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CONSTRUCTION WORKSPACE MANAGEMENT: THE DEVELOPMENT AND APPLICATION OF A NOVEL nD PLANNING APPROACH AND TOOL

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SUMMARY: *Activity Execution Workspace (AEW) is one of the main constraints and resources on construction sites. The proactive management of AEWs is a very challenging task due to the dynamic nature of construction sites, where the availability of AEW is continuously evolving and changing over time. Project managers are looking for proactive approaches and innovative IT tools to accurately manage workspaces on construction sites as this affects not only costs and duration of projects, but also the safety of construction sites. The review of current state-of-the-art shows that limited research has been devoted to this area and that significant methodological and practical limitations exist. This research paper presents a novel approach for the management of AEWs. The objective of this approach is to enable the management of AEWs by integrating the traditional planning process (CPM – Critical Path Method) and Building Information Modeling (BIM) data in a 4D/5D environment and providing real-time management and rehearsal of AEWs. The approach, prototype and pilot case study presented in this paper have proven that it is feasible and effective to proactively manage AEWs within a 4D/5D environment. This is in line with the principles of nD project management, where the ultimate aim is to give project planners the capability of rehearsing different construction options, before the construction starts, in order to improve the efficiency and productivity of construction processes.*

KEYWORDS: *Construction workspace, Building Information Modeling (BIM), 4D/5D Planning, Construction Workspace Management.*

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1. INTRODUCTION

Construction projects are complex and dynamic in their nature. One of the main resources and constraints that affect the delivery of construction projects is the space available on site to directly or indirectly execute site activities (Dawood et al. 2005). Spaces on construction sites have become more and more critical to the extent that new business models have emerged in Europe and the UK, where logistics companies (e.g. Stiller in the UK) use space buffers to free site space capacity, especially for construction projects built around large and busy cities. In addition, construction projects are currently characterized by a high degree of fragmentation and specialization, which shape both the work on site and in the upstream supply chain (Kassem et al. 2012). Activities on construction sites are usually performed by multiple trades who require, at any point in time, different workspaces such as: working areas for laborers; material storage; equipment, and support infrastructure. This increases the challenges associated with the management of AEWs.

The importance of AEW management cannot be overstated due to its effect on productivity issues (e.g. delays and wastage) as well as site safety. Current construction planning techniques like Gantt charts, network diagrams, and CPM have proven to be inadequate for managing AEWs and project managers require structured approaches and new project management tools that allow them to analyze, detect, control and monitor workspace conflicts (Dawood and Mallasi, 2006). There have been a number of previous studies that tackled the management of AEWs. In previous studies, the management of AEWs has been referred to using a number of different terminologies interchangeably (e.g. execution space analysis, workface planning, time-space analysis, etc.). In this paper, the terminology 'management of AEWs' is adopted and it refers to the processes of: generation and allocation of workspaces; the detection of conflicts between workspaces; the detection of congestion in workspaces, and the resolution of conflicts between workspaces. Previous studies, as this paper will show, are characterized by significant limitations in their models and approaches. This research advances these models and provides more pragmatic methods in term of how AEWs are generated and allocated, and conflicts are detected and resolved. This paper presents a novel approach that enables the management of AEWs within a 5D planning environment by integrating the tradition planning (CPM) with BIM data of construction models and providing real time management and visualization of AEWs. The paper is organized as follows: first, a critical review of previous studies that investigated the issue of management and visualization of AEWs is presented. Then, each of the processes that make up part of the proposed approach, such as the classification, generation and allocation of workspaces, the detection of conflicts both in schedules and workspaces, and the visualization and resolution of conflicts, will be explained in a separate section. Finally, the paper will present and analyze the finding from a pilot case study of a complex incinerator project, which is used to test the feasibility of the developed IT prototype, where the processes and techniques of the proposed approach were embedded.

2. LITERATURE REVIEW

This section presents an extensive and critical review of previous studies concerned with both the management and visualization of AEWs. The review is articulated around the main features of previous studies, which are relevant to the management of AEWs such as: physical constraints; workspace planning; integration with construction planning; algorithms used to detect conflicts; knowledge databases; visualization, and advanced optimization techniques used to support workspace planning.

2.1 Management of AEWs

The management of AEWs refers to the process of planning, controlling and monitoring construction workspaces on sites. This covers the workspace generation, the workspace assignment or allocation, the workspace conflict detection and resolution at any time during a construction project. In the literature, there are a number of studies concerned with the issue of the management of AEWs.

Thabet and Beliveay (1994) highlighted the need for a method to analyze workspaces on construction sites as incorrect decision by project managers could result in chaos on construction sites and could hamper the construction processes. They proposed a methodology to analyze available workspaces for activities on site. In their methodology, they first identify the physical spaces available within an AutoCAD environment. These

spaces are broken down into work blocks and activities are then allocated to the work blocks. This approach presents important limitations such as the low level of IT integration which requires all tasks to be carried out manually, except for the calculation of spaces in the completed building. In addition, this approach was limited only to the areas enclosed by the envelope of the completed building. However, it should be acknowledged that, at the time the research was conducted (1994), the technology limitations were a barrier to a greater integration.

Guo (2002) proposed a methodology to resolve clashes between different trades. The authors identify the spaces required by marking up the drawings produced in AutoCAD with spatial requirements for 'the execution of tasks' such as storage, temporary works, and paths. By marking-up the blocks of required space on the drawing, spatial clashes can be identified, and daily work plans could thereby be amended. However, their approach presents reduced automation in terms of execution and cannot cope with the dynamicity associated with construction activities and their required workspaces.

Akinchi et al., (2002) proposed a methodology to automatically generate the workspaces using '4D Work Planner Space Generator'. A space-loaded model is generated and then used to conduct a time-space conflict analysis and proactive planning of the construction site. The methodology captures spatial requirements of a given product breakdown structure (PBS) component within the 4D CAD model. This data is then manipulated to allow the schedule and product spaces to be related to each other before the clash detection process starts. Compared to the first two works discussed, this work presents substantial advancements. However, there are some important limitations related to the fact that the direct relationship is between product breakdown structure and model objects rather than between tasks (work breakdown structure) and model objects, which is a more popular approach for project managers. For example, this approach does not allow workspaces to be overlapped in the vertical plane and therefore, a reliable process for 'an efficient mechanism of workspace conflict detection' cannot be developed in their approach.

Dawood and Mallasi (2006) presented a critical space-time analysis (CSA) approach, which was developed to model and quantify space congestion and was embedded into a computerized tool called PECASO (patterns execution and critical analysis of site space organization). This was developed to assist project managers in the assignment and detection of workspace conflicts. Their methodology utilized a structured query language (SQL) to organize the product's coordinates to the required execution sequence, and a layer in AutoCAD to assign workspaces. The workspaces were then linked to activities in order to provide a 4D simulation of workspaces. While this approach is theoretically capable of dealing with the dynamicity of construction workspace, it is difficult to implement it in practice as the project planner is required to assign construction workspaces with the design authoring tool (i.e. AutoCAD). The other limitations of this work are the lack of interactivity and its inability to incorporate real-time decisions by planners and project managers. These issues have been considered and developed in the present work.

Wu and Chiu (2010) proposed a 4D workspace conflict detection and analysis system. They utilized Bentley Mircostation for 4D visualization and developed a plug-in extension to identify design, damage, safety and congestion conflicts on site. It provides a visualization environment to identify conflicts and presents the results using a color coding technique. However, as was the case with Dawood and Mallasi (2006), their work relied on third party systems and did not consider any resolution strategy to resolve the identified conflicts.

Bargstädt and Elmahdi (2010) developed a method called 'The Spatial Network' integrated with a plant simulation tool. In their methodology, workspace requirements are considered only at a relatively high level of detail as the Work Step Process (WSP). They broke down tasks into subtasks and subtasks into objects. Each object is composed of different elements or sections. The resulting tool is a simulation tool to assist project managers to plan and coordinate different trades within highly congested work areas. However, this approach did not include a 4D visualization capability or strategies for conflict detection and resolution.

Moon et al. (2009) proposed an integrated approach where workspaces are assigned individually to a model's objects and linked to schedule activities. They classified the workspaces and allocated workspaces using a semi-automatic generation method based on resource requirements. While this approach is more comprehensive than the previously discussed approaches, it still has significant drawbacks related to the fact that the workspace is assigned using a bounding volume and performed individually for each model object. Planners in practice tend

to identify the required workspaces not only based on model objects but also on schedule activities. Finally, their approach is based on AutoCAD rather than BIM and lacks strategies for conflict resolution.

2.2 Advanced visualization planning

Traditional scheduling techniques are often inefficient since they do not include the spatial (Zhang and Hu, 2011; Dawood and Mallasi, 2006; Dawood and Sikka, 2009, Chau et al., 2004; Koo and Fischer, 1998) or resource requirements (Zhang and Hu, 2011; Chau et al., 2004) of an activity, which makes construction workspace management challenging. Therefore, current construction planning techniques like Gantt chart, network diagrams, and CPM are considered to be inadequate for the planning of activity execution workspaces. Few researchers have attempted to add the spatial requirements to traditional planning techniques in order to implement a 4D environment for the visualization and management of AEWs. Li et al. (2003) highlighted that the lack of innovative IT tools for construction planners to assess and validate their planning can result in false operation planning, which causes significant reworks during the construction phase. They suggested that Virtual Reality (VR) technology could be the solution to this problem. They developed a knowledge base system called 'Virtual Construction laboratory Experiments' (VCE), which enables the planner to examine virtual experiments of advanced construction technologies, operations and processes.

Kuan-Chen and Shih-Chung (2009) argued that construction processes are getting more complicated due to the high number of objects including structural elements and equipment. They proposed an algorithm called 'VC-COLLIDE', which identifies conflicts on static or dynamic construction sites and determines the distance between large dynamic 3D objects in virtual construction sites using different scenarios. This algorithm rehearses the activities' sequence in order to detect the collision status in real-time virtual construction processes. However, this method considered neither space congestion nor resolution methods.

