2-1-2014

Spatial temporal measures: a new parameter for planning

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The American University in Cairo

School of Sciences and Engineering

SPATIAL TEMPORAL MEASURES: A NEW DIMENSION FOR PLANNING

A Thesis Submitted to

Construction and Architectural Engineering Department

in partial fulfillment of the requirements for
the degree of Master of Science

by Abdel Hady Ossama Ahmed Hussien Hosny

(under the supervision of Dr. Khaled Nassar)
July/2013

DEDICATIONS

I am dedicating this thesis to my beloved parents, my beautiful wife and my daughter, whom are the source of my inspiration, encouragement, guidance and happiness, and who share my goals and aspirations May ALLAH Bless and Protect them and give me the strength to ever repay them for their kindness.

ACKNOWLEDGEMENTS

First and foremost I would like to thank Allah for his gracefulness for providing me the enough patience, courage and wisdom for finishing my masters.

I cannot ever also forget to thank my father, first person to thank after Allah, my mother and brother for their continuous support and tolerance throughout my masters. They have shaped my personality and are the main reason behind who I am today.

I was an honor have Dr. Khaled Nassar as my advisor, as I would also like to thank the rest of the AUC faculty for their continuous support and guidance.

I also have to thank Dr. Ahmed Al Hakim, Dr. Mohamed Nour, Eng. Abdel Rahman, Eng. Mohamed Hussien, Eng. Zeina Adly and Eng. Hazem Hosny for their efforts in finalizing my thesis.

I can't forget also to acknowledge the help of Hosny Group and Dar Al Mimar Group for providing me with the resources needed.

I also can't forget to thank my grandfathers' Dr. Abdelhady Hosny, Dr. Ahmed Hosny and Commander Adel Soliman for inspiring me and being my role models.

Leaving the best for last always, I would like to thank my wife and my daughter whom I owe everything. They are my muses, my power and my main passion. They have been with me at each step and for that I am eternally grateful.

ABSTRACT

The American University in Cairo

SPATIAL TEMPORAL MEASURES: A NEW DIMENSION FOR PLANNING

Submitted by: Abdel Hady Ossama Ahmed Hussien Hosny

Under the Supervision of: Dr. Khaled Nassar

With the increase complexity and competition in the construction market, contractors are forced to deliver larger scale projects in shorter durations. In order to do so, more concurrent activities are scheduled durations are crashed. Having a large number of concurrent activities with various crews increases the risk of workspace conflicts on sites, eventually affecting the productivity, time, cost and quality. Thus, there is an increasing attention to identify measures that are able to detect and analyze the possible workspace conflicts that would occur in a project in the planning stage before execution. Currently, practioners perform workspace analysis via expert judgment manually, which usually fails when the number of objects increases in a project. There have been previous attempts to creating frameworks to generate the workspaces and estimate the clashes. However, most studies did not provide a complete solution covering the whole process from the automated generation of the workspaces till the evaluation of the clashes. Also, the previous attempts clearly underestimated the value of the clashes giving a false indication of the true problem.

Accordingly, this research proposes a new complete framework to detect, analyze and evaluate spatial temporal interferences in a project. The developed framework consists of 4 main modules: 4D Model Generator, Workspace Generator, Clash Detector and Clash Evaluator. These modules present methods for automating the generation of workspaces, clash detection mechanism and present a two level check clash magnitude estimator. The first check is performed on the days to identify the critical one that exceed the allowable tolerance levels, and the second check is performed on the activities to provide the user with a decision support system to optimize the clashes in a project.

This study has been verified and validated. The first was by creating a test model, where the calculations were demonstrated and have led to the desired optimum solution. The latter attempt was by applying the framework via a developed software tool to a residential building as case study. The results showed improvement of an average of 20% in the first level check results. The results were presented to experts in the construction field whom have praised the work and acknowledged its usefulness.

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GENERAL DEFINITIONS AND ILLUSTRATIONS

- **Workspace:** The volume needed on site for a specific activity to be executed on a targeted element.
- **Clash:** the overlapping that happens between more than one workspace as a result of them requiring the same space at the same time.
- **Clash Severity:** a quantification to differentiate between the clashes based on the size of impact they may have in the site (form of classification and ranking)
- **Visual 4D Model:** the current 4D models in the market which explain where and when the element is being built, but don't explain how.
- **Constructible 4D model:** the modification of the 4D model to account for the method statements and show the different productivity rates, starting points of construction and governing axis.
- **UML Diagram:** a unified modeling language diagram to describe the relations between the main classes in a database
- **Space-Loaded Model:** a constructible 4D model where each element has been assigned the proper workspaces, and has been decomposed to display the exact execution quantity and space on a daily basis.
- **Level 4 Schedule :** the detailed construction schedule according to the CSI master format.

CHAPTER 1:

INTRODUCTION

CHAPTER 1: INTRODUCTION

Time is an important aspect to all industries, especially in construction. Every contract stipulates a clause for time, where it either describes either the incentive for finishing early or the penalties for not sticking to the target. Obviously, time is not the only factor, contractors are also obliged to achieve their scope within the estimated budget and with the targeted level of quality, and the relation is usually as shown in Figure 1. However, with the rising complexity of design, challenging delivery date, higher quality expectations and increasingly tight budget, it is getting harder to achieve those goals.

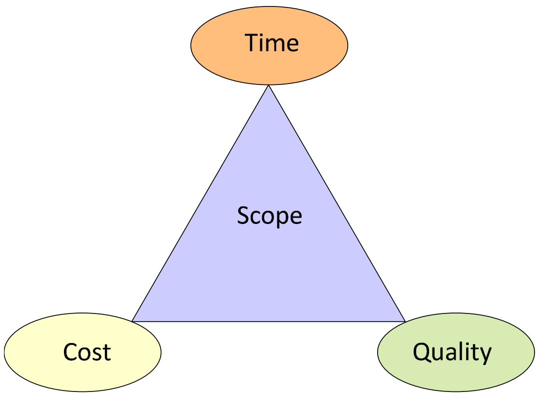


Figure 1 Time / Cost / Quality Triangle

1.1 Problem Statement

Developers are constantly pressuring contractors to deliver projects in the shortest duration possible. This means that the contractor will schedule more activities concurrently and lean on more subcontractors. This translates to a larger daily resource rate and accordingly needs more control. Therefore, contractors must be able to plan well for the project before execution. One of the main factors that they should consider is space planning. Previous literature (Akinci, Fischer, and Kunz 2002; Mallasi 2006; Akinci et al. 2002; Wu and Chiu 2010; Song and Chua 2005; Darwiche, Levitt, and Hayes-Roth 1989) has proven that lack of space planning leads to a huge number of space-time clashes. A space-time clash occurs when two or more workspaces share the same location at the same time. A workspace is defined as the estimated space needed by the resource to be able to perform its intended function. Workspaces contain spatial and temporal characteristics, they change shape with time progressing. There are many types of workspaces in any construction project.

Accordingly a clash is not a permanent issue, it would end once the resources needing the clashed workspaces have finished the job, yet the effects suffered due these clashes could be considered permanent. Space-time clashes affect most of the project aspects especially time and cost. It has been recorded in some projects that the productivity loss due to space-time clashes has reached to forty percent (Mallasi 2006). Thus, the need for a framework that can detect, estimate and analyze space-time clashes in the planning stage is growing greatly in the construction industry.

1.2 Scope of Work

The main aim of this study is to identify a new approach for planners to be able to analyze their schedule in the planning stage, and determine the possible space-time conflicts that could occur and have the enough data to prepare an alternative solution for them. The objectives of this study are as follows:

1. Define workspace types and the method for representation.
2. Define the possible clashes that would appear and quantify their severities to differentiate between the different space-time clashes.
3. Develop a multi-criteria function that will estimate the possible impact of the space-time clashes.
4. Develop the analysis tools needed to suggest the preferred optimizations

1.3 Study Methodology

This section explains the study methodology adopted in this research. This study shall pass by 4 main stages as shown in Figure 2 below, a 4D's method developed by the author: define, design, develop and deploy.

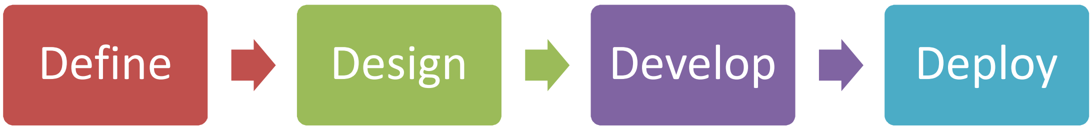


Figure 2 Research Stages

1.3.1 Define Stage

The define stage is the first stage in the research which shall deal mainly with the literature review and analysis of previous research in the same field. Since the topic of space-time planning is still new, the literature review shall be divided into a state-of-the-art section where it would describe the topics covered in this study. The other section would be the armed literature that would describe the previous work done by researchers to tangle the issue of space-time planning and clash detection. The literature review shall cover the following topics:

- Planning for contractors and the current short-coming in regards to space-time planning.
- Formulation of the 4D schedule as the first step for simulation and space planning.
- State-of-the-art literature review to describe:
    - Workspace generation and definition
    - Clash detection and definition
    - Clash estimation
- Armed literature review to discuss the previous work done.
- Analysis of the above

1.3.2 Design Stage

The design stage will cover the author's effort in designing the new framework that will discuss the new methods for workspace generation, the new types of workspaces, the research's clash detection mechanism and the new multi-criteria function for clash magnitude estimation.

1.3.3 Develop Stage

For the sake of this research, a software tool will be developed to generate the different workspace types, execute the clash detection mechanism, and estimate the conflicting volumes between the workspaces. The software tool is belt using the Python language on the Blender 3D graphical software.

1.3.4 Deploy Stage

In order to validate the framework developed and the software tool designed, the study will be tested twice: on a specially design test model and on an actual case study. The results of the case study will be presented to construction experts, whom will evaluate them to measure their usefulness.

CHAPTER 2:

LITERATURE REVIEW

CHAPTER 2: LITERATURE REVIEW

Many projects in construction industry undergo delays due to workspace interferences. Understanding the causes of the workspace interferences would help in decreasing the problem and contribute to an improvement in management and productivity, inevitably leading to country economic development. This chapter introduces the following subjects: Time planning and its importance in the construction industry, the current planning tools and their shortcomings in relation to workspace detection and analysis, the creation of the 4D schedules, workspace and clash definition and the previous work done by researchers.

Planning is one of the most important steps in any project. Planning is an activity that is present in all project aspects, such as scope, design, procurement, cost, risk, and quality management. From the forty two processes in the five process groups (initiation, planning, executing, monitoring and controlling) of the project management, there are twenty processes for planning, which constitute forty eight percent (Institute). In construction projects, the development of a good construction plan leads to the well estimation of the budget, resources and schedule of work. It also ensures the correct estimation of time and the utilization of resource in order to ensure achieving the project objectives. In addition the construction plan can help in the proper estimation of the bottlenecks and accordingly the completion time.

