conflicts and their resolution within a 4D environment in an interactive real-time manner. This is a significant approach, compared to those adopted in other studies, where some processes were executed in the design authoring tool (i.e. workspace allocation in AutoCAD or Autodesk Revit) — which are not tools that are frequently used by project planners — and other processes in the planning application (i.e. conflict detection in Microsoft Project) (Kassem, Dawood and Chavada, 2015).

According to the scientific literature, the general process of workspace management can be described as the sequence of workspace generation and allocation, conflicts detection and, finally, their resolution (Kassem, Dawood and Chavada, 2015). First of all, a general rule must be defined in order to classify workspaces. Several classifications and vocabulary to describe workspaces are available in literature; the lack of an authoritative categorization is a challenge for the process of workspace management (Kassem, Dawood and Chavada, 2015). The required workspaces for the construction activity of a building component are geometrically represented in a 3Dimensional environment through bounding boxes (Kassem, Dawood and Chavada, 2015). The bounding box method is most widely used in detecting virtual space collision; this method expands the space occupied by irregular objects and uses the convex surface in representation to simplify the collision detection algorithm (Ma, Zhang and Chang, 2020). Once collisions are detected, their severity must be computed in order to choose a resolution strategy (Hosny, Nik-Bakht and Moselhi, 2020). Digital twins have been introduced as the only approach that can reasonably deal with the complexity of processes involved in construction management. The authors in (Grieves and Vickers, 2017) have introduced the concept of the digital twin as a virtual representation of a manufactured asset; this promotes the idea of comparing a digital twin to its engineering design to better understand what was produced versus what was designed, tightening the loop between design and execution.

In the contribution that is reported in the rest of this paper, we claim that the integration or interface of game engines within digital twins to the purpose of construction management can provide benefits, such as the prediction of imminent spatial conflicts, which can support the work of site managers and supervisors thanks to a timely warning. This helps to realize the lean construction approach, such as the one suggested by the Last Planner System (Gao and Low, 2014).

A FRAMEWORK FOR AUTOMATED SPATIAL CONFLICT PREDICTION

Lean principles for workspace management

As reported in the previous section, the construction site is a dynamic environment where workspaces' geometry and location change over time. In this context, many work-related spatial information (e.g., the best route connecting consecutive workspaces) depends on contextual information (e.g., detailed site layout), available with short advance. As more detailed information can be accessed, the overall works schedule must be constantly refined, resolving likely spatial conflicts that may happen in the short-term. The general logic behind this approach fits with the Last Planner System (LPS). LPS is one of the best known Lean techniques which has been demonstrated to be a very useful tool for the management of the construction process and continuous monitoring of the planning efficiency (AlSehaimi, Tzortopoulos and Koskela, 2009). LPS-based project planning is divided into two different stages: the long-term planning stage and the short-term planning stage (Ballard and Tommelein, 2016). In the first category, the Master Schedule and the Phase Schedule are adjusted as needed to specify what should be done. In the second category, the Lookahead Plan, used to decompose activities from phase level to operations level, defines what can be done; the Commitment Plan (or Weekly Work Plan) specifies the individual work steps that will be done. Finally, the phase of Learning, describing the completed works (i.e., did), is considered as a tool for future planning optimization by tracking the performance of the short-term planning process (Ballard and Tommelein, 2016). An application example, which combines the Last Planner methodology with space scheduling, is the WorkMovePlan system, proposed in (Choo and Tommelein, 2000). WorkMovePlan supports the user step by step to plan work for the week ahead, assigning not only labor and equipment but also space to accommodate the execution of a work package on site.