Dawood et al. (2005) proposed a 4D planning tool called 'VIRCON' (VIRtual CONstruction), which investigates sequential, spatial and process conflicts of construction schedules. It allows planners to rectify and trade off the temporal sequencing of tasks with their spatial distribution while rehearsing the project schedule. In a similar vein, Huang et al. (2007) argued that 4D planning tools do not support the visualization of the design and construction of specific components such as scaffolding and temporary facilities including storage areas and the carpentry shop. They proposed a framework that allows project planners to check the safety, activity sequence, and temporary infrastructure based on Dassault Systems solutions (DS). The system enables the 3D visualization and animation of a construction plan and aids planners in rehearsing and analyzing virtual construction of a given prototype. Another similar system known as 'FORBAU', was developed by Borrmann et al. (2009). It is a virtual construction site project that focuses on distinct infrastructure projects to improve planning and management of construction sites. One of its main objectives was to rehearse the process flow from planning to execution phase. Zhou et al. (2009) used a methodology called 'Computer Supported Collaboration Work' (CSCW) to develop an interactive and collaborative communication prototype. It supports users interactive and collaborative communication while reviewing construction plans and providing a 4D simulation model.

2.3 Workspace criticality and optimization techniques

In close conjunction with the identification and resolution of conflicts, workspace congestion is considered as a major cause of productivity loss on construction site. Several researchers have tackled this issue by proposing a variety of optimization techniques with differing sets of variables (TABLE 1).

Sriprasert and Dawood (2003) proposed a methodology dubbed 'multi-constraint planning'. This method enables better decisions by promoting transparency in data information management. Visualization and optimization of multiple constraints including physical, resource, contractual and information are all variables integrated and managed by the multi-constraint planning technique. Soltani and Fernando (2004) presented a multi-constraint conceptual framework to plan the delivery routes on construction sites. They used a fuzzy-based and multi-objective algorithm to support the optimization of resource delivery. The system however, can only support medium to small scale projects. Jang et al. (2007) used a genetic algorithm (GA) to optimize space management in order to prevent workspace congestion. The findings suggested that implementing the GA technique can

improve the space utilization in a very congested area. Finally, Mallasi (2009) addressed the strengths and weaknesses of GAs and presented a software prototype using the GA technique, which generate a best execution strategy by optimizing three decision variables: the direction of work execution, work rate distribution types, and quantity of work per week.

TABLE 1: Review of different optimization techniques

Research	Algorithms	Dimensions	Decision variables
Sriprasert and Dawood (2003)	Multi-constraints (Lean construction)	Time and space	Resources, space
Soltani and Fernando (2004)	Fuzzy-based and multi-objectives	Time, distance, safety, and visibility	Mobile plant, vehicles and people
Jang et al. (2007)	Genetic algorithm	Time and space	Space management: material deliveries, staging areas and crane location
Mallasi (2009)	Genetic algorithm	Time and space	Space-conflict in interior building space

2.4 Conclusions from the review of related literature

The literature review, discussed in this paper, clearly showed the importance of proactively managing site workspaces. Most of the existing studies have significant limitations as to their approaches for assigning workspaces, the IT environment in which workspace management is performed, and the lack of a resolution strategy as part of their methodology. In fact, existing research has often utilized the design authoring tool to assign and detect the conflicts in AEWs. This takes away the problem of the management of AEW from the traditional planning techniques and obliges project planners to use design authoring tools, with which they are often unfamiliar. In addition, in most existing studies, the workspace was assigned for each object individually (object by object). This is impractical for models with high numbers of objects and may not be required in real life scenarios as multiple objects could be sharing the same workspace. In addition, previous studies, by assigning the workspaces to objects instead of activities, were unable to consider workspaces such as storage workspace which is not associated with specific objects. Another important limitation of most existing studies is that workspace management was separated from the existing scheduling techniques (i.e. CPM) and the geometric information was imported from non-BIM environments. The approach presented in this paper aims to enable the management of AEWs by integrating the current planning process (i.e. CPM) and BIM data of construction models within a 5D planning environment, where AEWs are first generated and assigned by planners in an interactive way and then conflicts and congestion are detected and resolved within a 5D planning environment.

3. AN nD APPROACH FOR THE MANAGEMENT OF AEWS

The approach developed for AEWs is organized into a number of structured processes, which have increasing levels of detail that reflect the logical workflow between the different functions and algorithms. These processes, along with the required definitions and embedded logic in each process, are explained in the following sections.

3.1 Top level process

The top level process is depicted in Figure 1. The model data is imported from BIM tools using a number of different file formats including the IFC format (Industry Foundation Classes - rules and protocols that describe the different building objects) and the schedule information from planning applications using an XML format. Then, the model data and schedule information are linked together to create a 4D model. A 4D model is a visual simulation of the construction schedule that can be enabled once 3D objects from the 3D model are linked to construction activities from the project schedule (Figure 1). The ndCCIR, where this initial 4D model is built, is an existing 5D planning environment (4D + cost), which allows project planners to rehearse construction processes before the work starts on site. This environment, which was selected for the implementation of the approach, allows for multiplicity in the linking between objects and activities − more than one 3D element can be linked to a single activity and vice versa (Benghi and Dawood, 2008). Once the 4D model has been built in the 4D environment, the process of the management of AEWs can start. The management will be enabled

through a number of processes and sub processes which include: workspace generation process; conflict detection process; congestion detection process, and resolution process. Each of these processes will be addressed in one of the following sections. The integration of the management of AEWs with the CPM and the BIM data within a 5D environment (Figure 2) is a main distinguishing feature of this approach compared to other studies and makes the approach proposed more likely to be accepted by project planners.

3.2 Generation and allocation of workspaces

This process enables the generation and allocation of different types of workspaces. Before explaining this process, it is important to explain the different types of workspaces considered in this approach. The classification of workspaces used in previous research was initially reviewed before presenting the present approach's classification of workspaces. Table 2 includes a summary of the types of workspaces found in previous studies. The approach presented adopts a new classification of workspace types by adopting a similar terminology to the one used in the manufacturing sector which distinguishes between value added and non-value added activities. The proposed approach divides workspaces into the following categories:

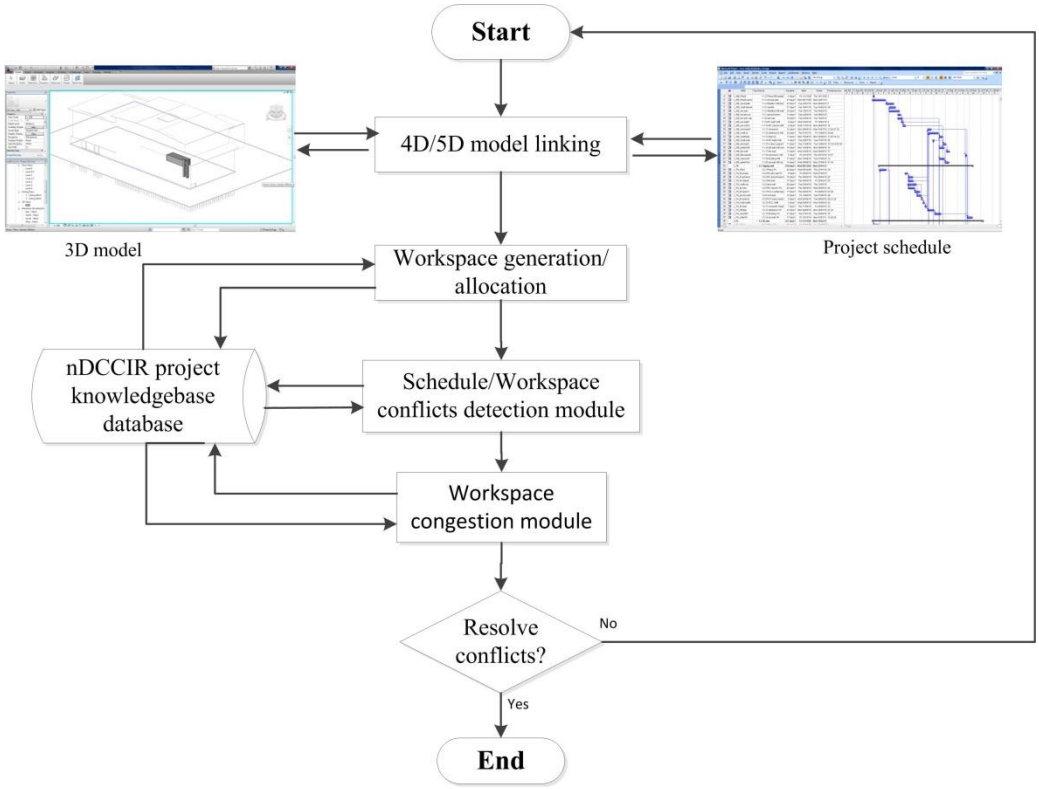


FIG 1: Top level process of the proposed framework

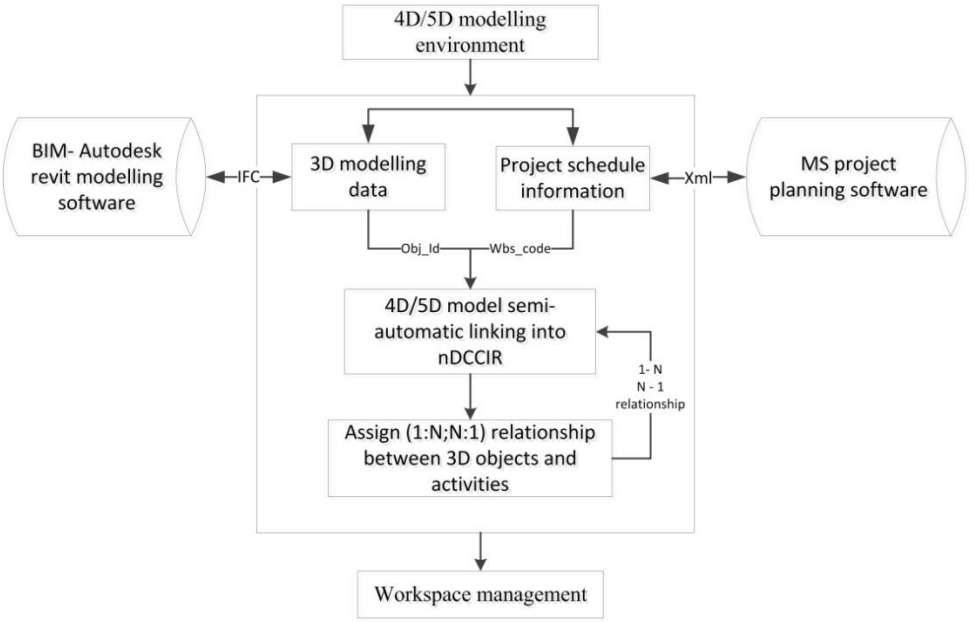


FIG 2: 5D visual modeling environment for workspace management

TABLE 2: Review of workspace type classifications

Riley and Sanvido (1997)	**Guo (2002)**	**Dawood and Mallasi (2006)**	**Moon et al., (2009)**	**Wu and Chiu (2010)**	**Chua et al., (2010)**
Layout area	Working space (laborers, equipment)	Product space workspace	Installation space	Path workspace	Process space
Unloading area		Process space	Prefabrication space	Material workspace	Resource handling space
Material area	Storage space (materials)	Equipment space	Transfer space	Laborer workspace	Product space
Storage area		Equipment path	Loading space	Equipment workspace	Interdiction space
Personnel area	Waste space	Storage Path	Safety space		
Staging area	Set-up space (Temp. facility space)	Path space		Site layout workspace	Usable space
Prefabrication area		Protected space			Dead space
Debris area		Support space		Building component workspace	
Hazard area					
Protected area					
Work area					
Tool equipment area					