2.1 Planning for Contractors

Planning is not just the state of creating the to-do list for a project, it deals with the policies and constraints stated in the contract or by normal practice to create well integrated network that considers the interrelations and dependencies from all project stakeholders. Thus, the team is creating a responsive decision support system that is able to map the most optimum method of achieving the target. The planning process is an iterative process, it is updated and refined every time a new input appears, and hence the planner must insure that the output of all influential parties is considering in every step of the project lifecycle. Cost and time plans are considered the primary planning steps (Darwiche, Levitt, and Hayes-Roth 1989). Planning can be developed in different stages: corporate strategic plans that assist the developer in determining the appealing factors for the client and market satisfaction, pre-tender plans that assist the contractor in determining the best action for long-term items such as equipment rental or purchase, pre-contract planning that is a factor in determining the most efficient contract to manage the project, and the construction plan which is most important to the contractors (Frimpong, Oluwoye and Crawford 2001; Park and Peña-Mora 2004). The construction plans uses the following inputs to usually generate the following outputs as shown in Figure 3 (Hosny 2011):

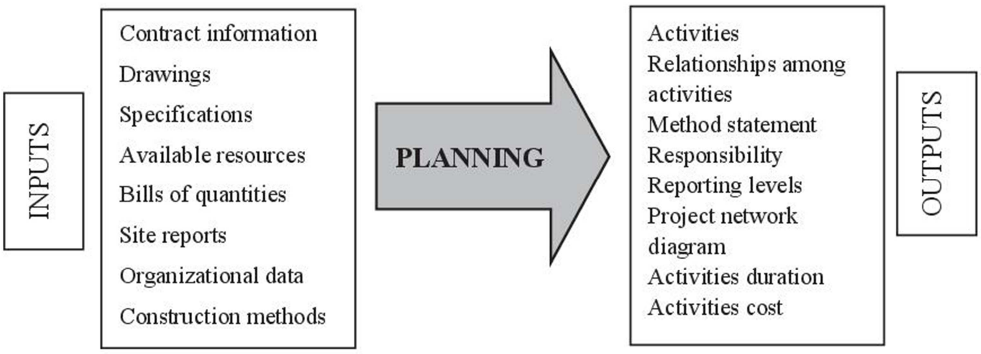


Figure 3 Inputs and outputs of the planning stage (Hosny 2011)

Once, the planner is successful in creating the construction plan, he/she then bears the responsibility of the continuous updating and reporting to the project team to present the progress of the plan and any new variables appearing. One would realize that the calculation of the workspace and detection of clashes is not one of the common inputs of creating the time schedules.

2.2 Current Planning Tools and their Shortcomings

The successful communication of the construction schedule to the site is as important as its design, as it ensures the clarification of the proper scope, work packages, targeted time and budget (Akinci, Tantisevi and Ergen 2003; Ganah, Bouchlaghem and Anumba 2005; Kähkönen and Leinonen 2001; Liston, Fischer and Winograd 2001; McKinney and Fischer 1997; Zhang, Anson and Wang 1997). It also should show the integration and interference between each crew and the other to guarantee the harmony and coexistence, without any impacts on the project objectives. However, the current communication tools used have shown some shortcomings in this area and these problems are getting bigger due to the increasing complexity and demanding construction market.

The current tools are site layouts, hand sketches, presentations and textual descriptions (Kamat and Martinez 2001; Morris 1994; Woodward 1975). Examples of these are the Gantt chart which a favorable method. When considering the Gantt chart as a communication tool, one would find that it is very useful to list the sequence of the activities; however it lacks the proper visual representation failing to convey the dynamic nature of the activities (Woodward 1975). Moreover, the Gantt chart does not explain the interaction between the construction activities (Mawdesley, Askew and O'Reilly 1997).

Not only that, but also this communication tools usually do not reach the level of detailing the construction plan for activities. To further clarify, let's take an example of planning the activities for foundation construction of a building, which consists of a number of isolated footings. Typically, the planning process would produce a Gantt chart with the following activities as shown in Figure 4 :

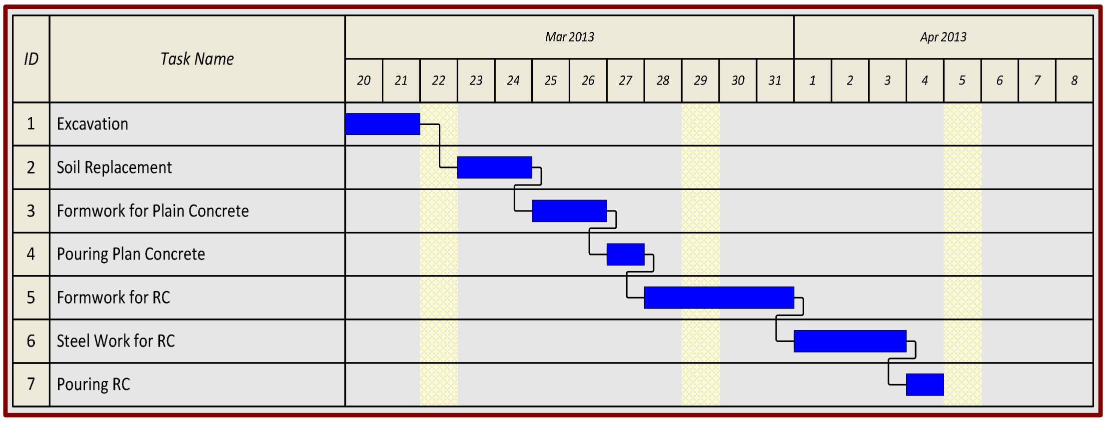


Figure 4 Example of the Gantt chart

The first observation would be that Gantt chart did not explain to the execution team the followed action plan, should they start from inside outwards, from the right side to the left side or how? Thus, this area is left to the decision of the workmen on site. Here is the problem starts, since each crew work with their own methodology and interferences in site increase (Mallasi and Dawood 2001).

Moreover, the use of the site layout techniques based on the 2D grid approach have neglected the implications that could happen due to the third dimension (Cheng and Yang 2001). Observing Figure 5 (Mallasi 2006), the man fixing the partitions is obstructed by the existing ducts. Such interruption was not shown with the current communication tools on the 2D level.

Figure 5 Example of interruption in the 3D level (Mallasi 2006)

Concluding, as explained by Hillier (1996) “space has properties related to their entities” the industry is now in great need to a framework that is able to capture the changes in the workspace execution throughout intervals of time, detect the conflicts and estimate the severity before construction.

2.3 Formulation of the 4D schedules

The first step to rectify this issue, to find a successful communication tool that would be able to capture the workspace changes was the production of the 4D schedules. A 4D schedule is a communication tool which connects the graphical aspect of a 3D model, example the Cartesian coordinates X, Y and Z to a forth parameter. This parameter could be anything that the user requires, cost, resources, etc. In this case, the interest is in considering the forth parameter to be time (Koo and Fisher 2000). This is done by linking the 3D graphical model producing from design software such as AutoCAD Revit to the chronological data produced from a CPM software such as Primavera, through a third-party technology, as shown in Figure 6 (McKinney et al 1996).

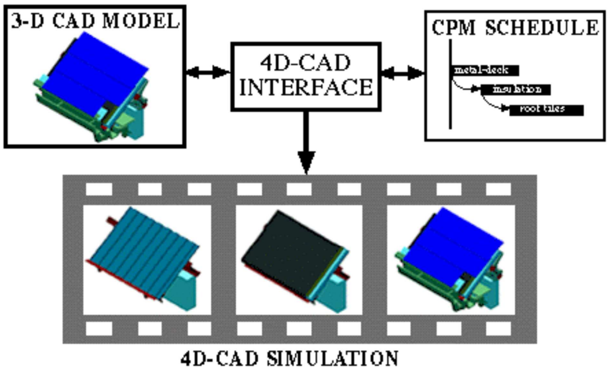


Figure 6 Mechanism for creating 4D model (McKinney et al 1996)

The 4D tool has proven to have many benefits such as:

- Better coordination between trades in the design phase.
- Identify the possible construction problems early in the planning phase.
- Better communicate the construction schedule to the execution team
- Minimizes the effort of transforming 2D drawings into reality, and saves time while issuing the shop-drawings
- Provides all project stakeholders with a common language where they are capable of discussing and optimizing the execution strategy and construction sequence. Moreover, this type of tool helps in detecting possible construction problems earlier in the planning stage before construction (McKinney et al 1996).

One of the early attempts to create a 4D schedule was in the "San Mateo County Health Center campus expansion". The San Mateo project was a multi-phased project scheduled for final completion in 1999. It involved over 280,000 square feet of new building floor area and over 40,000 square feet of remodeled space. This attempt was successful in producing the 4D animation; however the model was a mere representation of the model. This means that when the users needed to modify any data related to the graphical model or the scheduling data, they had to start the process again from scratch. This presented a challenge in order to produce alternative schedules and perform sensitivity analysis (McKinney et al 1996).

Currently, with the advancement in the technology of the 4D animation, it is easy to produce a "Collaborative 4D model". Main influential researches are those works of Clayton et al (1994), Norman (1988) and Smith, et al, (1982) in producing the concepts of the "interpretation" and "user's concept model". The "interpretation" concept is that of realizing that each graphical object has its unique characteristics which are the schedule data. The "user's concept model" concept is that vision of the functions and tool that could be needed by schedulers to be able to create understand, analyze and link the time schedules to the 3D models. Also, this concept in addition to the "interpretation" concept allowed planners to select the object, and assign it with its unique temporal properties (Clayton et al. 1994).

As much as no one could deny the many positive outcomes that have come from the creation of the 4D schedules, except it imperative to say that most its uses have been commercial, and not many researchers have attempted to utilize it in the workspace analysis and conflict detection.

2.4 Workspace Definition

Workspace is defined as the required space around any building element that would allow the appropriate execution of a certain activity within the planned time and allocated budget. Basically any workspace is a transparent volume around the subject element for the crew, equipment and feasible maneuvering space (Thabet and Beliveau 1994; Sirajuddin 1991). The size of any workspace could be attained from global standards or from equipment manuals that would specify certain surroundings for normal operation (Sirajuddin 1991). For example, there are safety manuals which would enforce a minimum area for each worker based on the type of construction, confined space or not (Safety, Health and Welfare on construction sites - A training manual 1995). There are also regulations for heavy equipment such as cranes, which would prevent any operation within certain radius around them (Levine 2008). Also, the method statements for the activities could be a good source that would help practioners in estimating the workspace size of activities.

There are many variables affecting the workspace of any element:

- **Shape and size of the element:** the workspace size and shape would be relevant to the size and shape of its element. Examples of the workspace representations of different building elements are shown in Figure 7.

