IDENTIFICATION, AND VISUALISATION OF CONSTRUCTION ACTIVITIES' WORKSPACE CONFLICTS UTILISING 4D CAD/VR TOOLS

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Abstract. This work addresses the problem arising on all construction sites: the occurrence of workspace interference between construction activities. From a site space planning context, this problem can lead to an inevitable roadblock to the progress of the scheduled construction operations. In real situations, when the spatial congestions occur, they could reduce productivity of workers sharing the same workspace and may cause health and safety hazard issues. The aim of this paper is on presenting a computer-based method and developed tool to assist site managers in the assignment and identification of workspace conflicts. The author focuses on the concept of 'visualising space competition' between the construction activities. The concept is based on a unique representation of the dynamic behaviour of activity workspace in 3D space and time.

An innovative computer-based tool dubbed PECASO (**P**atterns **E**xecution and **C**ritical **A**nalysis of **S**ite-space **O**rganisation) has been developed. The emerging technique of 4D (3D + time) visualisation has been chosen to yield an interesting 4D space planning and visualisation tool. A multi-criteria function for measuring the severity of the workspace congestions is designed, embedding the spatial and schedule related criteria. The paper evaluates the PECASO approach in order to minimise the workspace congestions, using a real case study. The paper concludes that the PECASO approach reduces the number of competing workspaces and the conflicting volumes between occupied workspace, which in turn produces better assessment to the execution strategy for a given project schedule. The system proves to be a promising tool for 4D space planning; in that it introduces a new way of communicating the programme of work.

1. Introduction

1.1. PROBLEMS IN VISUAL WORKSPACE PLANNING

Communicating the construction schedule and strategy of work among the project team members is a unique problem that takes place in most construction sites. This problem is even cumbersome as the built facility generates complex shapes of occupied site-spaces by the executed construction processes. The ideal solutions in traditional space-time planning techniques, have involved textual description, hand sketches with site layout templates, a number of graphical technologies, including bar charts, network diagrams, and 2D/3D scaled visualisation models Morris (1994). However, there are shortcomings of techniques in forming a visual representation of the construction execution workspace:

- Activity workspace execution: Considering the Gantt chart a favourable technique, planners are not capable of communicating visually the execution strategy and plan. In other words, the Gantt chart can be thought of as a '*what to do*' list and sequence of assignments concerning the construction activities. Cheng and O'Connor (1996) claim that, in field practice, construction planners have to interpret space information into poor visual descriptions. However, they do not seem to convey the dynamic behaviour of construction activities' workspace in 3D space and time.

- Mental rehearsal of site operations: Mawdesley et. al (1997) explained that Gantt chart technique does not furnish a *communication medium* on how the project activities on the construction site are to be executed. During the construction phase, the format of Gantt chart does not '*capture*' the visual interaction between the site operations. Consequently, the Gantt chart is not entirely adequate for rehearsing site operations, both in space and time.

- Loss of productivity: Productivity problems were investigated by Kaming et al. (1998) and showed that inappropriate workspace planning caused interferences between subcontractors. Many frequent visits by the workmen had occurred in some zones of the building, which resulted in work interruptions. There is evidence to suggest that workspace interference was a factor in decreasing productivity of work by 40%.

1.2. WHAT WAS NEGLECTED IN CONSTRUCTION WORKSPACE-TIME PLANNING EXERCISE?

Four important issues, therefore, were not highlighted in 4D workspace-time planning. They are:

1. Execution strategy representation: Traditional workspace-time planning methods, such as the space-time Chainage charts and layout motion diagrams, in their most general forms, are ambiguous. Construction planners often express the coordination of the planned schedules based on highly generalised conceptual space terms, such as North, South, East and West. Take an example of a construction planner conveying the execution of *Ground Floor Steel Columns* activity to begin from the East and progressing towards the West. The execution plan of such an activity is left to the workmen on the site. In such manner, work interruptions between site operations might occur Mallasi and Dawood (2001), especially in large complex construction projects, where the site space involves a number of constrained site operations.
2. Construction progress state simulation: The weekly visualisation technique used for the construction progress state is not realistic. Previous site layout planning applied such techniques from a factory/plant perspective that only featured linear patterns of direction for the produced work Zouein and Tommelein (1999). This research proposes a time-based 4D simulation of the activities execution workspace as the construction progress state changes dynamically.
3. Planning in three-dimension: Planning and analysis of construction workspace inside the building requires a three-dimensional approach. In some situations, for example, workspace conflicts could exist in different floors of a building project Cheng et al. (2002). Planners in some construction situations, such as the plant and equipment operation, need to analyse space three-dimensionally. External site layout techniques using the *Grid System* neglecting the analysis of spatial information in 3D, and applied 2D approach that only dealt with horizontal workspace conflicts.
4. Workspace-time connectivity analysis: In building construction, workspace-time connectivity analysis should be based on the intervals where activity execution workspace changes over points-in-time. Nowadays, the accepted view of most researchers is that space has properties related to things, explained Hillier (1996). Further, it is highly acknowledged that workspace behaviour is *'connected'* and relative to its defined properties. From one perspective, research in workspace planning did not provide workspace connectivity mechanism, so that to encapsulates the activity workspace behaviour at any point-in-time.

1.3. INCLUSION OF SPECIFIC VISUAL PLANNING FEATURES

Figure 1 indicates the two levels of project planning: strategic and operational. This study focuses on improving the conventional visual space planning features, utilised in the operational level. As revealed by Gardiner and Ritchie (1999), the planner systematically involves their technical judgment when making the decisions about what tasks will be performed, how the tasks will be performed, restrictions on how to perform them, and who will perform the tasks.

To some extent, these decisions are of a spatial nature and they do not appear to have the adequate visual representation in the traditional planning methods. There are four workspace planning tasks (Figure 1) that can be highlighted during project planning stages: (1) developing a space concept of the built facility (2) planning the workspace requirement based on the construction method and physical resources (3) the Critical Space Analysis (CSA) of workspace conflicts, and (4) the detail output of work execution strategy.

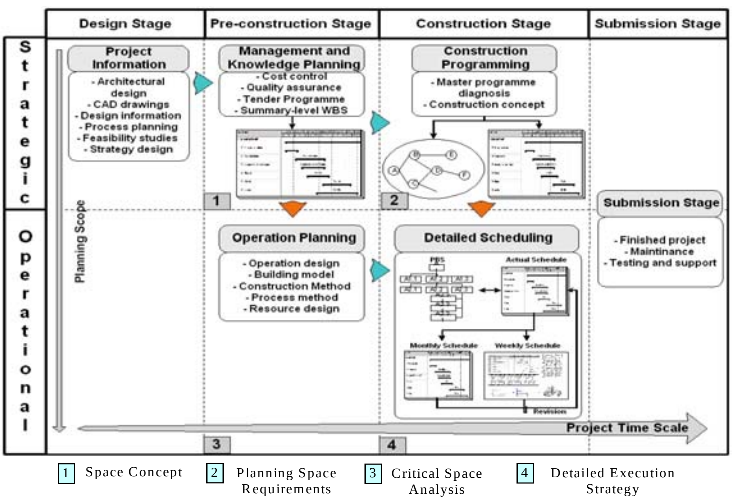

Figure 1. The two planning levels along the project stages including the four workspace planning tasks.

From the above, three main visual features are utilised to help in generating 3D visual representation of the activities workspace configuration. They are explained next.

1.3.1. Visualising Quantities of Work

Planners realise the importance of recording the progress of construction work at weekly intervals, then presenting it on a Gantt chart. This study, therefore, suggests three types for work rate distributions to be included in the 3D visualisation: *Uniform*, *High-Low*, and *Low-High* distribution. In this respect, the example shown in Figure 2 explains the significant correlation between the activity behaviour at a *point-in-time* (e.g. week six) and its completion, based on the three types of work rate distribution.