- **Main workspaces:** are associated with activities which contribute to physical changes to the building or are in direct contact with the building (value added activities). An example is the workspace required to install a new building element (e.g. doors, windows, curtain wall, etc), to build a new wall, and the space required for scaffolding. Workspace, which is required to assemble building components on site, belongs also to this category.

- **Support workspace:** are workspaces required for activities, which do not contribute to the physical progress of the construction (non-value added activities). An example of support workspace is the space required for material storage on site and the space required to transfer materials from one area to another.
- **Object workspaces** are the areas or volumes of elements included in the model drawings such as doors, windows, roofs, covers, etc. This is the only category of workspace which is considered permanent, once built by an activity and it covers all building objects.
- **Safety workspaces** are areas that allow a tolerance (safety distance) between two workspaces to prevent safety hazards such as collision between resources and falling objects.

The above classification of workspaces not only distinguishes the proposed approach from previous studies in term of workspace types but it also dictates the way the workspaces are allocated and managed. Firstly, the proposed approach recognizes the need to elaborate on construction methods while generating and allocating workspaces as schedules often do not have levels of detail that allow a comprehensive generation and allocation of workspaces. For example, some workspaces (e.g. access method) are freed at the finish date of an activity, while other workspaces (e.g. storage workspaces and support infrastructure) can be still required after the end date of an activity. Previous studies were unable to cope with such scenarios partly because they allocate workspaces to objects instead of activities and are performed in isolation of the planning environment. In fact, in previous studies, workspaces were generated in 2D drawings or 3D design within the design authoring tools (e.g. AUTOCAD or BIM) (Guo, 2002; Dawood and Mallasi, 2006; Bargstädt and Elmahdi, 2010; Kuan-Chen and Shih-Chung, 2009; Wu and Chiu, 2010). As a result, they do not include the time-dimension and it is difficult to identify the requirement in terms of workspaces at a particular project date. Only a few researchers (Akinchi et al., (2002), Moon et al. (2009)) allocated construction workspaces in 4D environments. However, as workspaces were assigned to objects, the properties of building objects in the design environment were used to define workspace requirements. This is a cumbersome task especially for large projects containing a high number of objects.

AEWs in the proposed approach can be generated within the 4D/5D planning environment and assigned to either the activities or objects in an interactive way. The proposed process to generate and allocate AEWs is depicted in Figure 3. This process starts with the allocation of resources (workers, equipment and materials) and the identification of the required support infrastructure for each activity. The framework assumes that project planners are capable or have access to such information once the construction method has been defined. This information is then used to assign the workspaces through a 3D mark-up within the 4D/5D planning environment. The user inputs the approximate workspace size and type to generate a bounding box of the workspace by considering the construction method. A bounding box will then be created as a result of this 3D mark-up process. All the different types of workspaces defined earlier can be assigned with a number of options, which allow the editing of the workspace attributes such as its volume, shape and position.

The positioning of the workspace within the 4D/5D environment can be controlled by using the 4 × 4 transformation matrix (1), in which *sf* and *pv* represents the scale factor and position value of the workspace respectively. The logic of the transformation matrix was embedded in the IT prototype to allow project planners to interactively control the size and position of the workspace through a graphical user interface.

$$\text{T matrix} = \begin{bmatrix} sf & 0 & 0 & 0 \\ 0 & sf & 0 & 0 \\ 0 & 0 & sf & 0 \\ pv & pv & pv & 0 \end{bmatrix} \quad (1)$$

Once a workspace has been generated and positioned, it can then be linked to one activity (a 1 to 1 relationship) or to more than one activity (1 to n relationship) in the schedule. In order to enable the subsequent processes of the approach (i.e. conflict detection and resolution), the attributes of each workspace, the model element(s) and activity(ies) to which the workspace was assigned, are stored in a relational database. Once this process has been completed, the workspace conflict detection process can start.

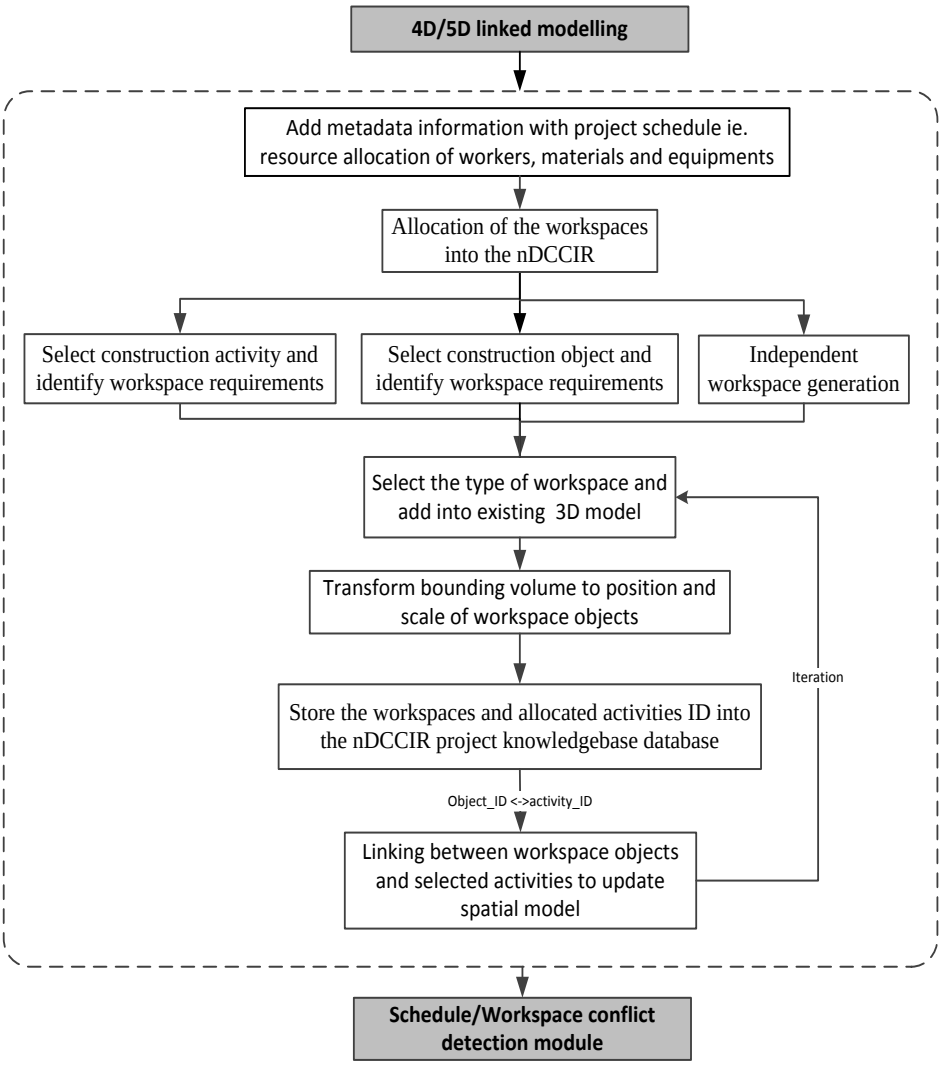


FIG 3: Process for workspace generation and allocation

3.3 Detection of conflicts in the schedule and between workspaces

This process enables the detection of both the temporal conflicts between schedule activities and the spatial conflicts between AEWs. The process adopted in the proposed approach presents significant advancement, in terms of the accuracy of the detection, when compared to previous approaches found in the literature. For example, most previous studies identified spatial conflicts by measuring the adjacency distance between two physical objects or workspaces. The proposed approach exploits game engine rules to identify spatial conflicts by utilizing the intersection test. This test utilizes the minimum and maximum values of the coordinates of each bounding box generated and identifies the overlaps using the intersection test. Moreover, this approach allows the quantification of both temporal and spatial conflicts and the storage of the results in an organized way in a

structured relational database (i.e. knowledgebase database). Such information can be used by project planners to understand the severity of conflicts and to subsequently make more informed decisions at the stage of resolution of conflicts.

A schedule conflict is a situation where a schedule presents a number of overlapping tasks. A workspace conflict may occur when overlapping tasks share the same space. Therefore, the schedule conflict (temporal conflict) is a preliminary condition that is required to be checked prior to the workspace conflict (spatial conflict) (Figure 4). The detection of schedule conflicts is performed for each activity and it evolves in a sequential order (Figure 5), which progresses according to the start dates of activities. For each activity, the process identifies its predecessor and successor and detects the overlap between the activities involved. The different situations and conditions for overlaps are depicted in Figure 6.