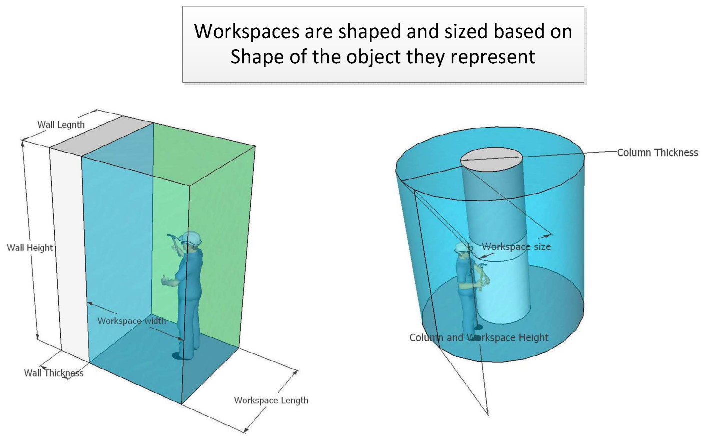


Figure 7 Workspace representations for different building components

- **Rate and Duration of the activity**: based on the rate of the activity execution, the workspace would adapt itself to accommodate for the production size. For example, the workspace size when half of a wall is executed is greater than if only a quarter is executed. Examples of the workspaces' sizes changing due to activity execution rate are shown in Figure 8.

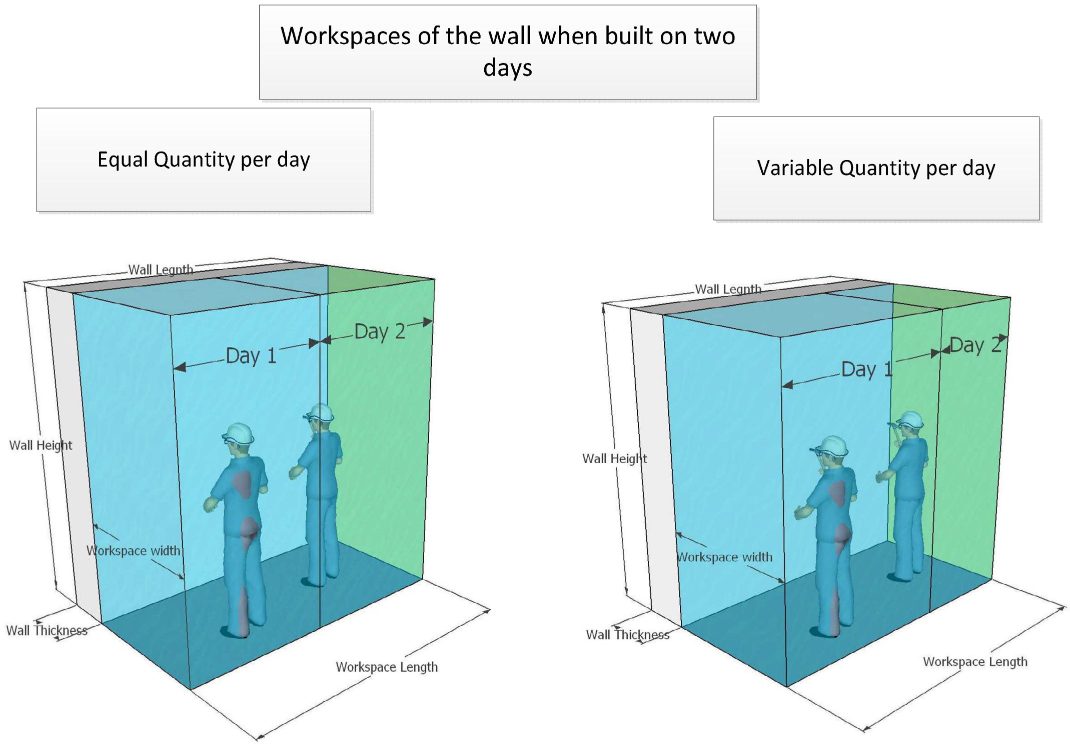


Figure 8 Workspace representations for different activity execution rates

- **Start point and Direction of construction**: Since the workspace depended on the rate and the duration of the activity, then logically it would depend on the starting point of the execution and the direction the construction shall move in. An example is shown in Figure 9, when a contractor decided to construct columns in the site from the east (left) side and working his/her way to the west (right) side, the workspace accordingly appeared in the east side first.

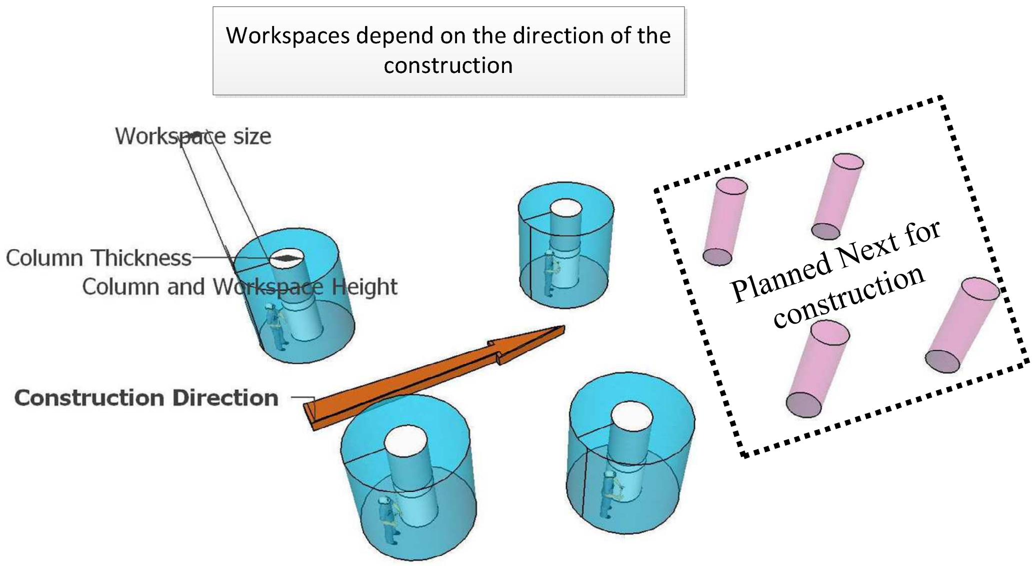


Figure 9 Workspace representations for different construction directions

- **Construction method (governing axes):** based on the construction method, quantity and size of the building component may vary. Thus, the workspace representing it will vary as well. For example as shown in Figure 10, when the construction method was to segment the wall vertically, the workspace was divided among the duration; but when the wall was segmented horizontally, the workspace remained the same throughout the duration. The main reason for this is to respect the workers heights and workspace.

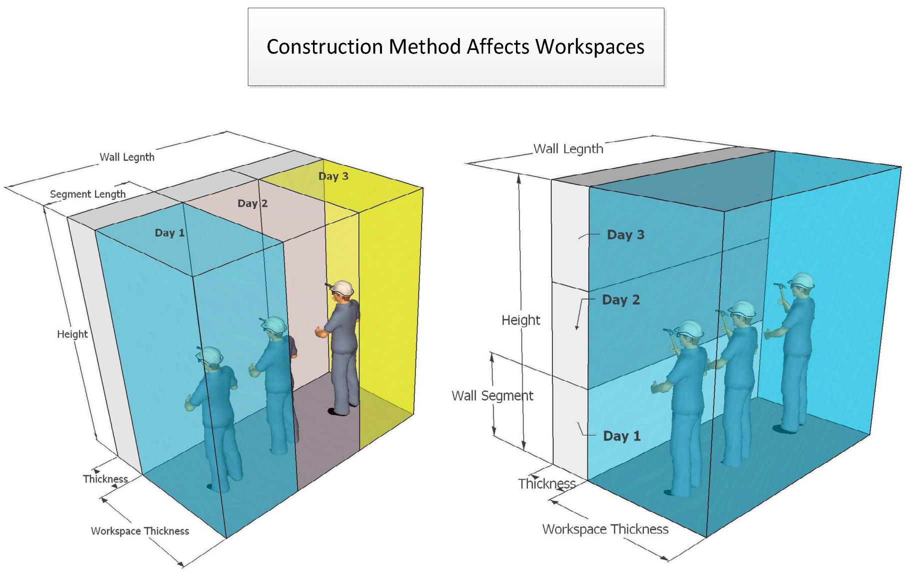


Figure 10 Workspace representations for different activity construction methods

- **Crew size and composition:** as shown in Figure 11, the size of the workspace depends on the number of labor crews, the amount of material stored, and if there are any equipment used.

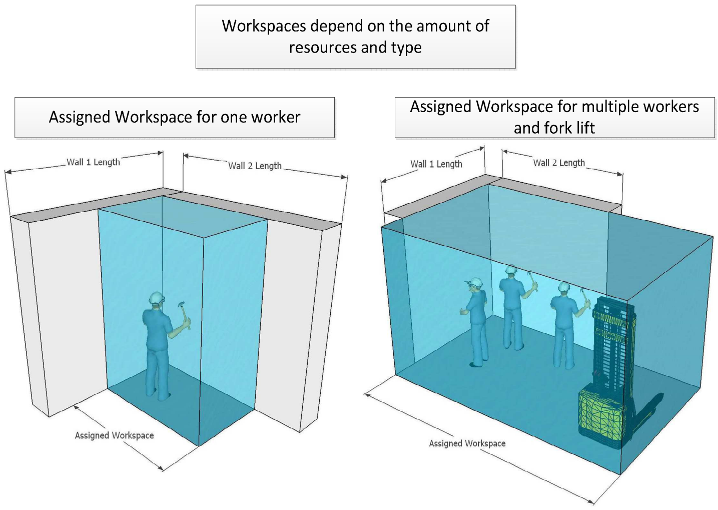


Figure 11 Workspace representation for different resource sizes

- **Modeling Approach (nature of activity):** The workspace's shape and appearance are according to the action or object it is representing. For example, if a workspace were to model the action of a concrete pump, then it would be assumed that the workspace could change location throughout the project, but would maintain the same dimensions most of the time (dimensions would change to represent the pump at idle state or in operation). On other hand, if the workspace were to model the material storage, then the workspace would not move throughout the duration of the storage area (excluding its movement to and from the storage area), but would rather change the dimensions, to increase or decrease based on the rate of storing of the material and its usage.

2.4.1 Researchers' generation and definition of workspaces

Depending on the technical expertise of the researchers, the case study projects that they used for their study, and the approach they used for modeling their workspaces, the types also varied more and more. However, there are some agreed upon types between researchers more than others. These common types are those which reflect the main components of any project. These workspace types are those that represent the planned execution spaces for the labor, equipment and material:

- The labor workspace is that virtual volume that any construction crew needs around the element. This volume is proportional to the number of workers in a crew and the nature of the activity being done (Akinci, Fischer, and Kunz 306-315).