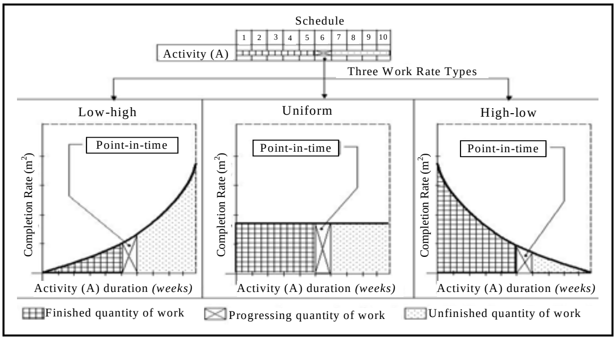

Figure 2. Activity-behaviour at point-in-time based on the three types of work rate distributions *(adapted from Mawdesley et. al (1997)).*

1.3.2. Workspaces Location and Overlap in Time

This concerns the representation of the physical location of workspace overlap between progressing activities across the horizontal and vertical space. This is a simple feature acquired from the Time Chainage overlapping method in one-dimensional space (1D + time). This representation, therefore, is suitable by means of giving an indication of where and when activities workspaces take place.

1.3.3. Execution Patterns (EP)

Planners analyse the execution strategy of work utilising Site Layout Motion diagrams Roberts (1998). This technique has been utilised in many literature to optimise the facility and site layout planning Zouin and Tommelein (1999). Equally, *EP* have been recognised by Riley and Sanvid (1997) as an important element in workspace planning. Visualisation of the motion diagrams technique and the *EP* is improved in this study by visualising the activity execution strategy in twelve *EP*.

This research project automates the above twelve *EP* in the 4D workspace planning. The overall combinations of these *EP* facilitate 4D visualisation of *'what-if'* scenarios based on *Progress of Work (PW)* direction and *Execution of Work (EW)* direction that are considered perpendicular to each other in Universal 2D Cartesian space (Figure 3).

Execution patterns are divided into two main categories. The first is the cardinal category (Figure 3, a), which occurs as a result of referencing the *PW* in the main cardinal directions and the *EW* perpendicular to it. This category produces four *EP* types (e.g. *PW* being executed from the West to the East, and the *EW* in both directions of North and South). The sub-cardinal directions are in the second category, which results in the eight *EP* types (e.g. *PW* being executed from North to South, and the *EW* being executed from the east-west accessed from northeast).

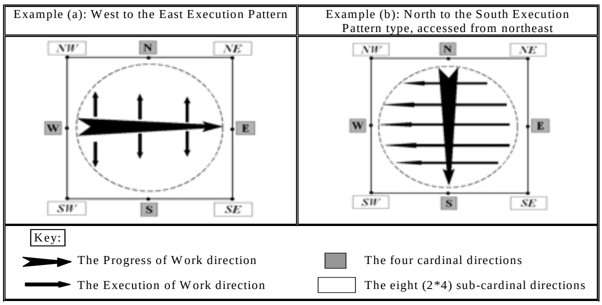

Figure 3. Illustration of two examples out of twelve EP types showing the mechanism of the PW and EW directions.

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2. Use of 4D Visualisation Technology

4D construction visualisation is becoming a popular technique in the construction planning. For the last fifteen years, both practitioners and researchers in construction management realised the great promise of such emerging visualisation techniques. Nowadays, the Construction Industry is becoming familiar with the uptake of 4D models to improve visualisation of construction schedules.

2.1. WHAT IS 4D-CAD VISUALISATION?

The most common about 4D-CAD visualisation is that it brings together the Gant chart schedule information (using any project scheduling software like MS Project®) and three-dimensional components of a construction project (using any CAD software). In 1987, the development of the first generation of 4D project scheduling were initiated by the engineering and construction firm Bechtel, in collaboration with Hitachi Ltd. and exploited the characteristics of the fourth dimension Rischmoller and Alarcón (2002). This firm, together with the Martin Fischer research team, from Stanford University, formulated the original technique and basis of visual 4D models, linking project schedule to the 3D CAD model to simulate the construction sequence.

Many researchers have addressed the concept of 4D-CAD in construction management. Although 4D visualisation does not quantify workspace conflicts between the construction processes, there were several research attempts in academia. Some examples can be found in the work by: Akinci et. al (2000a) who formalised construction workspace types and taxonomy; Akbas et. al (2001) identified 4D visualisations technique using *construction zone generation*. 4D-CAD space visualisation has also been identified throughout the Virtual Construction Site (VIRCON) project – a UK research initiative to develop a decision support system for construction project planning Mallasi and Dawood (2002); the technical survey of 4D-CAD research by Heesom and Mahdjoubi (2002) have benchmarked the construction knowledge, framework, and resources necessary to develop 4D models.