System architecture

The simulation environment, required to predict any spatial conflicts, shall be integrated in a wider framework, that may be realized implementing the multilayer system architecture shown in Figure 1, where five layers continuously collect and process information of the work that is being performed at the Physical Layer. The latter represents the totality of real entities involved in the construction process which, dynamically interacting, determine the achievement of the project's objectives. The daily activities are observed by several sources of data which define the Data Sources Layer. Here, both technical (more product-related) as well as social (more process-related) information are extracted. The concerned layer includes the data standardization tasks, where the extracted information is represented using open or de-facto standards, enabling future integrations and exchanges. In the Engineering Backbone Layer these standardized data are collected within repositories which store their evolution over time, i.e. a data history. In order to assist site managers and supervisors along the entire construction process, the Knowledge Extraction unit processes the data of the previous layer according to domain-specific ontologies (Abanda, Tah and Keivani, 2013); this task takes on a central role to assure that digital twins convey the most updated and coherent picture of the evolving construction site. The Digital Twin Viewpoints Layer contains different semantic dimensions which enable the digital twin to mimic relevant viewpoints of the construction process. Examples of these semantic clusters, applied in construction management, are Geometric Model, Crew Location, Site Layout, Jobsite Schedule, Work Progress and Temporary Works. Finally, at the Application Layer, the system architecture provides a set of interfaces through which site managers and supervisors receive a coherent view of the digital twins; every change the user applies through such interfaces is reflected on the Digital Twin Viewpoints below. At the Application Layer, we find tools and interfaces that support the supervisor along the activities included within the Project Execution Management unit. Examples of such interfaces, related to the construction management process, are the Work Progress and Deviations Control and the Spatial Conflict Prediction.

This paper focuses on the implementation of the Spatial Conflict Prediction unit of the Application Layer; an exhaustive description is provided in the following subsections.

Technology framework for the prediction of spatial conflicts

In this section, we claim that the integration of a game engine within the overall system architecture, described above, enables the detection of emergent spatial interferences by means of look-ahead simulations. This tool can help supervisors and engineers in charge of regular (e.g. daily or weekly) monitoring of construction site's activities to detect any issues. Serious gaming technology may have two main purposes: the first one is to predict possible spatial conflicts in the short time; the second one is to compute spatial variables affecting the re-allocation of resources on-site in order to support the decision process of the site engineer. This approach can be integrated irrespective of the adoption of automatic planning systems. Indeed, the action of the supervisor or site engineer can be either to re-allocate resources herself or to check any suggested work-plan developed by some decision support tools.

In Figure 2, we assume that the Digital Twin Viewpoints, introduced by the system architecture (see Figure 1), include two types of data monitoring systems scattered in the site: building progress monitoring and site monitoring. The first one makes it possible to update the progress of building construction (e.g., the progress of construction and installation of building components is mirrored in the building's virtual model). The link to the game engine could be provided by an IFC Loader, whose implementation is described in the following section, which progressively updates and automatically loads