- The equipment workspace is what represents the clear operation space for any heavy machinery, such cranes, pumps, etc. (Mallasi 2006)
- The material workspace represents the needed storage places for quick, safe and easy access to the materials on site. (Akinci et al. 2002)

Although researchers would agree on their name and nature, yet they usually would differ in the modeling approach due to the existence of other types of workspace unique to each researcher. Below is the description of some of the models used by previous researchers:

2.4.1.1 Thabet and Beliveau Model (1994)

Thabet and Beliveau (Thabet and Beliveau 1994) built their model on four main concepts: workspace demand, workspace availability, workspace variability, and construction execution policies. Workspace demand is the space required by any activity which is the summation of the physical dimensions of the resources, in addition to the needed surrounding space, which could be considered as a protection space. They explained that based on the type of the resource the proportionality between the physical and surrounding space varied. For example, the labor resource would occupy a small physical space (the space for a few workers) but will need an adequate amount for the surrounding space to protect the workers from any harm. The workspace availability is the available space for the activity to perform in light of the concurrent activities also in progress at that time. The workspace availability is the space left from the work area after subtracting the space demand of other concurrent activities. Workspace variability discusses that workspaces of the activity do not necessary occupy the same space throughout the duration. They further on explained that an example of workspace changing its size throughout the duration of the activity is the material workspace. The construction execution policies they considered in their study are those that could be determined by the construction managers or the main contractors. Basically, these policies dictate the relation the work area would have between different subcontractors. For example, policies could dictate that only one contractor is allowed to work in the subjected space as a certain time, prohibiting others to work even if the space allows it. Such situation must be considered during the space planning.

According to these four concepts, three classes of workspaces were created shown in Table 1 below:

Workspace	Description
Class A	The type of activities that would demand the whole work area for their workspace, either since the construction method requires large surrounding space or the policy dictates so. This type is considered to have a fixed workspace size throughout the duration of the activity
Class B	The type of activities which depend mainly on the labor and equipment and require very little amount for material storage. Those activities will also have a fixed workspace throughout the whole duration, and would allow other activities to work concurrently beside them, pending the condition that the remaining space will allow for the execution of other activities.
Class C	The type of activities which require large storage area at the start for assembly. As time progresses, the space demand for these activities will decrease as the materials are being used. The space that decreases is that for the material storage, whereas the labor and equipment workspaces remain fixed as in Class A and B

Table 1 Thabet and Beliveau 's Workspace Classes (Thabet and Beliveau 1994)

The above classes are based mainly on two types of space demands: those for manpower and equipment (SD-1), and those for material (SD-2). They assumed that SD-1 would be the same throughout time for all classes, and SD-2 would be the same for class A and B but for class C would be a decreasing stepping function. The equations for calculating SD-1 and SD-2 are shown by Equation 1 and Equation 2 below:

$$SD - 1 = \sum Quantity \times \left(S_{physical} + S_{surrounding}\right)$$

Equation 1 Estimating the SD-1 (Thabet and Beliveau 1994)

$$SD - 2 = \sum \left(Quantity \times S_{physical}\right) + S_{surrounding}$$

Equation 2 Estimating the SD - 2 (Thabet and Beliveau 1994)

2.4.1.2 Akinci et al Model (2002)

Akinci et al (Akinci et al. 2002) clarified that the types of workspaces could be categorized into micro and macro-level categories. Macro-level workspaces are those described as the actions being done on site but not directly related to the elements installation, such as material transportation or removal of excavated soil of the site. Figure 12 shows an example of macro-level workspaces, where the equipment on site is obstructing the path of the truck to transport materials to or off the site.

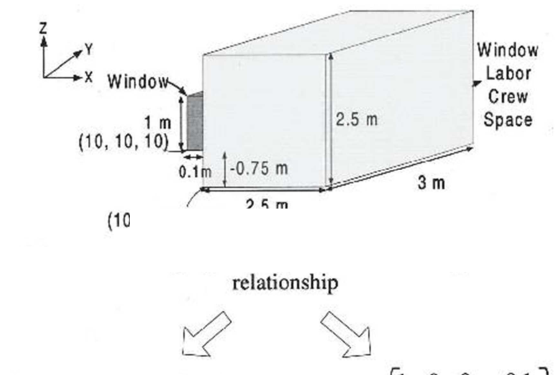
Figure 12 Macro-level Workspace

Micro-level workspaces are those types that would directly affect the installation process, and are being done with very close proximity to the element. They divided these micro-level workspaces as shown in Table 2:

Workspace Type	Description
Building Component	This represents the space occupied by the building components.
Work Space	This represents the space occupied by the crew.
Equipment space	This represents the space occupied by the equipment.
Hazard space	This represents the danger zone that no work should be permitted in. in other words, the space which would pause safety threats to the work.
Protected space	This represents the contingency space around the building elements which would prohibit any damage.
Temporary Structure Space	This represents the space occupied by temporary structures such as scaffolding.

Table 2 Akinci et al Workspace Types (2002)

The authors were focusing on generating the workspaces related to the building components through the qualitative descriptions given by the construction managers. For example, for a subcontractor to install windows using a scissor lift, then he would detail the requirements as follows: the labor crew to be on the right side of the window, with dimensions 3*2.5*2.5 m for the length width and height respectively, the equipment below the window with dimensions 3*2.5*4 m. Accordingly using the transformation matrix, the authors would generate the workspaces and shown in Figure 13 below:



$$T = \begin{bmatrix} 1 & 0 & 0 & 0.1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -0.75 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 13 Akinci et al Transformation matrix (2002)

The qualitative orientation descriptions that they used were: outside, inside, above, below, and around. In view of that, these qualitative were transformed into the graphical description as follows in Table 3 from which the transformation matrix would calculate the workspace dimensions taking the building object as the reference point:

Qualitative Orientation	Graphical representation to the building object
Above	Top Side
Below	Bottom Side
Outside	Exterior space
Inside	Interior Space
Around	Connection surface

Table 3 Geometry of Akinci et al Qualitative Orientation (2002)

2.4.1.3 Guo Model (2002)

Similar to Thabet and Beliveau (1994), Guo determined that one of the main factors to define any space-time conflicts is to first determine the space availability on site. Thus, he categorized the space available on site into 4 categories: exterior to the job site, interior to the jobsite, inside the structure and space for temporary facilities. The space related to the jobsite focused on outlining the area on the ground level, while the inside the structure space was to determine the existing space within the confines of the building structure. In most cases, the inside the structure space would be broken down into levels to represent the story heights, and into zones to represent the working areas in each story. The main idea of the space availability was only to create a medium to assign the workspaces, and was not included in the calculations.

He classified the workspaces into four types: labor and equipment to resemble working spaces, material to resemble storage, and temporary facility to resemble the set-up and preparation spaces. Knowing these facts, the workspaces were assigned as graphical boxes to the created layers and zone in the CAD drawings. He concluded that the space demands are attained mainly for the time schedule which is then broken down into a hierarchical structure as shown in Figure 14 below. As seen in the figure, once the type of workspace was determined, Guo’s model worked on determining the possible paths it would take to reach the destination.

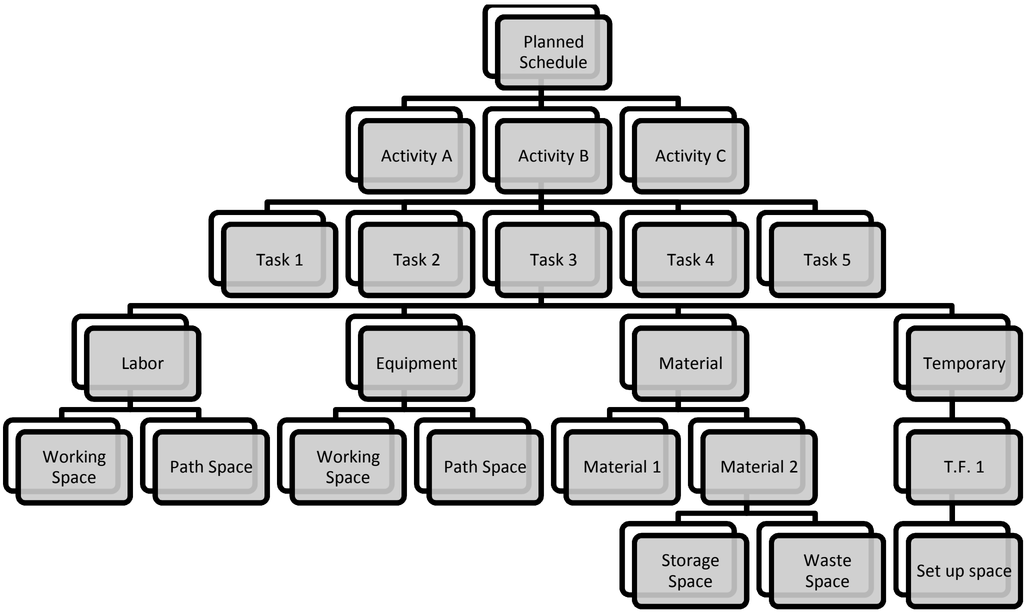


Figure 14 Guo's Hierarchical Structure (2002)

2.4.1.4 Song and Chua Model (2005)

Researchers like Song and Chua focused on trying to illustrate the workspaces from the view point of the intermediate functions. They explained that any construction process has to have two functions, the transformation function and the intermediate function. The transformation function is the attempt to change the state to a building component, such as fixing the column rebar, and could be done by either the labors or the equipment. The intermediate functions are those support functions that help achieve the transformation function (Song and Chua 2005). They further explained that any intermediate function has four main parameters: function provider, function user, available function criteria and available interaction criteria.

Their focus was to investigate the topological relationships between the transformation and the intermediate functions. They believed that the workspaces could be derived from a component-relation structure, where the space system is broken down into fewer hierarchies, reaching to the lowest level which would be a graphical CAD component that can be represented as shown in Figure 15.

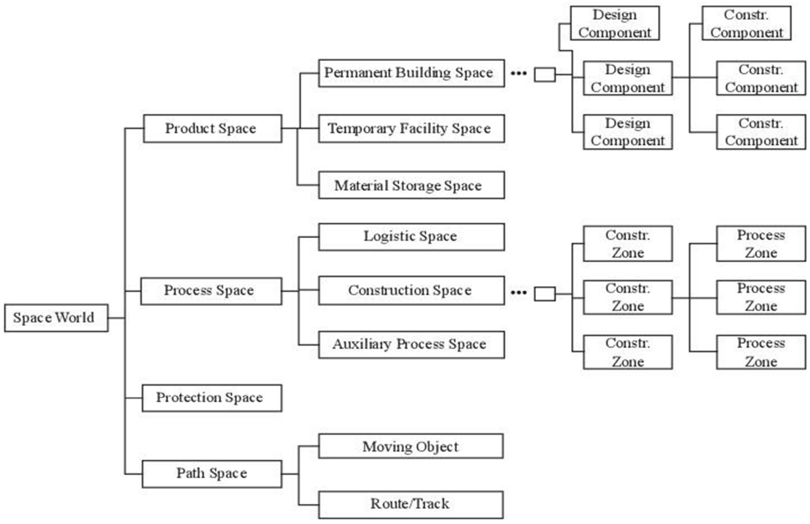


Figure 15 Song and Chua Space System (2005)

As seen in the above figure the main components of the space world are those workspaces explained in Table 4 below:

Workspace Type	Description
Product Space	Which reflected the elements that would actually occupy volume at any certain time as building components and/or temporary facilities and/or material storage
Process Space	Which reflected the virtual spaces needed at any project such as the logistical space, construction space and auxiliary process space
Protection Space	This reflected the virtual space needed to protect the newly built components from any damage.
Path Space	Which the angle of movement and direction of any moving object on site.