3. The Context for Workspace Competetion

3.1. RATIONAL FOR CRITICAL SPACE-TIME ANALYSIS (CSA)

The proposed CSA associates the visual features for workspace planning with the workspace competition. CSA deals particularly with analysing the space-time competition that occurs between construction operations. Therefore, CSA verifies the occupied workspaces by construction operation as competing together. The focus will be on how to quantify the nature of this competition, by assessing criticality of the workspace conflicts sharing the same space. The key assumptions are that the dynamic nature of workspace usage and change should be traced continually and so accommodate space connectivity in the fourth dimension. Once the space connectivity mechanism is established, it would then be possible to quantify the particular effect of critical spaces on the construction work progress.

Hence, the PECASO prototype was developed in this work to evaluate the outcome of the CSA. The 4D-CAD prototype integrates MS Project® scheduling application with the AutoCAD® ADT, via the MS Access® database. A graphical user interface (GUI) is built on top of AutoCAD, utilising the advanced features of Visual Basic for Applications (VBA) programming.

3.2. USE OF PAST CLASSIFICATION OF WORKSPACE CONFLICTS

For the purpose of analysing the workspace competition, the CSA mechanism must provide a reasoning mechanism, in order to minimise the criticality of a construction workspace. If a workspace conflict is expected to occur in a specific week, for example, questions, such as 'which space-types are expected to interfere during that week?' and 'what is the severity and knock-on-effect of such interference on the construction progress?' must be raised. By providing answers to these questions, the severity (i.e. degree of space-conflict) of the interference can be assessed and work execution adjusted, to allow increase in the productivity of workers on the job.

The theoretical approach for classifying the clash types, was developed by Akinci00a, space-time conflict taxonomy. The space-time taxonomy considers the conflicting space-types among the properties for classifying the clash types (Figure4). The outcome from this is a classification to include the main clash types like congestion, damage, and safety hazard. The result from this taxonomy is the detailed sub-clashes of the main clash types - because different level of congestion might exist on site.

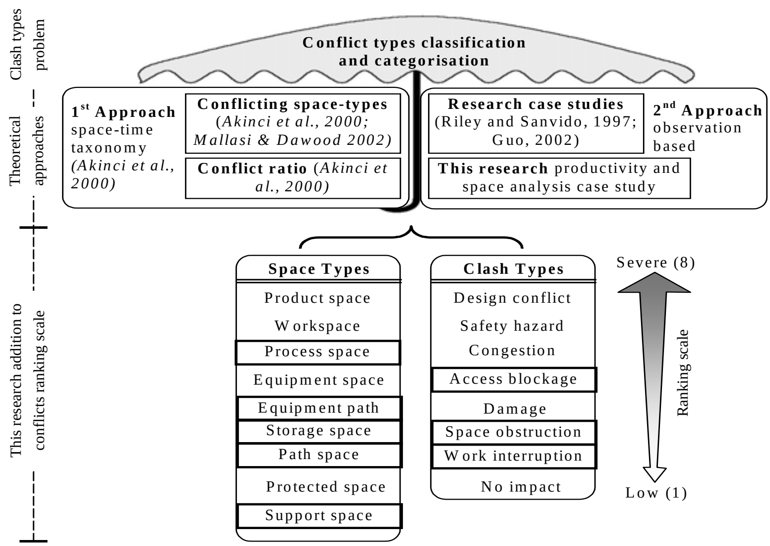


Figure 4. The theoretical approaches for classifying the ranking system associated with workspace conflicts.

As can be noticed in Figure 4, it has been practical in this research to rank the severity of workspace clash types. Some conflict types were added, such as work interruption, space obstruction and access blockage.

3.3. QUANTIFICATION OF WORKSPACE CONFLICTS

The immense amount of spatial data related with the analysis of activity construction workspace emphasises the importance of developing the CSA quantification approach. This is a complex issue and an on-going area of research that has started to receive some attention among the construction research community. The crucial point that is beginning to emerge is the determination of the variables associated with the measurement of space criticality, therefore minimising the severity of workspace conflicts.