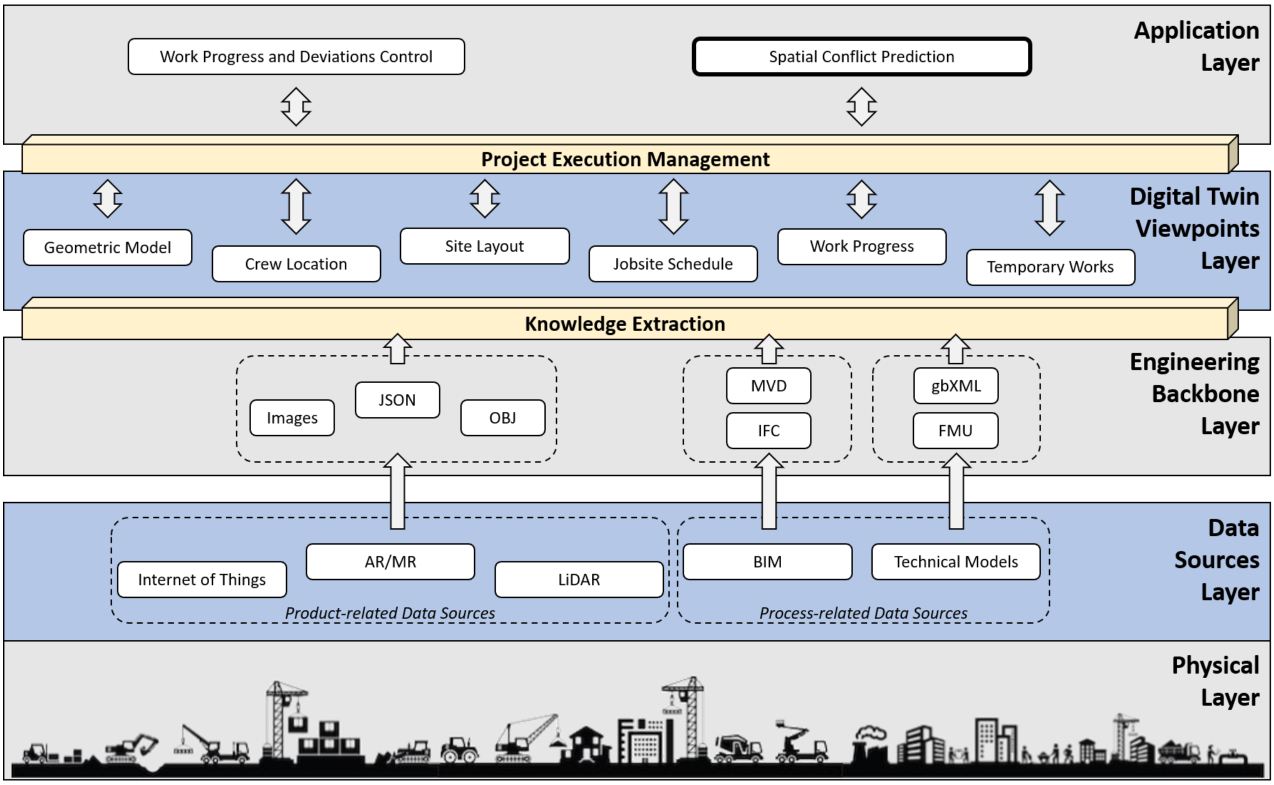

Figure 1: Overall system architecture.

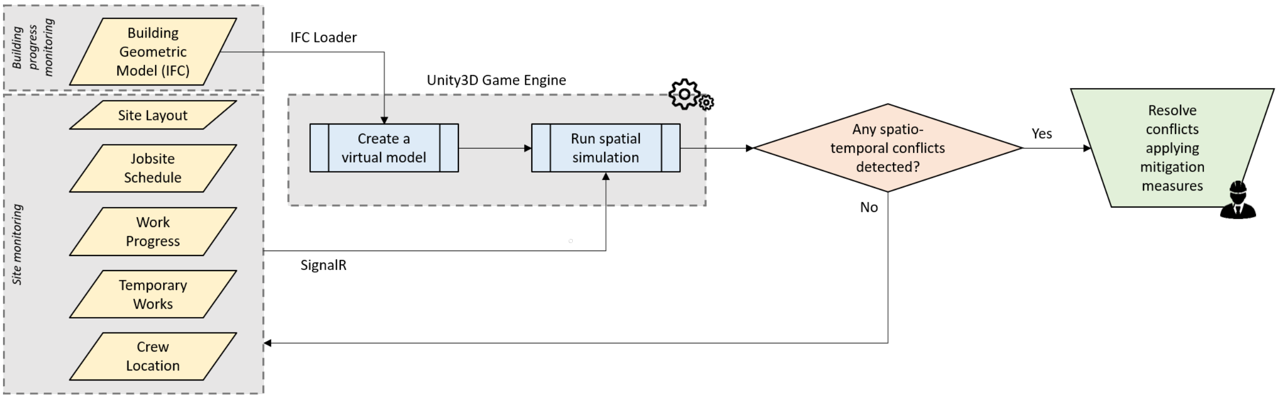

Figure 2: Technology framework for the implementation of the Spatial Conflict Prediction unit in the Application Layer.

the IFC data model within the game engine. As a result, a virtual model is created within the gaming environment. The site monitoring system, instead, enables the virtual model to replicate the layout and dynamics of a construction site (e.g., virtual equipment and human avatars can mimic the behaviour of physical assets); this can be implemented by means of the software library SignalR and a SignalR server, which define an asynchronous messaging system able to send real-time data to the running game engine (Microsoft Corporation, 2021). At this point, having combined the latest IFC model with synchronised site data, a look-ahead simulation of the activities scheduled in the short term must be run in order to find out possible spatial interferences resulting from emergent behaviors. In case any conflicts is detected, the supervisor/site engineer is asked to resolve spatial congestions and conflicts and to update the work-plan accordingly.