Table 4 Song and Chua Workspace Types (2005)

After identifying the workspaces, they defined a “finite time interval (FTI)”, where they argued that there is a period of time where the spatial temporal characteristics of any element are fixed and unchanged, which could be a week, a day, or even an hour according to the accuracy required. By this analogy, any construction process could be broken down into a series of discrete events. These discrete events then can be represented by an existence vector, which is a series of binary codes. The length of the existence vector is according to the duration and the defined FTI. Each binary code has only two values, either 1 to represent true or 0 to represent false.

Example of the use of this system is shown in Figure 16 of the excavation of a trench and the movement of a mobile crane. The duration of the example is nine days. The excavation process was broken into smaller discrete events to be able to represent them by an existence vector.

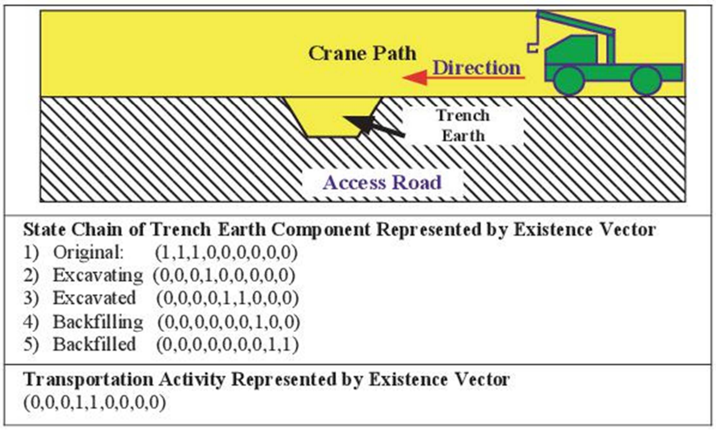


Figure 16 Example of Song and Chua's Binary System (2005)

2.4.1.5 Winch and North Model (2006)

This model has developed five types of spaces: total space (t), product space (p), installation space (i), available space (a), and required space (r). Similar to Thabet and Beliveau (1994), the total space represents the complete work area, where tasks would be assigned to. The product space reflects the permanent elements such as the building components. The installation space represents the space needed for the execution of the task, which could be the space for prefabrication or site installations. The available space is the empty space left from the total space after assigning the product and installation spaces. The required space is the planned space needed for the activity execution strategy. The researchers believed in importance of developing well integrated tool that can easily automate and link most aspects of the space-time planning together. Thus, the generation of the workspaces was done on three levels.

Their system generates a 2D drawing of the work area with the product spaces. The user then manually selects the available space for tasks' execution using a tool called "AreaMan". The next step is importing the tasks from the schedule, which each task is linked to the types of workspaces, and the number of resources. The types of the workspaces and resources are imbedded in the "VIRCON" database, so the user simply selects from a drop-down list for each activity. The authors defined also a site boundary parameter to identify the projects total works area. This parameter is only for visualization aids and does not affect any calculated areas. Figure 17 below shows the classification of the workspaces used in the model.

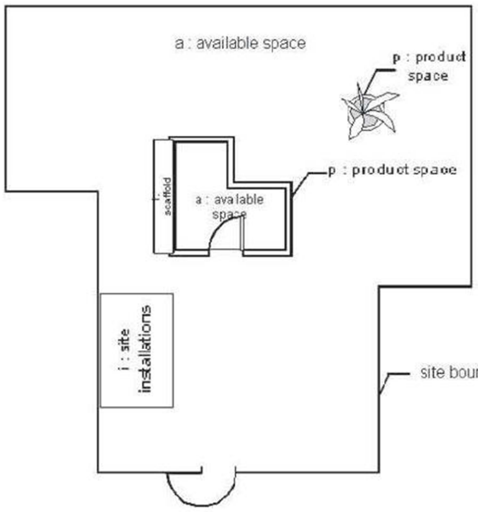


Figure 17 Winch and North Workspace Types (2006)

2.4.1.6 Mallasi Model (2006)

Mallasi (2006) utilized the space-time taxonomy that was done by Akinci et al (2002) and added other types of workspace that allowed the model to view both the macro and micro workspace levels shown in Table 5 below.

Workspace Type	Description
Process Space	This represents that space occupied for performing the task.
Equipment Path	which represents the path taken for the equipment to perform the activity
Storage Space	which represents the material storage locations
Path Space	which represents the path taken for any moving object on site
Support Space	This represents the space needed by the crew beside any building element to perform the task, a location to store the materials for the specific task for example.

Table 5 Mallasi's Additional Workspace Types (2006)

The combination of these workspaces formulated the workspace of the activity. Mallasi used the Boolean operator "Union" to combine between them to formulate one workspace for the activity. Mallasi depended on two major concepts when visualizing the workspaces in a construction project:

- The variable productivity of an activity: Mallasi argued that any workspace behavior is directly proportional to the productivity rates pattern of the activity. Thus in his study, he formulated three type of rates shown in Figure 18, high-low, constant, low-high:

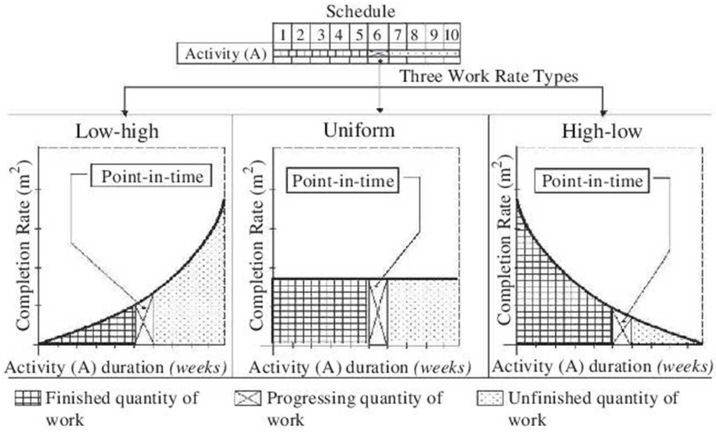


Figure 18 Mallasi's Completion Rates (2006)

- The execution patterns: Mallasi developed twelve different execution patterns in his study to explain the execution direction of the activities. The execution patterns depended on the cardinal coordinates north, south, east, and west, and were divided into two types:
    - Work progress that can be expressed in one direction only: assuming that there are sufficient resources to perform the works on both locations perpendicular to the direction, the execution patterns could be either: north-south, south-north, west-east, and east-west.
    - Work progress that cannot be expressed in only one direction: normally in the site, the resources would be limited and consequently the execution would need more than one direction to resemble it. I would also need a diagonal resemblance to explain it. The execution patterns resulting from this are: north-south beginning from northeast, north-south beginning from northwest, south-north beginning from southeast, south-north beginning from southwest, east-west beginning from northeast, east-west beginning from southeast, west-east beginning from northwest and west-east beginning from southwest.

2.4.1.7 Wu and Chiu Model (2010)

Wu and Chiu (2010) adopted a different approach when choosing the workspace types. They preferred to focus only on the main components as building, labor, equipment and material workspaces. However, they added one important parameter which is the site workspace. This workspace has proven to be very useful, as it represents the allowable space for the construction crew to work in without invading the neighbors' space. In many construction sites, invading the allocated space for construction could cause many penalties on the contractor, reaching to termination of contract in some cases.

The dimension of any workspace type was determined by Equation 3:

$$Workspace = Space_{object} + Space_{Operation} + Space_{Safety}$$

Equation 3 Estimating the Workspace Size (2010)

The object and operation definitions varied according to the type of the workspace. For example when estimating a building component, then the object space would be the physical dimensions of the building element and there would be no operation space; but when estimating a labor component, then the object space could be the space the crew needs at static position and the operation space would be the maneuvering. The safety space is a protection or buffer zone for the workspace.

The authors used “Constructive Solid Geometry” to create the workspaces and created a workspace data model which represented their 4D model. It consisted of six main sets, each with its own subsets, as shown in Figure 19. The target was to be able to define each workspace by its unique characteristics and to store the data in an organized matter that would help in the clash detection and analysis.

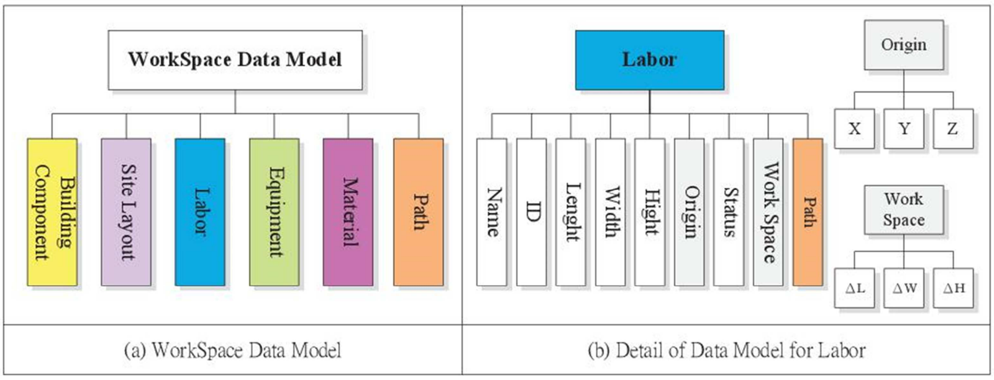


Figure 19 Wu and Chiu Workspace Data Model

2.4.2 Researchers approach to Workspace Representation in 4D

As explained above, any workspace has spatial and temporal properties, in which it has certain dimensions, appearance rate and duration. Accordingly, the representation of the workspaces differed from one case to the other. Representation in this study is defined as the attempt to transfer the unique properties of the workspace adopted from the parameters explained before, into objects which could be used afterwards in 4D animation and analysis. The main problem was the graphical representation, as the temporal properties were inherited from the time schedule, which revealed the fact that the dimensions of any workspace are concurrent to the design of the building component itself. This presented the researchers with a major dilemma that workspaces' graphical properties could be irregular and hence pause challenges when used in further analysis and calculation. Thus, most literature adopted the rectangular prism as an acceptable approximation for representing the graphical properties of the workspaces. Further arguments were raised describing how that the behavior of the actual elements on site are better represented with regular shapes for the workspaces. Figure 20 shows the transformation from irregular representation of the workspaces to the regular rectangular representation.