This study developed the quantification approaches for CSA, based on literature survey presented in Table 1. The table shows clearly the gaps in the justification of an approach for obtaining the related space properties in critical space-time analysis; also in terms of linking the measurement of the space conflict to the criticality, or severity, of that conflict. As a consequence, there are currently no 'mature' benchmark quantification approaches to spatially analyse and enable a measurement of the performance of the construction schedule. The next subsection describes the proposed measurement and assessment for quantifying the workspace competition.

3.4. PROPOSED QUANTIFICATION METHOD

The proposed assessment of workspace competition quantifies the CSA value. In the interest of CSA, therefore, a multi-criteria evaluation function has been developed. The multi-criteria function will provide a measurement for CSA value, and so values the different criterion for the construction schedule and the workspace data. The multi-criteria function utilises weighting between the multiple criteria. Ramulu and Kim (2003) believe that multi-criteria function measurement is the first important step to formulating a solution to the problem.

The multi-criteria function comprises of the sum of five schedule and spatial related criteria, using various weight coefficients for each criterion. Figure 5 illustrates an abstract example for applying the calculation of the CSA value, based on Equation 1. This study has developed the multi-criteria function $f_A(scr)$ for the possible conflicts between A number of activities during monitoring period D (*per week*) as follows:

TABLE 1. The theoretical approaches for identifying space and clash types.

	Properties and quantification approaches								
Author(s) and date	Variables	Preserve CSA	Volume conflict analysis	Workspace types	Conflict details	Conflict ranking	Visualisation medium	Optimisation approach	Apply CPA criteria and priorities
Thabet and Beliveau (1994)	- Space Capacity Factor	No	Yes	No	No	No	CAD	N.A.	No
Akinci et al. (2000a)	- Conflict Ratio - Clash severity sub classification	No	Yes	Not all	Yes	Yes	4D-CAD	N.A.	Yes
Guo (2002)	- Interference Space Percentage - Interference Duration Percentage	No	Yes	Yes	No	No	4D-CAD	Manual rescheduling	Yes
Winch (2003)	- Spatial Loading	Yes	No	Not all	No	No	4D CAD/VR	Brute force algorithm	Yes

$$\underset{A}{f}(scr) = vw1.\underset{D}{f}(co) + vw2.\underset{D}{f}(r) + vw3.\underset{D}{f}(no) + vw4.\underset{D}{f}(st) + vw5.\underset{D}{f}(cr) \quad (1)$$

where $f_{(scr)}$ = the project schedule space criticality calculated value;
$f_{(co)}$ = the criteria function for the percentage of conflicting workspace.

where

$$f(co) = \frac{\sum TotVolConflict}{\sum TotVolOccupiedSpaces} \quad (2)$$

$f_{(r)}$ = the criteria function for the total number of workspace conflicts with respect to the rankings; $f_{(no)}$= the criteria function for the total number of conflicting activities; *f(st)*= the criteria function for the conflicting space types; *f(cr)*= the criteria function for the critical activities (1 for critical and 0 for non-critical); vw_i = the weighted coefficients for each criteria in the function $f_A(scr)$.

The weighting coefficients vw_i (sometimes referred to as variable weights) are an estimated measure for each criterion governing a priority scheme. By doing so, the performance of the value of $f_A(scr)$ function can be assessed. Although these coefficients could be obtained through trial and error, they could also be *user-defined* values from the project planner. This is most preferable, as explained by Chang et. al (2002), because the value for each weight will be given, according to the 'relative importance' of the criteria attached to it.

Generally, the sum of these weights should satisfy the following conditions:

$$vw_{(i)} = vw_{(1)} + vw_{(2)} + vw_{(3)} + vw_{(4)} + vw_{(5)} = 1 \quad (3)$$

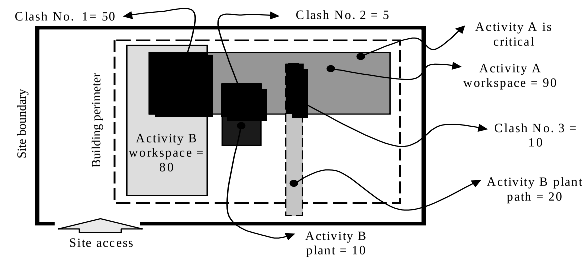
and

$$0 \le vw_{(i)} \le 1 \quad (4)$$

The values for vw_i in Equation (3) are the measures of priority for each criterion that is chosen by the project planner. These values range from Zero to One: more important criteria will get a higher weight, and less important criteria will get lower weights.