In the following section of this paper, we show the potentials of a serious game engine based on Unity3D$^{\mathrm{TM}}$ and applied to a demonstrator relative to the retrofitting of residential buildings.

Implementation of the serious gaming environment

Serious game engines are promising tools to integrate semantically rich models, that can be provided in the form of BIM, and simulation engines. 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). Later, serious game engines became widespread for other re-

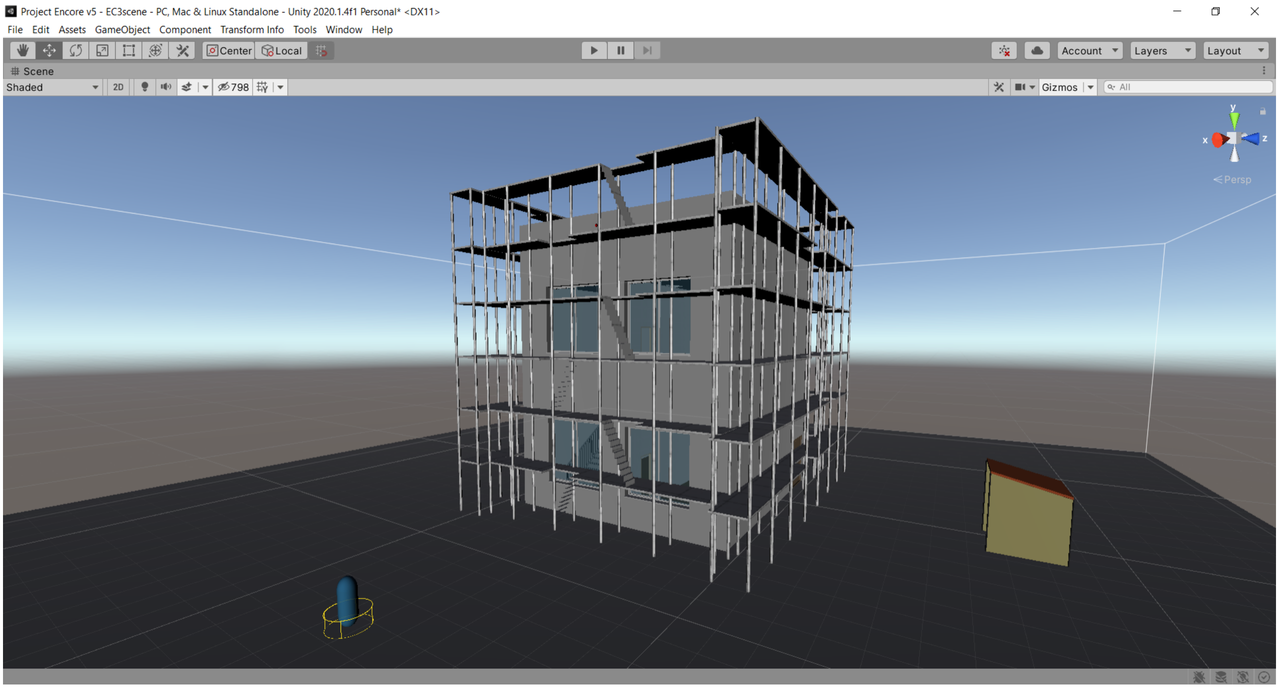

Figure 3: Virtual model of the case study obtained loading the IFC file in the Unity3D^{TM} gaming environment.

search purposes such as 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 field experiments in some research areas, such as construction management, which usually requires quite huge budget and time efforts to set up an experimental pilot. The use of game engines facilitates the deployment of virtual test-beds and the execution of relative tests. Examples of serious game engine applications for 4D-simulation purposes are provided by Hosny, Nik-Bakht and Moselhi (2020) and Kassem, Dawood and Chavada (2015).