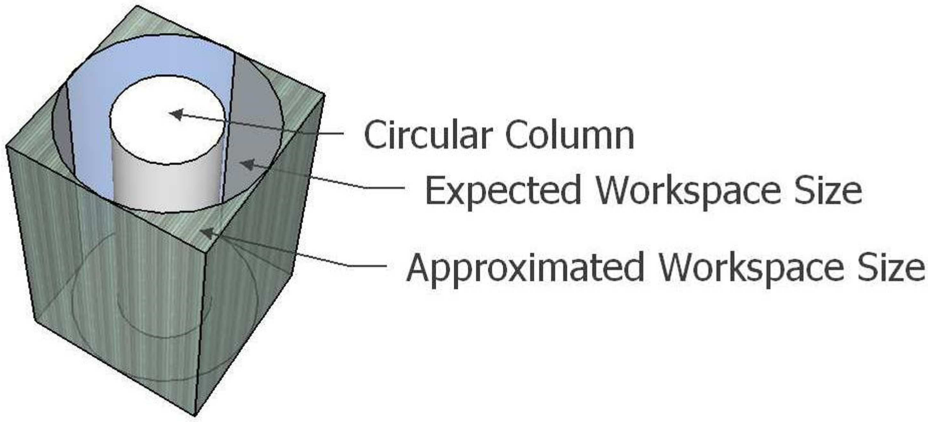


Figure 20 Using Rectangular Prisms for Workspace Representations

2.5 Clash definition and estimation

As explained above, the workspace of any object or action is needed in order to guarantee the optimum execution on the planned time, allocated budget and with the targeted quality. However, this is not always the case in construction projects. Many researchers have observed different activities on site and found much interference between different workspaces. Riley and Sandvino (1997) witnessed over seventy different interferences between various workspaces, when observing only four trades for a period of two months.

The interference between workspaces occurs when they require the same space unit at the same time and this is defined as a clash. For example, Figure 21 shows the workspaces for two walls, where their workspaces overlap (green section).

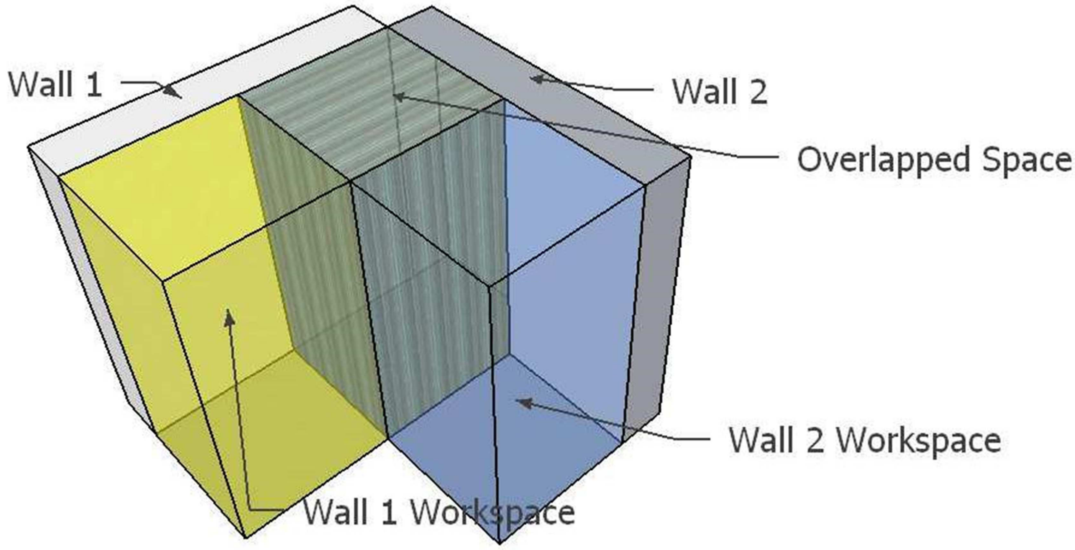


Figure 21 Overlapping Workspaces of 2 Walls

The practical explanation of the clash is when two workspaces share the same spatial-temporal requirements. Since, the size of each workspace is known and their rate, and then it is easy to calculate the size of the clash, which leads us to the next question, what is the impact of these clashes and how could they be estimated?
In order to be able to effectively estimate the clash, one should first understand what happens when the clash occurs. As explained above, the clash occurs when two or more activities require the same space unit at the same time. The physical meaning is usually one of two things: either the allocated workspace per activity shrunk at the time of the clash since it is now being shared with another one, that the worker now is working in a tighter environment, making it harder to perform the scheduled tasks; or that a certain area of the allocated workspace has been completely blocked due to any activity imposing itself on the other, and hence the worker cannot access the area entirely. In terms of project aspects, the clash can affect the following:

- The time of the project: assuming that the impacted activity is on the project critical path, then the blockage or the shrinking has created an uncomfortable environment to the worker affecting the productivity and thus the actual duration of the work will exceed the planned duration
- The quality of the works: the hard access to certain areas will affect the performance of the worker.

- The safety: if we are to assume that the clash is happening between the workspaces for labors and for equipment, then there is a risk that the labor could get harmed standing in the path of the equipment
- The cost of the project: the increase in cost could be the results of many things:
    - The low productivity would force the contractor to retain the services of the labor and /or the equipment longer than planned, increasing the costs.
    - The doubted quality of the work may lead to re-executing the job, which means demolition of the existing, purchasing new material, and hiring another crew and renting equipment again.
    - If the workspace is out of the project boundaries, then the contractor could suffer from penalties.

A great risk also is the damage of some of the already constructed spaces. This could happen when the workspaces for the equipment interfere with the building components, or if the sequence of the construction didn't account for the size of the equipment being used. Figure 22 shows an example of a forklift needed to carry materials into the house, but is bigger than the opening. So in order to be able to use it, some of the façade will have to be removed and then re-constructed again.

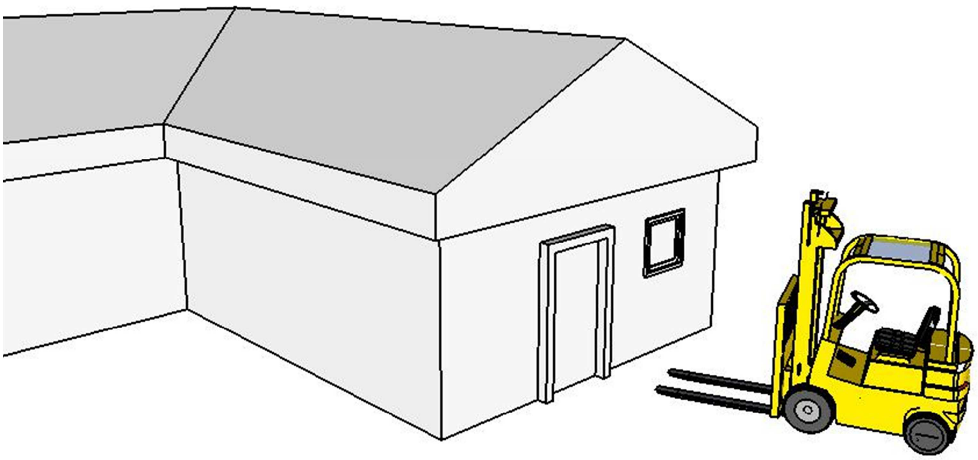


Figure 22 Forklift obstructed by small opening

To imagine the impact of the clashes on projects, a questionnaire was conducted on the thirty one different project managers, whom were asked to rate the problems occurring on site. From the eleven problems raised in the questionnaire, such as lack of material or tools and equipment breakdown, the workspace interferences ranked the highest (Kaming et al. 1998). Another study was performed on the University of Teesside that estimated a thirty percent loss in productivity due the workspace interferences resulting from the lack of detailed space planning and improper communication of the time schedule (Mallasi and Dawood 2001). The remaining issue still exists, which is “what are the possible factors that contribute to the estimation of the clash?”

Literature has shown that the first main governing factor that estimates the clash is the detection mechanism that each researcher uses, how the model will be viewed and what are the expected clash types that shall result. Other factors could be the size of the clash, workspace types clashing, the importance of the activities clashing etc. (Hosny, Nassar and Hosny 2012; Mallasi 2006)

2.5.1 Researchers detection and classification of clashes

This section describes the approach that researchers used in order to detect and classify the clashes in a construction project, in light of the illustrations shown above in section 2.4.1.

2.5.1.1 Thabet and Beliveau Model (1994)

One of their study’s main concepts was to measure the available workspace for an activity by subtracting the available space in the work area from the spaces demanded by other activities. Hence, their model was based on the idea of defining the work area and the activities allocated to it. They divided a typical floor into zones, based on the floor layout plans, and then each zone was broken down into layers. The layers contained the activities that are going to be executed at the same time. Once the activities are known, they started calculated the space demand for each activity using the SD-1 and SD-2 explained above. This way, they have created a work area which is the area of the layer, and know the space demand for each activity.

Using a CAD model they draw the space of the zones, layers and activity space, differentiating between the spaces for the manpower and equipment and that for the material allocation. If the spaces for the activity were allocated entirely in the layer area, then it would be confined to this area only. But if the spaces of the activities were allocated to more than one layer, then presumably they would be stretched to be included in all the layers. This case was more common with the allocation of the material spaces. An example of the allocation techniques is shown below in Figure 23 below:

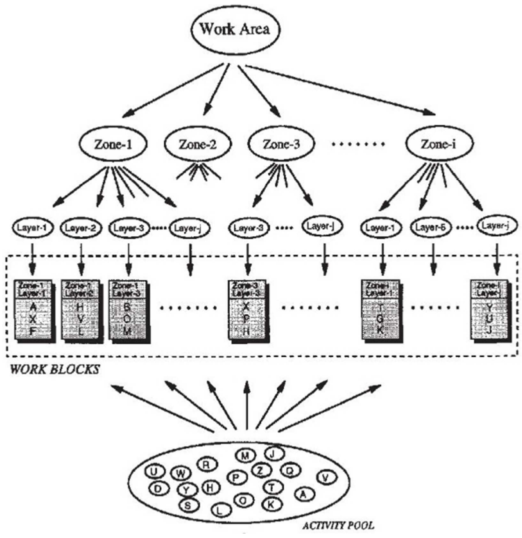


Figure 23 Thabet and Beliveau Allocation Techniques (Thabet and Beliveau 1994)

Once the work in a layer was completed, another layer with a tighter work area would be created and the next set of activities would be linked to it. Their argument mainly depended on the fact that as the work is completed on site, the work areas become more determined and smaller. For example at the start of the project with the concreting and the block work activities, there are still no space limitation and thus material can be stored easily and manpower and equipment would perform safely. When the concreting and block work is done, the site now is divided into rooms with smaller work areas, which are the new layers. Thus the area for the mechanical and electrical work is smaller. Bearing this concept into mind, the model starts to check for any clashes by an equality equation, if the space demanded for any activity is equal to what is left from the total work area after subtracting the space demand for other activities progressing at the same time.