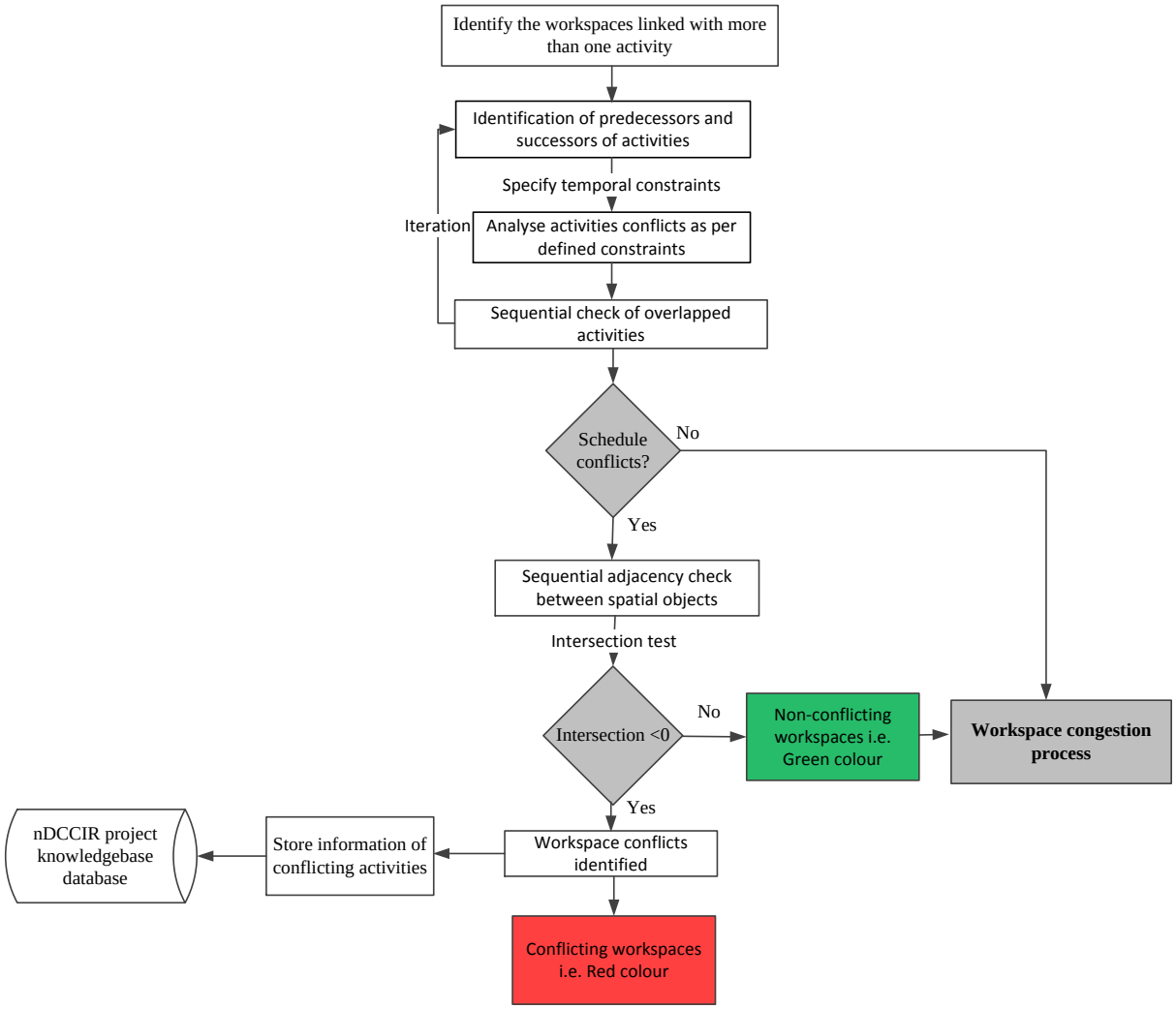


FIG 4: Process for detecting schedule and workspace conflicts

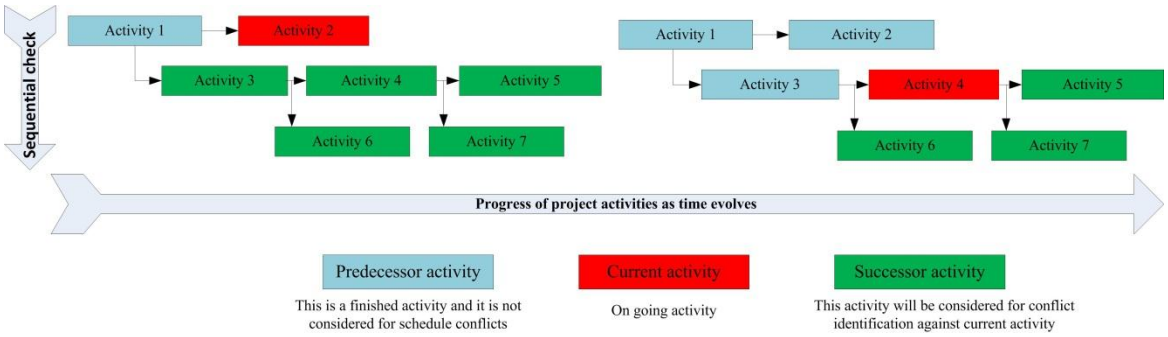


FIG 5: Sequential schedule conflicts check

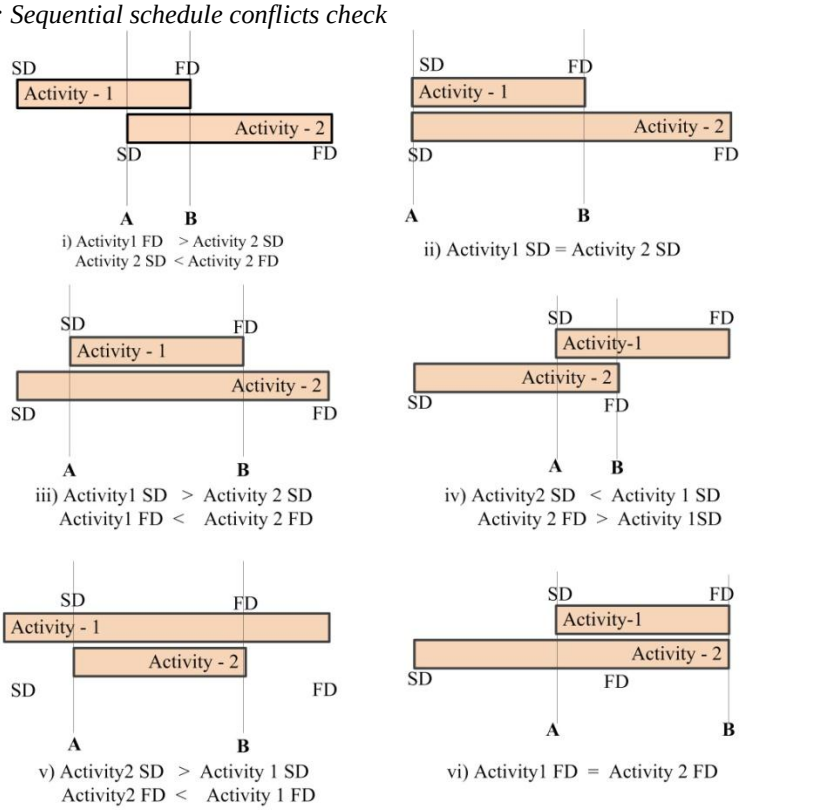


FIG 6: Conditions of schedule conflicts embedded in the approach

During this process, if the six conditions in Figure 6 are false, the schedule has no temporal conflicts. In this situation, a congestion test is still required as congestion may occur in cases where there are no spatial and/or temporal conflicts. The workspace congestion is explained in the next section.

If the process detects a schedule conflict, it will first calculate the severity of the conflict (SC) using Formula 2. In Formula 2, conflicted duration refers to the overlapping duration between two activities and the current activity duration refers to the duration of the activity for which SC is being calculated. It will then store SC and the unique identifiers of the activities involved, in a relational database and perform the intersection test between the two bounding boxes, which represent the activities' execution workspaces. This concept is widely used in

game engines, where very fast intersection tests are used to detect the collision among a large number of 3D objects (Ericson, 2005; Tantisevi and Akinci, 2007; Xiong and Chen, 2011). The bounding box of a geometric object is a simple volume that encloses the object, forming a conservative approximation of the object. An intersection test aims basically at detecting the physical clash or geometric conflict among the workspaces associated with the conflicting activities. This conflict can be detected by carrying the intersection test in each of the Cartesian directions (X, Y, Z). There are a number of techniques available to generate bounding volumes such as a sphere, an axis-aligned bounding box (AABB), an oriented bounding box [OBB] (Cohen et al. 1995), and a discrete-oriented polytope [k-DOP] (Klosowski, 1998) and convex hull. In this research, the axis-aligned bounding box (AABB) was used to store all spatial objects in a scene. An AABB can appropriately fit prismatic rectangular objects that are aligned along the three major axes. In construction, most building components such as beams, columns, and floors, can be modeled in a scene with prismatic objects which are aligned along the three coordinate axes and therefore, this assumption and the use of AABB would not affect the accuracy of the system. In such cases, the AABB intersection test can efficiently and accurately identify spatial conflicts. The intersection test utilizes a direct comparison of the individual coordinate values of the AABBs. In particular, it compares the minimum and maximum coordinates values along each axis. Two bounding boxes called A or B conflict if all the three conditions described in Formulae 3, 4 and 5 are true.