In this research study, the game technology was applied in order to develop a virtual model which reflects the as-is status of the construction described by an IFC file. For the purpose of this paper, the gaming platform Unity3D^{TM} was adopted. The possibility of importing the physical status of the building progress, as updated by periodic data collection, into Unity3D^{TM} from an IFC model with its structure was showcased. To that end, an IFC Loader, based on the IFC Engine DLL library (RDF Ltd., 2006) was developed, in order to import topological information, properties of materials and all semantic information from the BIM model. This tool models the 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. Relying on this virtual model, walkable surfaces within the construction site can be automatically detected in Unity3D^{TM} exploiting one of its native functions, called NavMesh Baking (Unity Technologies, 2020a). 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. Implementing graph traversal and path search algorithms, such as A*, it is possible to compute the best path between two given points in Unity3D^{TM}. A* search algorithm is formulated in terms of weighted graphs: starting from a specific starting node of a graph, it aims to find a path to the given goal node having the smallest cost (least distance travelled, shortest time, etc.) (Nilsson, 1980). In this application A* search algorithm was implemented using the A* Pathfinding Project Pro tool (Granberg, 2020). It is one of the most popular dedicated pathfinding Unity3D^{TM} asset, which includes also an advanced function for NavMesh generation, called Recast Graph. This technology stack has been tested in (Naticchia, Messi and Carbonari, 2019) to develop a BIM-based holonic management system for real-time support during fire emergencies. Gaming environments, such as Unity3D^{TM}, integrate physics engines which, ensuring that the objects correctly accelerate and respond to collisions, gravity and various other forces, make simulations closer to reality (Unity Technologies, 2020b). In addition, serious game engines enable the implementation of 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 humans' avatars the awareness about what is happening around them. This can be done in Unity3D^{TM} by modelling the field of view (FOV) as a collider; a user can see an entity simply if her/his FOV collider intercepts the entity itself. This feature has been tested by Messi, Naticchia, Carbonari, Ridolfi and Di Giuda (2020) in order to develop a twin model mock-up which implements Bayesian networks to compute collision probability during drilling operations. Finally, in (Messi, Corneli, Vaccarini and Carbonari, 2020) the authors developed C# scripts in Unity3D^{TM} to define avatars' behaviours, such as random wandering, and sensors for impacts checking to the aim of anticipating fall hazards within the construction site. Thus, the Unity3D^{TM} model is complete and can be run to compute expected dynamics of the site and to detect spatial interferences before they occur. In this way, mitigation actions can be applied in advance and any productivity loss due to spatial congestions and conflicts can be avoided. A case study application is described in the next section.

SIMULATIONS AND RESULTS

The technology framework, described in the previous section, has been tested in the a case concerning the cost-effective retrofit of a two-story residential building. The virtual model of the case study has been recreated in the Unity3D^{TM} loading the IFC file by means of the IFC loader described in the previous section (see Figure 3). In order to spatially simulate the above mentioned renovation activities in the gaming environment, the scaffoldings and the depot have been modelled in Unity3D^{TM} using an integrated package, namely ProBuilder, which enables the modelling of custom geometries (Unity Technologies, 2021). In addition, a C# script has been defined in Unity3D^{TM} to automatically instantiate workspace volumes, derived from the bounding boxes of the game objects affected by construction works.

In this paper we have focused on the following four renovation macro-activities: the replacement of windows, on the west and east facades, and the installation of thermal coating, on the external side of the north and south walls. It must be noted that the replacement of windows and the installation of thermal coating, since requiring different skills, are usually executed by different crews; for this reason, a traditional activity-based planning may schedule them to be executed simultaneously without considering any constraint related to the space resource.