3.5. IMPLEMENTATION OF TIME-BASED 4D WORKRATE SIMULATION

A key concept in the visualisation of workspace competition is the technique for simulating construction product and processes in a time-based fashion. The time-based simulation mechanism involves the construction progress state in space-time and is done dynamically. Research by Kamat and



Clashes	Clash description	Total occupied volume	f(co)	f(r)	f(no)	f(st)	f(cr)
1	Workspace A and workspace B *(work interruptions)*	90 + 80 + 10 + 20 = 190	50	1	2	4	1
2	Workspace A and B equipment spaces *(space obstruction)*		5	2			
3	Workspace A and B path spaces *(damage)*		10	3			
Totals:		Final *f(co)* value = (50+5+10)/190 = 0.34		6	2	4	1
Applying user-defined (vw_i) weights to normalise each criteria:		0.34 * 0.8 = 0.27		6 * 0.1 = 0.6	2 * 0.1 = 0.4	4 * 0.1= 0.4	1 * 0.1= 0.1
Space criticality value $f_{(scr)}$:		0.27 + 0.6 + 0.4 + 0.4 + 0.1 = 1.7 *(severe critical space)*					
4) CSA scale range for the criticality values, and legend							

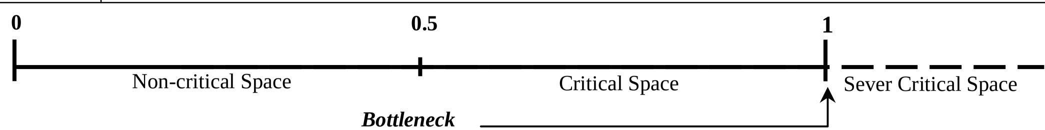


Figure 5: Examples showing the developed approach for calculating the CSA value of $f_{(scr)}$

Martinez (2001) confirmed that 4D time-based simulation was suitable and highly scalable in designing a generic 4D visualisation system. Arguably, representing the activity-workspace change in time is an abstract simulation mechanism to process the change of activity-workspace behaviour. This way, 4D time-based technique becomes a snapshot of time and workspace simultaneously. The mechanism utilises a visualisation clock as a controller (*dates and times*) for altering the time forward and backward (Figure 6).

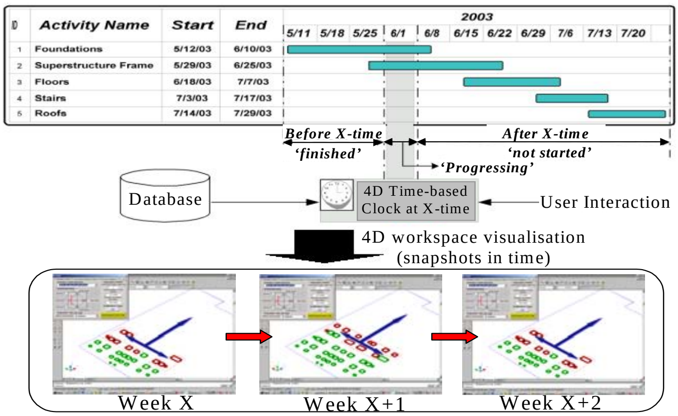


Figure 6. The 4D time-based simulation and the clock control at X-time.

The time-based concept simulates the *Quantities of Work per week* ($QW_{(prog)}$) during three time-based frames (or intervals). The first time-based simulation frame (Figure 6) visualises the '*progressing*' activity-workspace during '*X-time*', based on Equation (5).

$$QW_{(prog)} = QW_{(tot)} / AD_{(tot)} \quad (5)$$

Where $QW_{(tot)}$ = total quantity of work value obtained from the database; and $AD_{(tot)}$ = total activity calendar duration obtained from the schedule information.