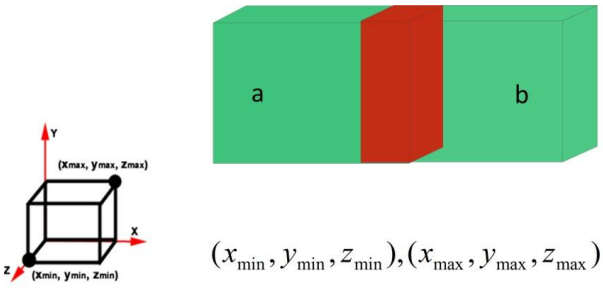
$$\text{SC} = \frac{Conflicted\ duration}{\text{Current activity duration}} \text{x } 100 \quad (2)$$

$$| X_{maxA} < X_{minB} | \text{ or } | X_{minA} > X_{maxB} | \quad (3)$$

$$| Y_{maxA} < Y_{minB} | \text{ or } | Y_{minA} > Y_{maxB} | \quad (4)$$

$$| Z_{maxA} < Z_{minB} | \text{ or } | Z_{minA} > Z_{maxB} | \quad (5)$$

FIG 7 shows an example of two conflicting workspaces and the conflicting volume between the two workspaces. For all conflicting activities, the process checks the 3 conditions (Formulae 3, 4, 5) in the three directions of the AABB. The system will then visualize in 4D real-time the results of the process of conflict detection using color codes. Conflicting workspaces appear in red and non-conflicting workspaces appear in green or the default color chosen for the workspace. One of the advantages of using this approach is that it allows project planners to detect the conflicts in each of the 3 directions (i.e. X, Y, and Z) and therefore, the project planners can use this information in the subsequent conflict resolution stage to design targeted resolution strategies. The real-time capability of the proposed framework refers to the fact that the proposed framework can deal with the dynamic nature of workspace as is the case with real construction sites. Figure 8 shows a dynamic scenario where the bounding volumes of different workspaces on a construction site change as time progresses. It is important to mention that the different points in time T_n to T_{n+3} belong to different activities rather than to the same activity. At the end of this process, the system stores the results from both processes (i.e. detection of schedule conflicts and detection of workspace conflicts) in a relational database so that data can be used to resolve the conflicts in the subsequent processes. The proposed approach also anticipates the importance of filtering the list of critical and non-critical activities involved in the conflict at any project date. This could be an important functionality that can be used by project planners to prioritize their corrective actions at the resolution stage of conflicts. This functionality was implemented in the IT prototype and tested in the pilot case studies, as will be shown in Section 4.



$$(x_{\min}, y_{\min}, z_{\min}), (x_{\max}, y_{\max}, z_{\max})$$

$$x_{\min} \le x \le x_{\max}$$
$$y_{\min} \le y \le y_{\max}$$
$$z_{\min} \le z \le z_{\max}$$

FIG 7: Conflicting workspaces

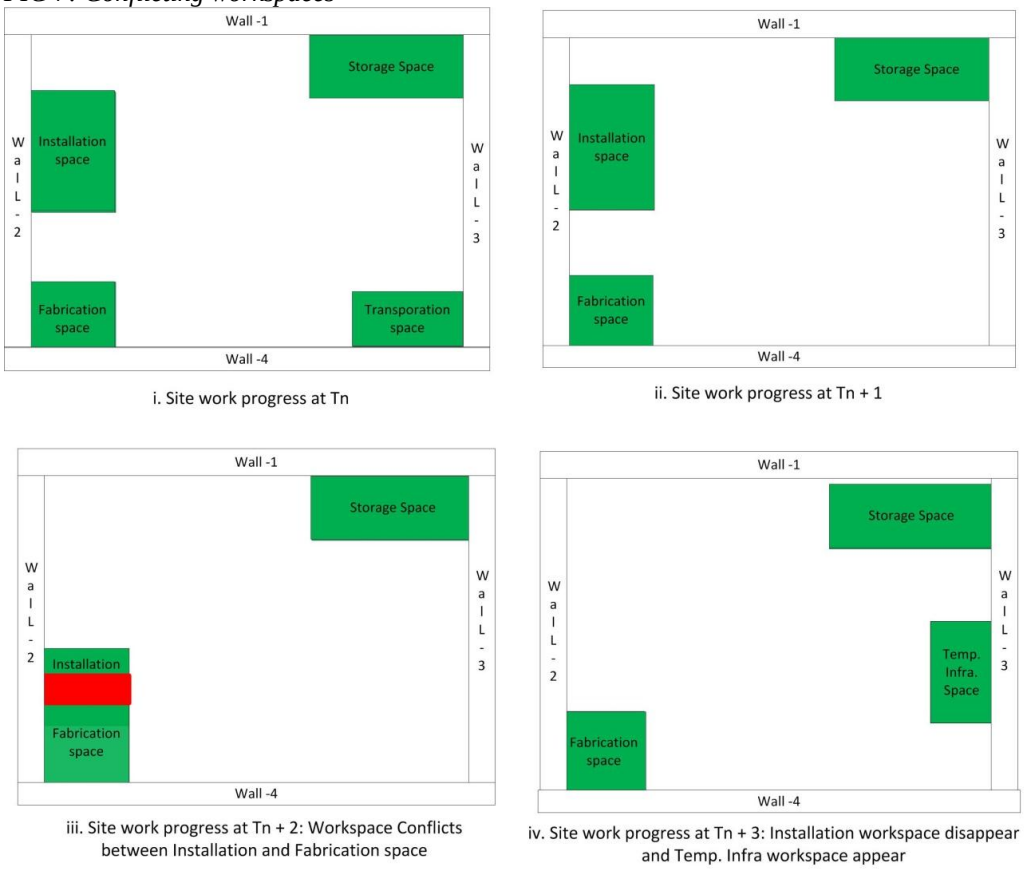


FIG 8: Dynamic nature of construction workspaces

3.4 Detection of workspace congestion

Workspace congestion is a situation that occurs when the workspace available for the resources of an activity or group of activities is either limited or smaller than the required workspace for such resources. This situation can occur even when there are no temporal and physical conflicts. The process for checking workspace congestion is illustrated in FIG 9. The criticality of workspace congestion is determined by the supply and demand of resources on site (Dawood and Mallasi, 2006; Winch and North, 2006; Wu and Chiu, 2010, Chua et al., 2010). Table 3 presents the workspace criticality equations used in previous studies to identify the workspace

congestion/utilization/capacity/loading level on construction sites. Higher ratios imply greater congestion levels on site. The workspace congestion is measured through the severity of congestions (Formula 6), which express the congestion level for each activity as the ratio between the available workspace and the required workspace for the resources allocated to the activity.

$$\text{CgS}\ (\%) = \frac{\boldsymbol{\Sigma}\text{Required activity }\mathbf{r}\text{esources} \times \text{Unit volume}}{\text{Available workspace volume for activity}} \quad (6)$$

CgS is the ratio between the volume for required resources and the volume available for activity execution. The required volume includes the volume for resources such as workers, equipment and materials which are required to execute the activity. To calculate the severity of congestion, data about the unit volume of each resource used on site is required. From the review of previous research, data about the space required by each resource unit appears to be varying in a wide range. Chua et al. (2010) assumed that each laborer requires a space of 0.6 m^3. Horner and Talhouni (1995) stated that 28.3 m^2 as the desirable lower limit for effective task execution. Thomas and Smith (1990) reported that studies conducted by Mobil suggest that 19 m^2 per person is required and that 50% more man-hours are required when this declines to 10.4 m^2, which is an absolute minimum. In the present research, a decision was made to leave these data as user inputs so the different needs of different users can be accommodated. Once the CgS is calculated for each workspace, the system utilizes three thresholds and color coding (green, blue, and red) in order to visually communicate congestion in real-time 4D simulations. These thresholds are indicative and can be adapted to different organizations' needs. They are user defined values which could be used to visualize the levels of workspace congestion. In this research, three congestion levels were defined: low (1-33%), medium (34-66%) and high (more than 66% and can exceed 100%) and can be visualized using green, blue and red, respectively. The visualization of CgS will assist the planner in identifying the most critical areas and reducing congestion risks before construction work starts. It is important to highlight that the three levels of severity (i.e. green, blue and red) do not give indications about the risk severity in health and safety (H&S) terms but only an indication about the severity of the congestion at every project's date. In fact, at all the three levels (green, blue, and red) H&S issues may arise and the planners should be alerted to check H&S issues for all the three levels. For example, low congestion in a workspace shared by moving equipment and laborers (green) may entail more hazardous safety risks than a highly congested workspace used as a storage space.

TABLE 3: Workspace criticality equations from previous research

Authors	Equation	Definitions
Chua et al. (2010)	$Us = \frac{\Sigma\ OS}{TBS}$	• Spatial utilization (Us) is the ratio index of the space required by the operator/equipment to the total available space allocated to an activity; • The Operator Space (OS) being the amount of space necessary for the operator to perform the activity. Multiple crews may be considered by summing up the total operator spaces needed. • The Total Boundary Space (TBS) refers to the amount of space depicting the activity space.
Dawood and Mallasi (2006)	$f(co) = \frac{\Sigma\ TSN}{\Sigma\ TSA}$	• f(co) = the function for the ratio of conflicting workspace volumes. • $\underline{Total\ volume\ of\ space\ Needed\ (TSN)}$ = Total volume of conflicts between 3D execution spaces of activities. • $Total\ volume\ of\ Space\ Available\ (TSA)$ = total volume of all execution spaces of activities.
Winch and North (2006)	$s = \frac{r}{a} \times\ 100$	• s = Spatial loading is the ratio of required space to available space. • r = Required space

		• a= Available space which is sum of product space and installation space minus total space.
Thabet and Belliveau (1994)	$SCF = \frac{SDA}{CSA}$	• Space capacity factor (SCF) is proposed to measure the degree of congestion in any given work block of the floor. • Space demand for activity (SDA) defines space needed for manpower and equipment and handling of material (e.g. storage, moving, etc.) within the floor area. • Critical Space Availability (CSA) defined by the amount of space available for any activity during the time period the activity is considered for scheduling.