In the rest of this section, two different schedule scenarios are presented and discussed. It has been assumed in both of them that the A* Pathfinding Project Pro tool can search for paths to reach the top of the walls only on the scaffoldings. Figure 4 shows the results of the look-ahead spatial simulation in the first scenario, where the crew allocated to the thermal coating installation task will move from the south facade to the north facade and the windows replacement task has not started, yet. The yellow volume represents the workspace required by the crew allocated to the thermal coating installation task. The Recast Graph function of the A* Pathfinding Project Pro tool has been applied to scan the virtual construction site in order to detect all surfaces allowed for crew's access. The net of accessible areas are highlighted in blue in Figure 4. The same figure demonstrates that a worker avatar, represented by the capsule, can access the whole area required for the installation of the thermal coating on the north facade, walking through the west facade. In fact, the blue surfaces cover all the scaffolding levels on the west facade. In addition, the A* Pathfinding Project Pro tool can compute the shortest path to reach the top of the north wall (see green line in Figure 4). Figure 5 shows the results of the look-ahead spatial simulation in the second scenario. In this case, we assume that the windows replacement on the west and east facades has been anticipated and, hence, scheduled simultaneously to the thermal coating installation on the north facade. Besides the workspaces required for the thermal coating installation (see the yellow volumes in Figure 5), also the ones for the replacement of windows must be instantiated in Unity3D^{TM} (see the red volumes in Figure 5). In this second scenario, a spatial conflict occurs in the point in which the green line encounters one of the red volumes (see Figure 5). As a consequence, the A* Pathfinding Project Pro tool cannot compute any path to reach the north facade walking on the scaffoldings' surface. In fact, the net of accessible areas (see blue surfaces in Figure 5) is interrupted where the red volumes have been instantiated. This means that the crew allocated to the thermal coating installation cannot continue his job unless the works schedule or the site layout have been updated in order to avoid the detected spatial conflict.

CONCLUSIONS

Traditional activity-based scheduling techniques, not considering spatial representation, can be enhanced in terms of managing site workspaces. In order to reach high efficiency in the execution of construction works, both planning and construction management methods must be able to cope with the complexity inherent in the construction domain and the limited availability of space resource. To this aim, the current research proposes a concept of framework that can integrate real-time monitoring systems, predictive simulation tools based on gaming environment and human intelligence to resolve conflicts that can affect the overall site.

Technically, a serious gaming simulator, which generates a virtual model of the construction site from the IFC model and detects workspace interferences, has been developed using Unity3D^{TM}. It has been tested on a demonstrator concerning a typ-