2.5.1.2 Akinci et al model (2002)

In light of the workspace generation and types explained above in section 2.4.1.2, the authors implemented a discrete event simulation in order to detect the possible space conflicts that could occur in the project. Since all space requirements have been assigned a graphical object, therefore the check for the spatial conflicts has become geometric clash detection throughout discrete events. They explained that mechanism is as follows: the system starts with the activities that has no predecessors and hence can start concurrently, setting the discrete event as the duration of the shortest activity. Then the model keeps adding the successors and setting the other discrete events as the duration of the activity of the earliest finish as shown below in Figure 24, an example of six activities:

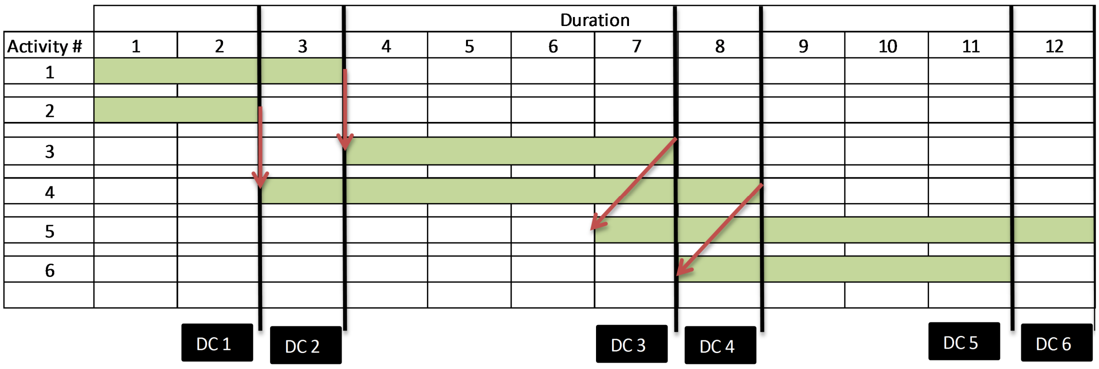


Figure 24 Akinci et Al Discrete Event Simulation Mechanism (2002)

During each event period, the model pairs up the concurrent activities and check for the possible geometric clashes between the spaces requirements of each. Since each activity usually would have more than one space type, then it is possible that more than a clash type would arise from that. Therefore, the generated clash types that were considered in the model were as shown in Table 6:

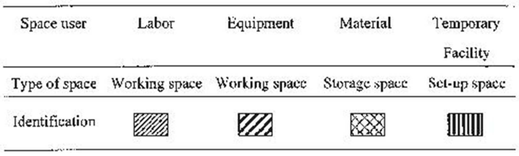
	Building component	Workspace	Equipment Space	Hazard Space	Protected Space	Temporary Structure Space
Building component	Design Conflict	Congestion	Congestion	No Impact	No Impact	Congestion
Workspace		Congestion	Congestion	Safety Hazard	Damage Conflict	Congestion
Equipment Space			Congestion	Safety Hazard	Damage Conflict	Congestion
Hazard Space				No Impact	Damage Conflict	No Impact
Protected Space					No Impact	Damage Conflict
Temporary Structure Space						Congestion

Table 6 Akinci et Al Clash Types (2002)

The congestion in the above table is later broken into three types, mild, medium and severe, based on the degree of congestion that should be determined by the conflict ratio.

2.5.1.3 Guo Model (2002)

This model depended on the idea of design coordination between drawings. This means that at each point of time, the workspaces and path spaces would be drawn in the CAD layers and the overlapping spaces would be shown as graphical intersections. Although this model didn't conclude any clash types, it was easy to determine the clash was a result of which type of workspaces according to the drawing code in Figure 25 below that shows the unique representation of each workspace.



Space user	Labor	Equipment	Material	Temporary Facility
Type of space	Working space	Working space	Storage space	Set-up space
Identification				

Figure 25 Drawing Representations of Guo's Workspace Types (2002)

The clash detection concept was based on detailing the workspaces of the activities in each zone, and then overlapping them above each other to determine the clash. This concept is similar to the discrete event simulation that was adopted by Akinci et al (2002). The concept is clarified in Figure 26 below, two main checks were done, first the workspaces and then the paths, and if any clashes then the whole arrangement would be investigated.

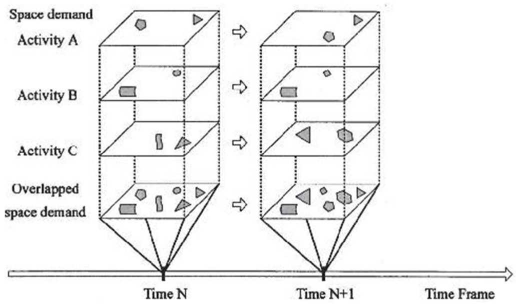
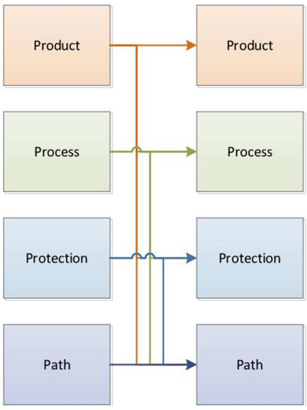


Figure 26 Guo's Clash Detection Concept (2002)

2.5.1.4 Song and Chua Model (2005)

As explained above, Song and Chua used discrete event simulation and the existence vector to represent the spatial temporal characteristics of the different activities on the site. The possible clashes that could result from their framework based on the choice of the workspaces were ten combinations as shown in Figure 27:



#	WS Type	WS Type	Clash Category
1	Product	Product	Non-Compromising
2	Product	Process	Compromising
3	Product	Protection	Compromising
4	Product	Path	Non-Compromising
5	Process	Process	Compromising
6	Process	Protection	Non-Compromising
7	Process	Path	Compromising
8	Protection	Protection	Non-Compromising
9	Protection	Path	Non-Compromising
10	Path	Path	Compromising

Figure 27 Song and Chua Clash Types

The method for detecting the clashes was based on the Boolean operators "And" and "Or" between the existence vectors of the space entities. The "Or" operator was to combine between the discrete events of a construction. This operator led to one existence vector that represented the activity. The "And" vector was used to check the applicability of two different vectors co-existing at the same time. Based on these operators, the detection method was broken into two diagnostic rules: "the compromising/non-compromising criteria" and the "allowable limit of interference space percentage".

The first diagnostic rule categorized the clashes into two categories compromising and non-compromising, based on the space types interfering. As shown in Figure 27 above, the non-compromising are those where the overlapping between the two space types is strictly prohibited and no tolerance will be allowed, hence the construction method that was suggested which resulted in these clashes is completely rejected. On the contrary, the compromising clashes are those where the overlap between the space entities is allowed to certain limit that is decided by the construction planner, which leads the user to the second diagnostic rule.

The second diagnostic rule is to calculate the degrees of congestion between the overlapping activities, since it is inevitable that in any construction project, two or more activities share the same workplace. The researchers utilized the previous work of Akinci et al's "Conflict Ratio" (2002) and Guo's "Interference Space Percentage" (2002) to estimate the overlapped: workspace ratio and accordingly set the congestion levels of the project.

2.5.1.5 Winch and North Model (2006)

The clashes in this model were identified through 2D drawings. As explained above in section 2.4.1.5, the user identifies the available space, and then assigns the workspaces and resources types and the VIRCON system estimates the sizes of them based on it library. The model calculates the required space by summing up the space needed for the resources, while adding a protection zone for safe operation. The model investigates some relation to determine the clashes in the system. These relations are: the size of the available space to the size of the required space, and the overlapping of the required spaces in an available space. The model calculates to main factors for each activity, its time criticality according to the standard CPA method, and its space criticality according to the developed CSA approach. The model would then use red and green lights to identify the status of each activity. A screenshot of the interface is shown in Figure 28 below where the green and red lights on both sides of the activity. The left lights indicate the time status and the right lights indicate the space status. The system developed lacked the usage of the third dimension, which meant that it could not capture any vertical clashes.

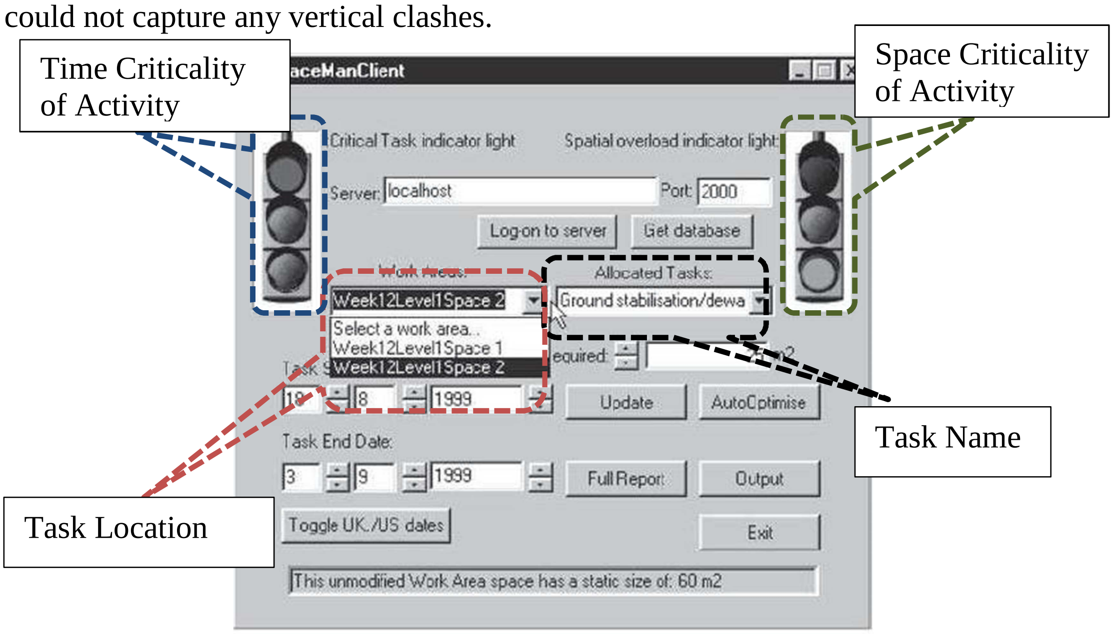


Figure 28 Winch and North's Space Man Client (2006)

2.5.1.6 Mallasi Model (2006)

As explained above, the activity workspace is the summation of the different workspace types suggested. Mallasi's model then stores the new formulated workspaces and lays them out on a new cad layer. After that, a simple overlapping algorithm is applied which denotes the workspace occupying the same location at the same time, and accordingly the intersection is calculated. When the intersection occurs, it is able to define which component of each activity workspace has overlapped. An example is shown below in Figure 29 of the mechanism:

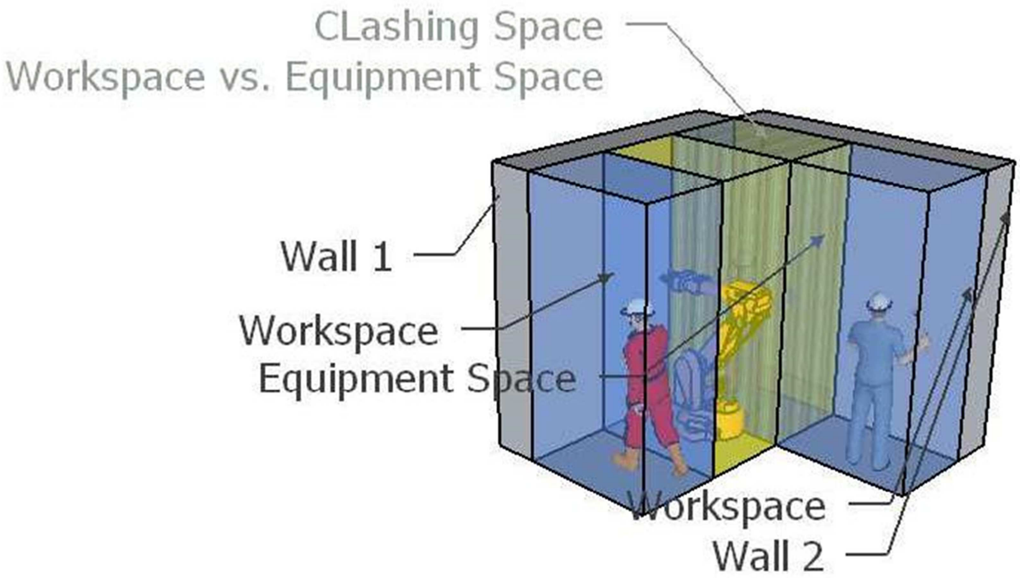


Figure 29 Mallasi's Clash Detection Concept (Mallasi 2006)

The interferences resulted in one of the following clash types: design conflict, safety hazard, congestion, access blockage, damage, space obstruction, work interruption and no impact. The clash types could be extended more to contain different levels of each, such as severe or mild congestion.