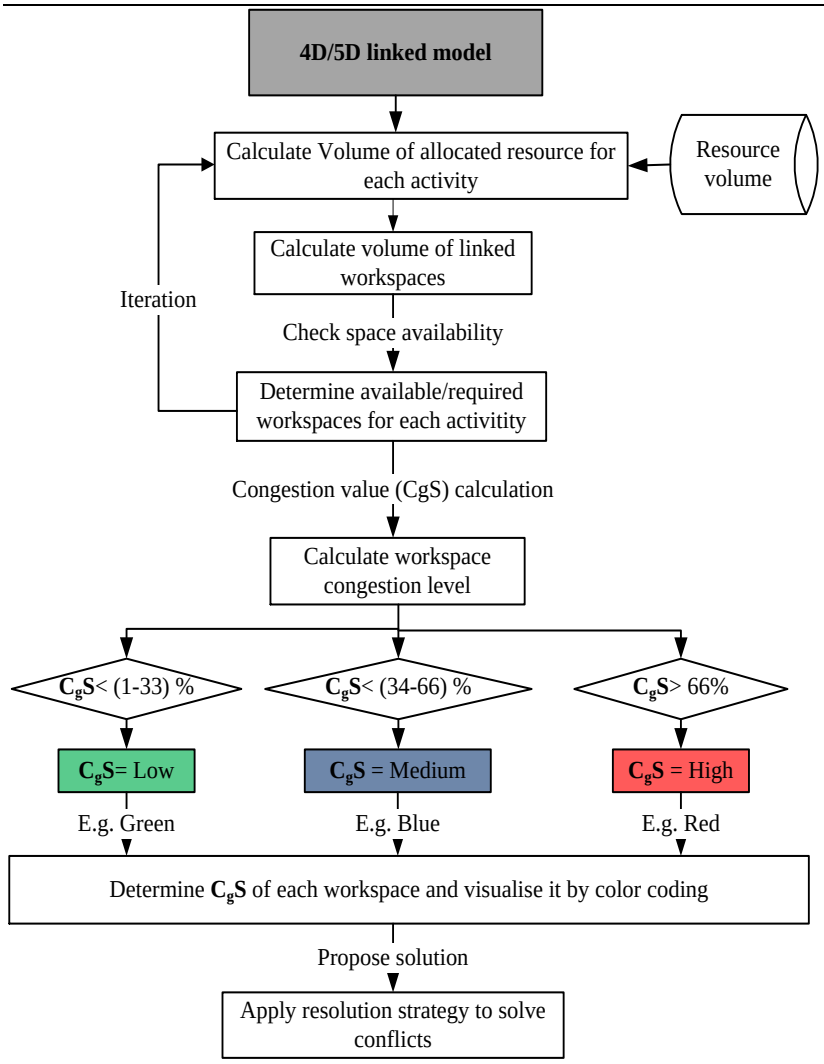


FIG 9: Process for identifying workspace congestion

3.5 Resolution of workspace conflicts and workspace congestion

The resolution of workspace conflicts and workspace congestion represents the last process of the proposed approach. The data generated in the previous processes are utilized to resolve the identified conflicts. Although this stage is one of the main stages in the management of AEWs, most of the previous research was limited to the identification of workspace conflicts and lacked resolution capabilities. Only two studies (Bansal, 2011; Guo, 2001) included conflict resolution processes in their methodologies, which utilize the conflicting activities and the sizes of overlapping workspaces. In the proposed approach, once the processes of workspace conflict detection and workspace congestion identification have been completed, a resolution strategy can be enabled to reduce or eliminate the conflict and congestion. Some of the features of the previous modules were accurately designed in order to enable the resolution strategies. For example, the interactivity provided in the process of workspace generation and allocation allows project planners to control the position and the size of the workspace in the 3D environment. In case a conflict is identified, project planners can interactively modify the size of an object to resolve conflicts and the system will iteratively analyze the effects which emerge as a result of changing the size of the workspace. The second process (i.e. schedule and workspace conflict identification) has some features such as the SC calculation and the filtering of conflicting activities as critical and non-critical activities. This feature can be used by project planners to resolve the conflicts by focusing on non-critical activities without affecting the project's end date. In summary, the approach proposed enables project planners to implement a number of options during the conflict resolution process, although the process is heuristic. Heuristic is a way of solving the conflicts by using resolution strategies that are based on a set of rules, which derive from user's experience, historical data and site observation. These strategies include: changing the start date of a conflicting activity; changing the duration of a conflicting activity; changing the size of the workspace, and changing the physical location of the workspace. These resolution strategies were derived from previous studies (Guo, 2001) and from discussion with industry peers. The approach developed offers the analytical means (i.e. percentage of overlap among conflicting tasks; percentage of conflicts between conflicting workspaces at any date in the project; filtering of conflicting activities in critical and non-critical activities) and interactive capability (i.e. interactive positioning of workspaces and setting workspace sizes) to implement all the aforementioned resolution strategies. While resolving conflicts, priority should be given to those strategies, which do not change the critical path (i.e. use the float time of non-critical activities, if the conflicting activities have float time; changing the location and/or size of the workspace; use a different construction method), even though the approach proposed has the capability of interactively calculating the new critical path and workspace conflicts. Therefore, the proposed approach enables the resolution of conflicts, one after another in a heuristic way, until all conflicts are resolved by involving project planners in the process.

4. CASE STUDY

The proposed approach was implemented in an IT tool called nD Planning System. In line with the definition of 4D/5D planning, the tool enables the real-time rehearsal of the management of AEWs for the construction project before the construction starts. The integration of the different processes required for workspace management and their encapsulation within the IT tool required a significant effort in terms of coding. The entire system has been coded in the C# language in the .NET environment and the XNA game engine was used for the real-time visualization. A pilot case study was conducted on a complex incinerator, built by BAM Nuttal in the North East of England. The case study was limited to 71 planned activities of the construction plan, which are associated with about 1474 objects in total. Figure 10 presents the 2D/3D drawings of the incinerator. The 5D simulation (time and cost) of the incinerator project is illustrated in Figure 11. The incinerator model was imported from a BIM authoring tool (i.e. Revit) using the IFC (Industry Foundation Classes) format and the schedule from the planning application (i.e. Primavera) using an XML format.

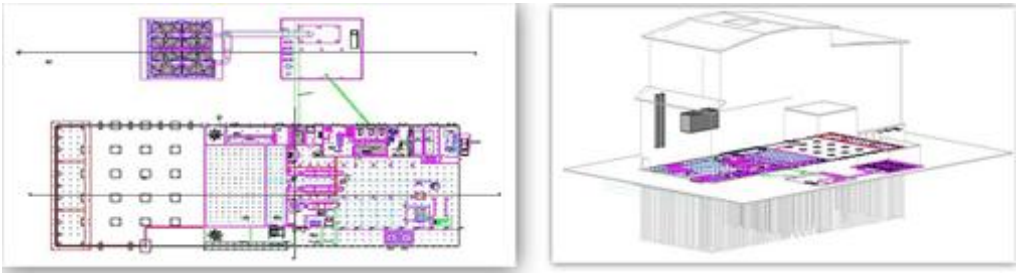


Figure 10 : The Incinerator project used a pilot case study

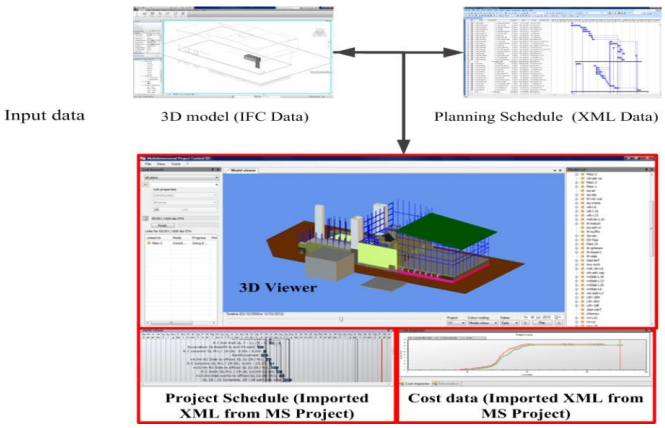
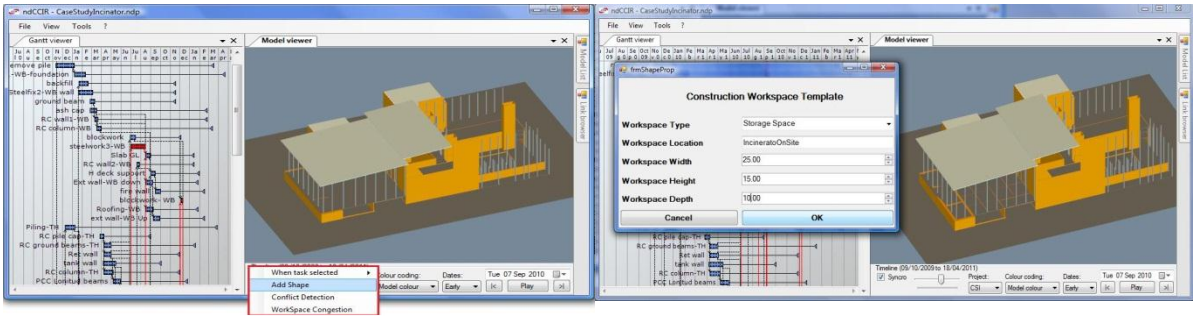


FIG 11: 5D model of the incinerator project

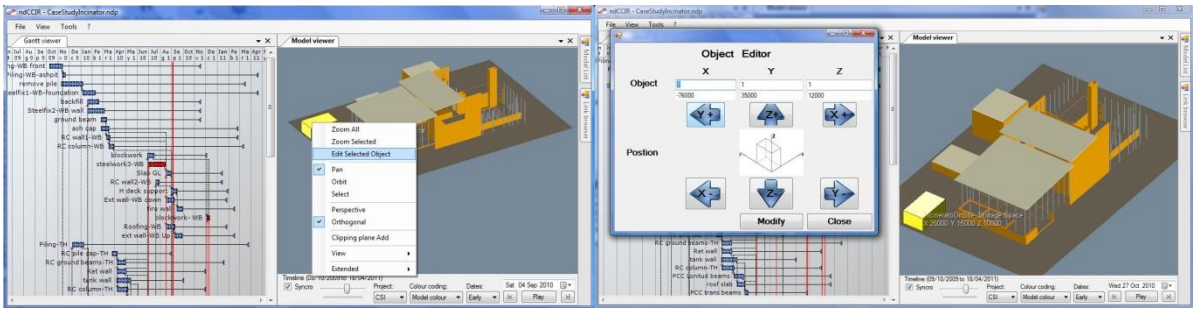
Before starting the process of the management of AEWs, there was an initial analysis of the 4D model, which identified that some construction activities did not have corresponding objects in the 3D model and other 3D model components were not planned for in the construction schedule. Then, the testing of the processes of workspace generation, schedule and workspace conflict detection, and workspace congestion and resolution, was conducted.