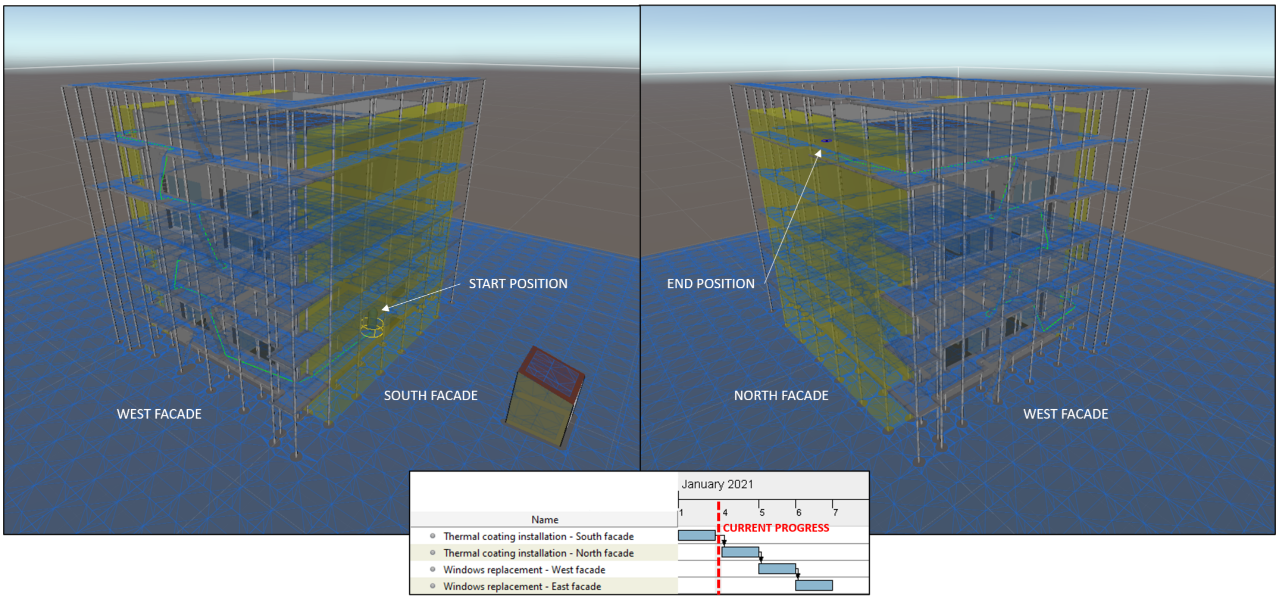

Figure 4: The look-ahead simulation, executed within the gaming environment Unity3D^{TM}, does not detect any spatial conflict if tasks are scheduled in sequence.

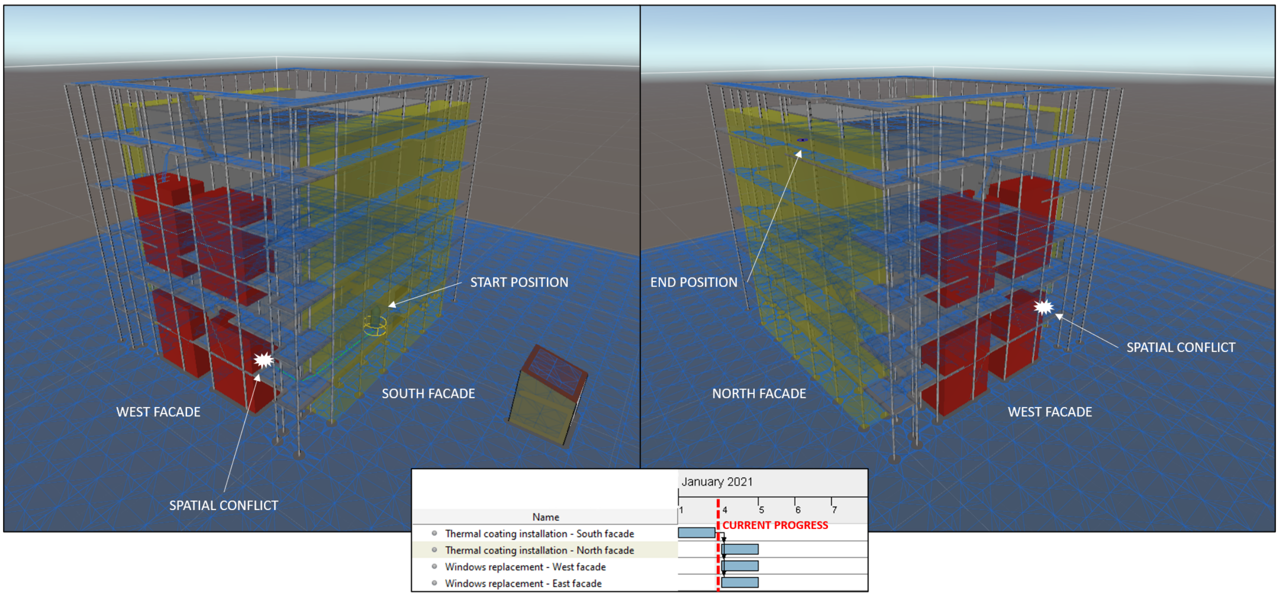

Figure 5: The look-ahead simulation, executed within the gaming environment Unity3D^{TM}, detects a spatial conflict due spatial interference between different tasks.

ical residential building retrofit case. Two scenarios have been tested in this paper; the aim is to demonstrate that the virtual model is able to integrate an IFC model about work progress, simulate the path of resources by identifying walkable surfaces and assess collisions between workspaces hampering the expected allocation of crews during works execution in order to anticipate unexpected events. Future research developments should address the integration of real-time data collection about the site layout and the enrichment of the virtual model with additional behaviours.

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