The second time-based simulation frame obtains the *Quantities of Finished Work* ($QW_{(fin)}$) from previous week(s) '*before X-time*', which represent the state of completed work. Equation (6) is utilised in identifying this amount of $QW_{(fin)}$.

$$QW_{(fin)} = QW_{(prog)} \text{ (thisMonWeek-Week)} \quad (6)$$

where $QW_{(fin)}$ = quantity of finished work calculated during *X_Monitoring_Week* (*X_MonWeek*)

The third time-based simulation frame deals with activities that have not started yet *'after X-time'*, and also determines any *Unfinished Quantity of Work* ($QW_{(unfin)}$) for progressing activities (Equation 7).

$$QW_{(unfin)} = QW_{(tot)} - (QW_{(fin)} + QW_{(prog)}) \quad (7)$$

where $QW_{(unfin)}$ = quantity of unfinished work calculated during *X_Monitoring_Week* (*X_MonWeek*).

4. Assignment of Workspace

4.1. EXISTING TECHNIQUES

Sirajuddin (1991) and Thabet and Beliveau (1994), propose that construction workspace is a combination of resource gangs, including their equipment and tools. This is a situation where resource gangs operate and manoeuvre equipment within the direct workspace at the activity location. Another typical case is similar to pouring concrete into pad foundations, using a concrete mixer and a concrete vibrator. Sirajuddin suggested that, to some planners, these workspace dimensions could be obtained either from their previous work experience, or from data, such as equipment and tools manuals. Similarly, Akinci et. al (2000b) incorporated a concept for assigning project-specific space requirements associated with a construction method model into the 4D WorkPlanner Space Generator. The positional information about space was modelled using an allocentric representation (such as, roof scaffolding outside or inside a building envelope).

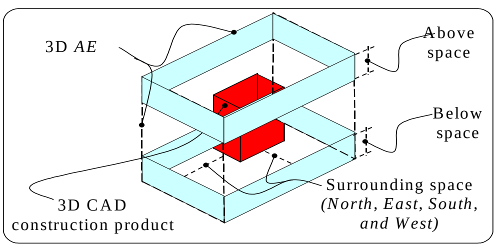


Figure 7. The three workspaces properties associated with the 3D *AE* around a construction product.

To specify the workspace requirement in a dynamic way, while satisfying a set of spatial dynamics and change of workspace usage over time intervals, is a difficult problem as there are many alternative space strategies to apply on the logic of work execution. Therefore, it was decided in this research to design the construction workspace based on the *Approximation Envelope*

(AE) that uses a 3D Box to represent the activity workspace (Figure 7). The *AE* technique improves previous research efforts, by including the characteristics of workspaces like: above, below, and surrounding (*North*, *East*, *South*, *and West*).

4.2. CAPTURE OF DYNAMIC REQUIREMENTS FOR WORKSPACE

The assignment of workspace based on the 3D *AE* provides the planners with generic capture of different workspace requirements, according to the nature of the construction activity. The application and concept of the 3D *AE* for workspace representation is provided in the example in Figure 8. The example shows two construction product groups 'A' and 'B', and the plant associated with them (Figure 8, a and b). Even when the location and position of the products associated with the construction activity are changed, the assignments of the workspaces are dynamically reconfigured utilising the 3D *AE* (Figure 8, c and d).