The case study started by generating and allocating the workspaces for the schedule's activities and/or model's objects within the 4D/5D environment. At the end of this stage a 4D/5D space-loaded model is obtained. Figure 12 shows clearly the interactive process of generating and allocating the workspace. This includes the selection of the shape (i.e. rectangular); type (i.e. storage workspace), and a user friendly interface (object editor) for the positioning of the workspace within the 3D space. This presents a significant advancement compared to most approaches found in previous studies, where workspaces have been generated and allocated in design authoring tools (e.g. AutoCAD), which planners may not be familiar with and their link with the temporal dimension is difficult to maintain. Limited research has attempted to generate workspaces in 4D environments by using building object properties to define the workspace area using the bounding box information. However, such an approach has significant drawbacks as it is impossible to generate and assign multiple workspaces to a single object, which limits the usability of this approach. With the proposed approach in this paper and tool developed, once the workspace is created, users can create different relationships between the workspace(s) and the activity(ies). The tool allows '1to n' (one activity linked to multiple workspaces) and 'n to 1' (multiple activities linked to one workspace) links. As a result of all the functionalities discussed, the first process of workspace generation and allocation and its implementation in an IT tool represents a significant advancement over the approaches and tools found in previous literature. In addition, the tool, by exploiting the interactivity available in game engines, is capable of making the workspace appear and disappear at the right date and thus it truly reflects the dynamic nature of construction sites.



i) Select a project activity and add its workspace in the 3D model

ii) Classify the workspace and specify its dimensions



iii) Open the object control editor

iv) Interactively control the object's size

FIG 12: Workspace generation, classification and allocation

A conflict is detected when the three conditions (Formulae 3, 4 and 5) defined earlier are all true. Figure 14 demonstrates the real-time workspace conflict detection, where the red area represents the conflicting workspaces in the incinerator project. The planner, by selecting the red area and right clicking, will be able to see the corresponding schedule activities whose workspaces are conflicting. Also in this process, there are important advancements over the approaches used in the literature. The proposed process enables a more accurate detection of spatial conflicts compared to the adjacency test (distance between two physical objects) used in previous studies and an interactive capability to select and interact with conflicting activities and their corresponding activities. In addition, the results of temporal and spatial conflicts are saved in a structured manner within a database and project planners can use such data during the resolution stage. Figure 16 shows a section of such a database which contains a list of conflicting activities and their attributes for the incinerator project. Following the spatial conflict detection, the congestion process is conducted even when there are no spatial conflicts between the workspaces. This process was missing from previous studies, where only spatial conflict detection processes were considered. This proposed process identifies in real-time the levels of congestion using the Formula (2) previously presented and visualizes the result using color codes for the different levels of severity (low, medium, high). Figure 15 presents the implementation of this process. In Figure 15, the congestion level of the storage space for 'STEELWORK_WB' activity is medium but as the time progresses, the same storage space is linked to another activity (e.g. ROOFING_WB) and its congestion level changed from medium to low. This reflects the dynamic nature of construction site where site congestion levels keep changing as the site progresses. Once the process of workspace generation and allocation is completed, the process of schedule and workspace conflict detection can start. This process detects first the temporal conflict (i.e. schedule conflict) and then the spatial conflict (workspace detection). Figure 13 shows the results of temporal conflict with the original plan on the left side and the conflicting activities on the right side. It identifies that out of the 64 linked activities, 13 activities are detected as conflicting. At this stage, the spatial conflict detection process can start. This is done in real-time by performing the intersection test for the bounding volumes (Axis Aligned Bounding Box -AABB) representing the workspaces.

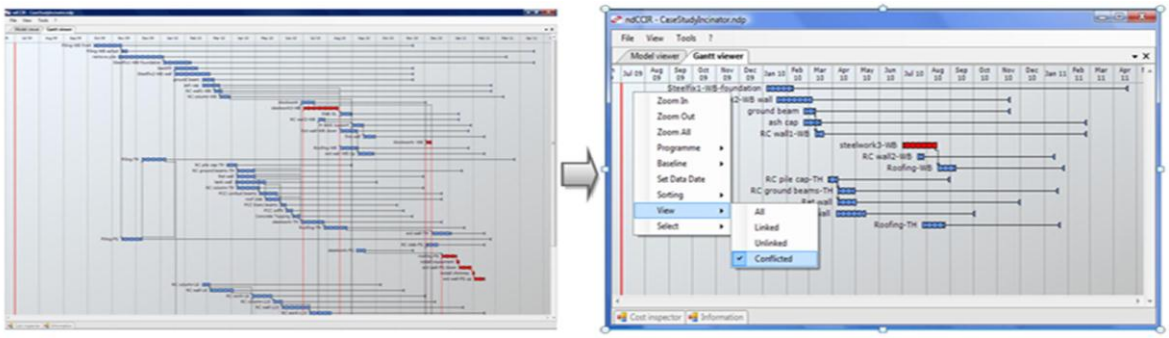


FIG 13: Results of the detection of schedule conflicts

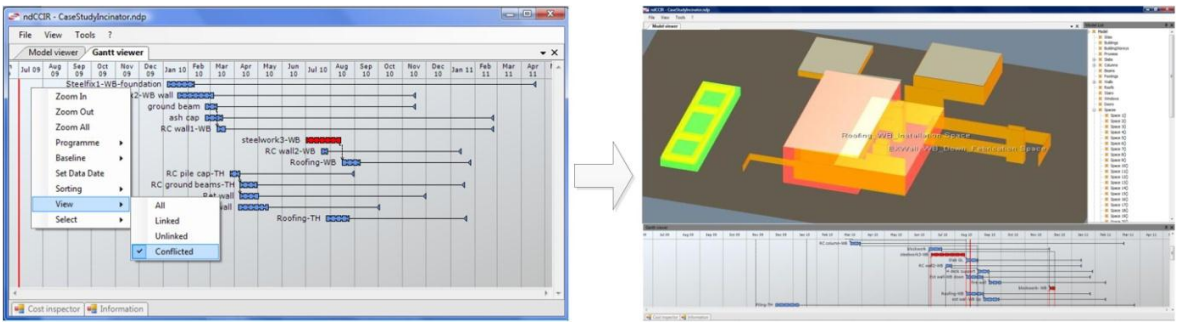


FIG 14: Visualization of conflicting AEWs

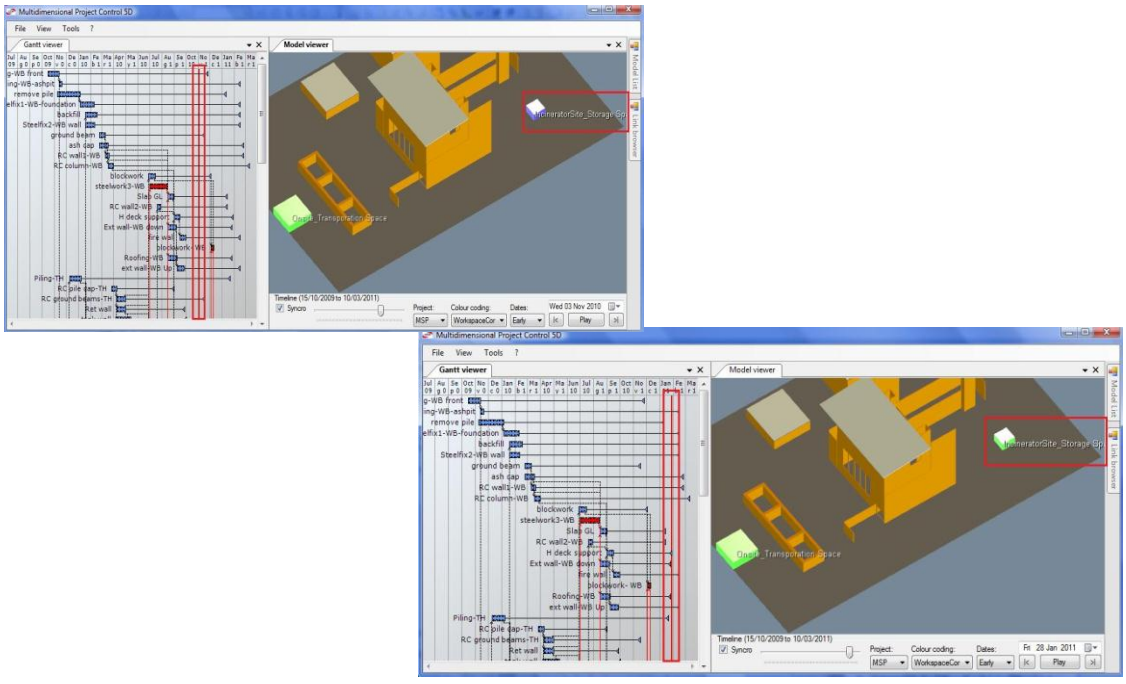
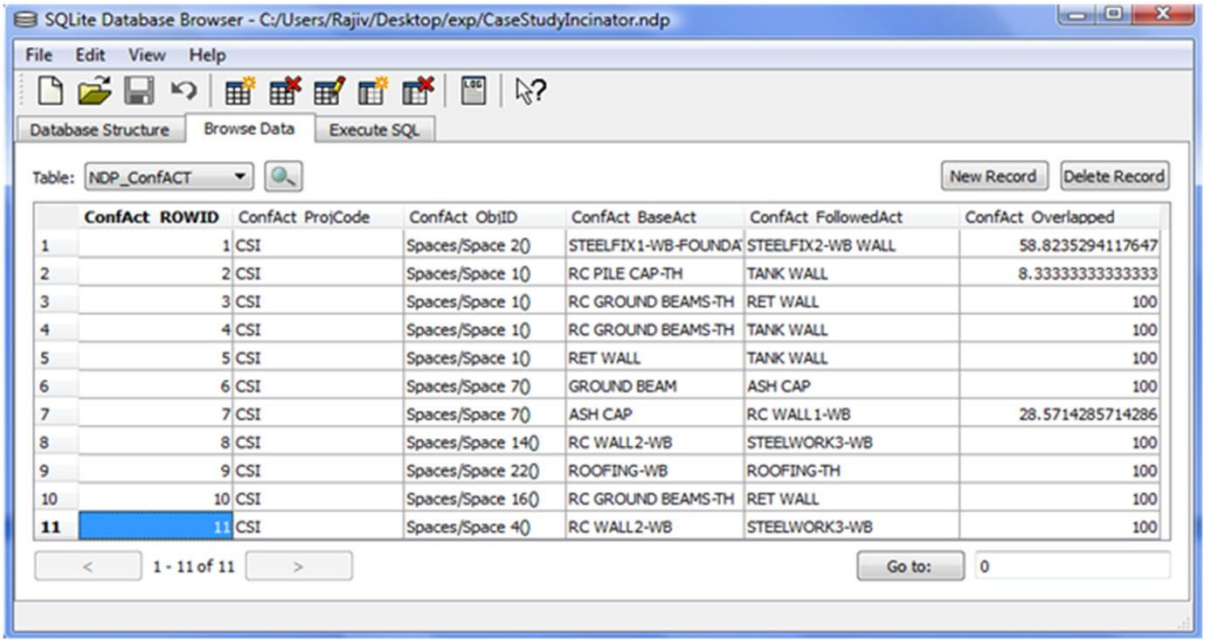


FIG 15: a workspace's congestion level changing from medium (blue) to low (green) for the same workspace used by 2 different activities at different project dates.



	ConfAct_ROWID	ConfAct_ProjCode	ConfAct_ObjID	ConfAct_BaseAct	ConfAct_FollowedAct	ConfAct_Overlapped
1	1	CSI	Spaces/Space 20	STEELFIX1-WB-FOUNDA	STEELFIX2-WB WALL	58.8235294117647
2	2	CSI	Spaces/Space 10	RC PILE CAP-TH	TANK WALL	8.33333333333333
3	3	CSI	Spaces/Space 10	RC GROUND BEAMS-TH	RET WALL	100
4	4	CSI	Spaces/Space 10	RC GROUND BEAMS-TH	TANK WALL	100
5	5	CSI	Spaces/Space 10	RET WALL	TANK WALL	100
6	6	CSI	Spaces/Space 70	GROUND BEAM	ASH CAP	100
7	7	CSI	Spaces/Space 70	ASH CAP	RC WALL1-WB	28.5714285714286
8	8	CSI	Spaces/Space 140	RC WALL2-WB	STEELWORK3-WB	100
9	9	CSI	Spaces/Space 220	ROOFING-WB	ROOFING-TH	100
10	10	CSI	Spaces/Space 160	RC GROUND BEAMS-TH	RET WALL	100
11	11	CSI	Spaces/Space 40	RC WALL2-WB	STEELWORK3-WB	100

FIG 16: Storage of data about conflicting activities and workspaces within the relational database

The system concurrently checks the temporal conflicts (schedule conflict process) and spatial conflicts (workspace conflict process) and visualizes the results for both processes at any date on the same screen. Figure 17 shows that there are two conflicting activities (EX Wall-WB-Down and Roofing-WB), which are progressing at the same time and their construction workspaces are clashing. By interactively clicking on the Gantt chart or running the full simulation using the time-liner, the tool displays in real-time the results of the conflict detected. To date in previous studies, similar approaches and tools that enable the real-time management of construction activities workspace could not be found. Once conflicts are identified, the resolution process can then be started. As explained earlier in the approach, the resolution stage is enabled by the analytical and interactive capabilities of the tool and conducted in a heuristic way with the involvement of project planners, using the criteria explained earlier. For the situation illustrated in Figure 15, the conflict could be simply resolved by moving the 'Roofing-WB' within its float, which is greater than the 'EX Wall-WB-Down' duration. However, as a result of making this change, a new conflict between 'EX-wall-WB-Down' and 'RC-wall-GL-RM-Clad' arises. In this new conflict, 'EX-wall-WB-Down' is a non-critical activity but 'RC-wall-GL-RM-Clad' is a critical activity. In this case, the remaining float of the 'EX-wall-WB-Down' was not enough to resolve the conflict and the delay of 'RC-wall-GL-RM-Clad' would delay the end date of the whole project. Therefore, the strategy to resolve this conflict was to change the workspace requirements. This could be obtained by selecting a suitable orientation for the progress of work for the activities. For example, EX-Wall-WB-Down can be started on one side of the building and RC-Wall-GL-RM-Clad can be started from the other side and once the two activities are completed on their respective sides, they can exchange sides without hampering each other's workflow. Also this resolution strategy could be enabled with the proposed approach and tool developed provided that the two activities are broken down into a number of smaller activities, which reflect the construction method and are linked to their corresponding workspaces.

The tool, in which the presented approach was embedded, showed that all processes involved in the management of AEWs (i.e. workspace generation and allocation, schedule conflict, workspace conflict, workspace congestion, workspace conflict/congestion resolution) are feasible and enable project planners to proactively manage workspaces and avoid clashes before the construction starts. Not only each process, making part of the proposed approach, is characterized by significant advancements compared to the approaches and tools found in the literature, but also the whole approach, being integrated with the traditional planning tool and developed within an nD environment, represents a major breakthrough. In fact, the system integrates BIM data and schedule data in a game engine environment within a 5D planning tool, where the management of workspaces is

conducted and rehearsed in a visual real-time mode. This is in line with the principles of nD project management where the ultimate scope is to give project planners the capability of rehearsing different construction options, before the construction starts, in order to enhance the efficiency and productivity of construction processes.

The pilot case study has shown that the deployment of the proposed approach and its prototyping in the nD planning environment are fully feasible and could lead to a significant improvement in site productivity, efficiency and safety as a result of the detection of conflicts in AEWs. In particular, this pilot case study demonstrated the successful implementation and testing of the processes and algorithms (i.e. workspace generation, classification and allocation of workspaces; detection of schedule and workspace conflicts; detection of workspace congestion, and resolution of conflicts) making part of the approach proposed and embedded in the IT prototype. In each of the proposed processes, there has been an advancement compared to the approaches found in the literature. The whole approach and its implementation provided an environment where workspaces could be managed in an integrated way with the traditional planning (i.e. CPM) and rehearsed prior to the onset of site works.

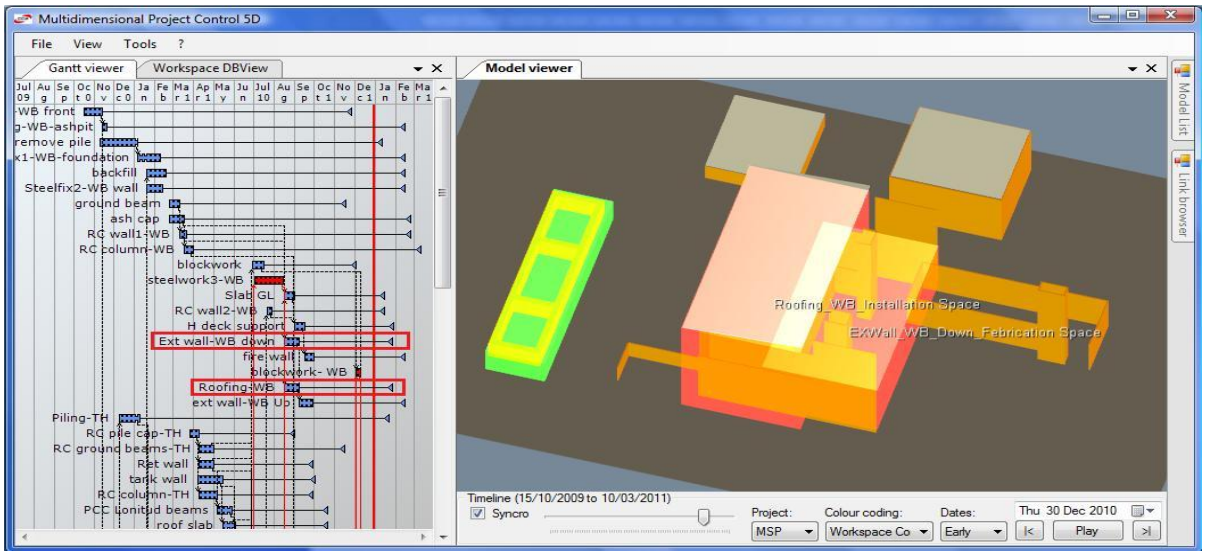


FIG 17: Detection of a conflict between 2 workspaces associated with 2 conflicting activities (i.e. Roofing WB and Ext wall-WB down)

5. CONCLUSIONS

This research tackles an important issue in construction planning and scheduling which is the management of activity execution workspaces (AEWs). Previous research projects have concluded that conflicts between AEWs could lead to productivity issues (e.g. delays, wastage) as well as safety hazards. In fact, AEWs are considered as one of the most important resources on site and previous literature has developed theoretical models and methodologies to tackle the problem of managing AEWs. This research advances these models and provides more pragmatic methods in term of how AEWs are generated, allocated and managed. The proposed approach allows the management of AEWs through integrating workspace management with the current planning process (i.e. CPM) and the BIM data in a 4D/5D environment and providing a visual and real-time rehearsal of the process of management of AEWs. This represented one of the major advancements over the approaches and tools found in previous studies, which have significant limitations such as: the management of workspaces was separated from the traditional scheduling process; the workspace generation and allocation were performed within the design authoring tools, and the geometric information was imported from non-BIM environments. This research presented other advancements in the way workspaces are generated and allocated and conflicts are detected and resolved. With the proposed approach, the workspaces (i.e. sizing and positioning) could be

generated within a 4D/5D environment in an interactive manners and could be allocated to activities or objects using '1 to n' and 'n to 1' relationships, while in previous studies workspaces were generated within the design authoring tool and allocated to objects. The process for the detection of conflicts between AEWs provided a more accurate way for the detection of workspace conflicts, through the use of the intersection test between bounding boxes, compared to previous studies, where the adjacency test was utilized. In addition, this research implemented two additional processes (i.e. the congestion process and the conflict resolution process), which although fundamental to the management of AEWs, were lacking in previous studies. A pilot case study of a complex incinerator project was used to test the approach proposed and an IT tool developed. The case study demonstrated that the proposed approach and the IT tool were feasible and could enable the management of AEWs in real-time mode, which reflects the dynamic nature of AEWs on construction sites. The proposed approach and its successful prototyping within a 5D planning environment represents a major milestone and is in line with the principles of nD project management, where the ultimate scope is to give project planners the capability of rehearsing different construction options before the construction starts. The assumption that all AEWs could be represented with prismatic rectangular shapes that are aligned along the three major axes is one of the limitations of the proposed approach. However, alternative bounding techniques and intersection tests were identified and will be implemented in future research in order to improve the accuracy of the approach proposed.

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