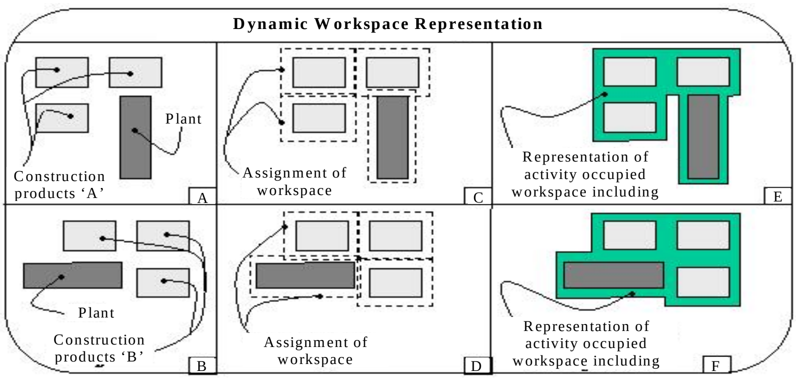
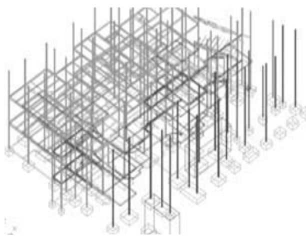
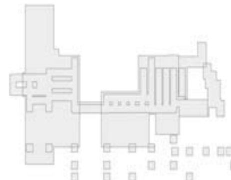
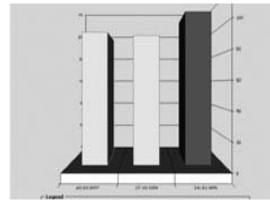
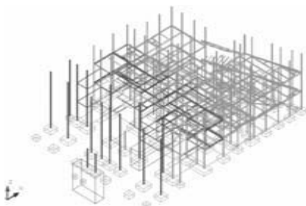
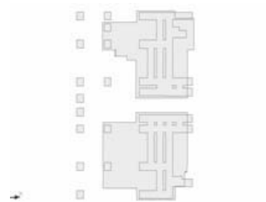
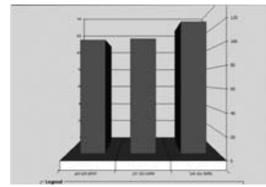
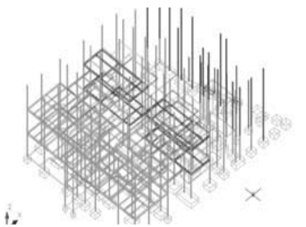
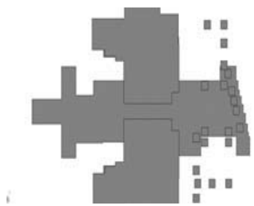
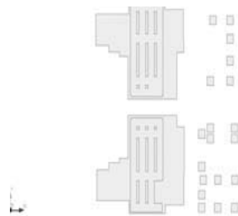
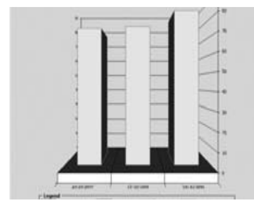


Figure 8. Representation of dynamic workspace configuration utilising the 3D *AE* concept.

5. Experimental Results of Workspace Competition

The author utilised the PECASO 4D tool to experiment with CSA results and hence evaluate the workspace competition concept. The CSA values are obtained after running three scenarios utilising the PECASO 4D simulation approach. It was important to consider in the analysis the occupied workspaces by the resources on site like plants, material paths, and storage areas. On a weekly basis, the simulation results were exported to the MS ACCESS database for future evaluation of the space criticality function $f_A(scr)$.

TABLE 2. Three weeks of workspace variation and minimisation of CSA values $f_{(scr)}$ for three experimental 4D simulation runs

Run No.	4D Visualisations	Top View pf Site Space Usage	Top View of Site Space Conflicts	CSA Chart Report
1) *EP*: North-South				 Original CSA ≈ 1.08
2) *EP*: East-West				 Max. CSA Value ≈ 1.21
3) *EP*: West-East, access South-West				 Min. CSA Value ≈ 0.83

A typical experimental illustration for minimising workspace conflict is shown bellow in Table 2 and applied on the School of Health project case study. The simulation began with a max CSA value of 1.08 representing the actual project schedule (run No. 1). The alteration of the above variables for minimising workspace conflicts indicates a reduction of CSA by 0.25 less than the original schedule (run No. 3). The reason for this minimisation is due to the variation in *EP* type for the Ground Flooring Concreting activity (North to South), while the rest of the activities were progressing from the West to the East. At the same time, the occupied workspace by the plant moved to a space free of congestions and reduced the total number of conflicting space types *f(st).*

6. Summary

This paper introduced the workspace competition as a new concept for minimising workspace congestions occurring on construction sites. Visual planning features like: twelve execution pattern types, three different work rate distribution types, and time-based QW simulation were identified and implemented in the developed 4D visualisation environment. The design of a multi-criteria function was the core of the PECASO approach for evaluating the CSA value. Based on the experimental results, the PECASO CSA approach is expected to increase the planner's awareness for workspace planning and become more confidence when using 4D visualisation for communicating the project plans. One could argue that the advancements in 4D space-time conflict analysis relies on capturing the dynamic nature of construction site operations. The results also suggest possible future use of the proposed technique in 4D workspace planning.

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