2.5.1.7 Wu and Chiu Model (2010)

Before going into the detection of the clashes, two major concepts that the authors developed should be discussed. The first is the aggregation of the workspaces, which deals with the size of the workspaces when two or more are combined. The author claimed that the combination of workspaces could result in a “direct combination” or an “aggregation” of workspaces. The “direct combination means that the workspaces are simply being added up, since each one has its own independent space that it cannot share, such as combining between the workspaces of labor and equipment. The “aggregation” means that certain parts of the workspaces being combined could be overlapped to become one and thus the dimension of the resulting workspace is less than the sum of the workspaces alone, such as combining the workspaces of a building and material because there is no space needed between the two elements and hence can be removed.. This concept has affected the clash detection as the elements in the aggregation are not considered. Figure 30 describes the “direct combination” and the “aggregation”.

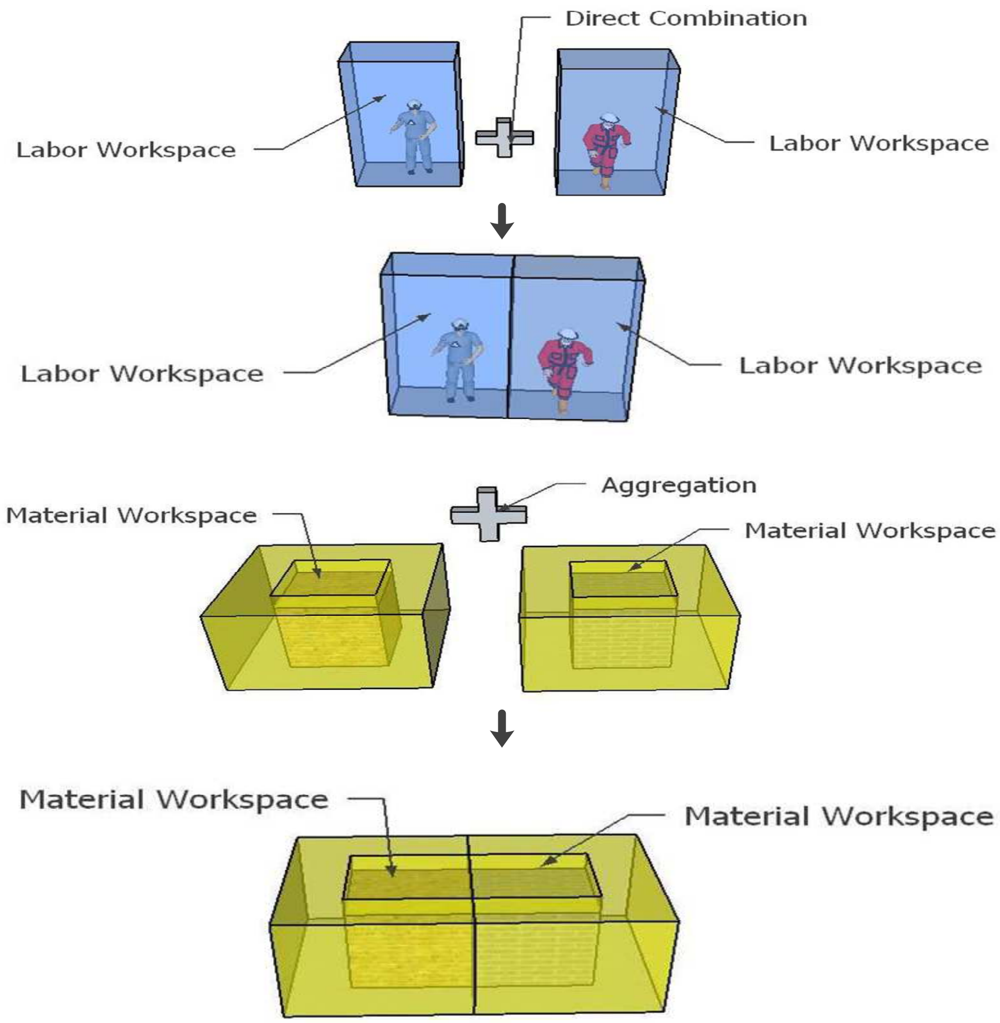


Figure 30 Wu and Chiu Direct Combination and Aggregation Techniques (2010)

The second concept was the second type of workspace classification the authors used in their model: static and dynamic objects. Static objects are those that preserve the same volume and location throughout time such as a building component. Dynamic objects are those which either change shape or location throughout time such as transportation of material. Those concepts along with the workspaces formulated the conflict types as shown in Table 7 below:

#	Clash Type	Result of		
		Static vs. Static	Static vs. Dynamic	Dynamic vs. Dynamic
1	Design	Building vs. Building		
2	Safety			Equipment vs. Labor
3	Damage		Building vs. Equipment	
4	Congestion	Material vs. Material	Labor vs. Material	Equipment vs. Equipment

Table 7 Wu and Chiu Clash Types (2010)

The design conflict arises when two or more building components share the same space. This would happen regardless of the time and hence is considered as "static vs. static". The physical meaning is that more than one discipline required the same space in the design, such as the overlap between the column's rebar in the structure design and the electrical conduits in the electrical design. The safety hazard occurs when the equipment and labor workspace intersect. This would happen only if the two workspaces are dynamic, hence "dynamic vs. dynamic". The physical meaning is that the labor crews are probably working near the hazardous zone of operating equipment, such as working in the way of a mobile crane.

The damage conflict occurs when the workspace of the equipment interferes with a building component. This would only happen if the equipment is operating near to the building, hence "static vs. dynamic". The physical meaning is that within the needed space for the equipment to operate, lays a building component, such as using a forklift in room after installing the door. The congestion conflict is the overcrowding of difference workspace types at the same time and location. This could happen in any case, when more than one subcontractor intends to use the same material storage space "static vs. static", or when the stored material block the access for labor to work "static vs. dynamic", or when more than one equipment work operate closely to each other that at any point of time they could intersect.

Although the clash types are sufficient to describe the interferences in any project, an argument is raised whether is it preferable to classify them as shown above in Table 7, or should the system be more flexible? For example, not all equipment vs. equipment are congestion only, rather most of them could be damage or even a safety hazard, such as a crane hitting an oil tank.

2.5.2 Researchers clash estimation techniques

This section presents the previous attempts to estimate the clashes, and how researchers dealt with the matter. The data presented here below is arranged according to the date of development, where each technique is explained and evaluated upon.

2.5.2.1 Thabet and Beliveau Model (1994)

They developed the space capacity factor shown in Equation 4:

$$SCF = \frac{Space\ Demand\ for\ activity}{current\ space\ availability}$$

Equation 4 Space Capacity Factor (Thabet and Beliveau 1994)

Where the space demand for the activity and the current space availability were explained above in sections 2.4.1.1 and 2.5.1.1. Their focus was not clash detection as much as it was to estimate the possible decrease in productivity that would occur due the activity having less than the required space. They developed a hypothetical relation between the crew productivity in any layer and the SCF factor shown in Figure 31 below. This relation in addition to other decision factors would determine the new modified schedule of works. According to these factors, the activities were modeled by three ways: either the activity would start on time but with a decreased productivity, or the activity would start on time with the planned productivity and be segmented into two or more segments (the work is interrupted in the middle), or the activity would be delayed and start later than planned with the planned productivity.

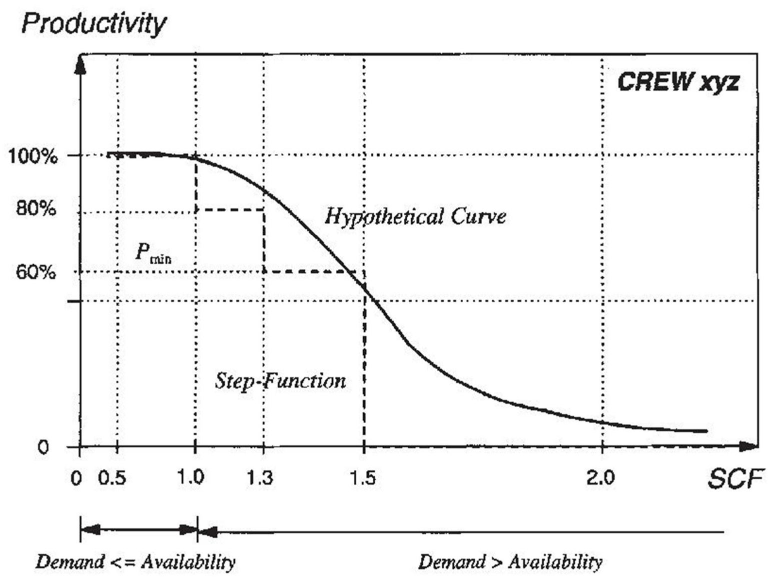


Figure 31 SCF - Productivity Hypothetical Relation (Thabet and Beliveau 1994)

This study was mostly hypothetical and didn't focus on determining the types of clashes or the severity of each. There was no criteria to differentiating between workspaces and didn't accommodate for the different severities that could occur and would force the work to stop, such as hazardous impacts. The useful concept of this study that inspired the site workspace is the confinement of the activities in fixed spaces.

2.5.2.2 Akinci et al Model (2002)

They developed the conflict ratio:

$$ConflictRatio = \frac{\sum Conflicting\ volume}{\sum Volume\ of\ space\ required} \times 100$$

Equation 5 Akinci et al Conflict Ratio (2002)

Where the $\sum Conflicting\ volume$ is the summation of the conflicting volume at each instance between the workspaces of each activity, and accordingly the $\sum Volume\ of\ space\ required$ shares the same idea of summing the total of the volumes required of the required spaces of the workspaces that bared the conflicts. As explained before in sections 2.4.1.2 and 2.5.1.2, their model depended on a pair wise approach, where each activity would be paired with the rest in the discrete event period and checked for clashes. Along with that, each activity has a number of objects and workspaces tied to it, hence the same clash usually happened between the same pair of activities at more than one instance. The clash ratio's mechanism was the aggregation of these instances.

To further illustrate this notion, let's imagine a window installation activity. This activity would be linked to a number of windows, and each window would have one or more workspace linked to it. So, if any other type of workspace for another activity (say installation of c-channels) were to clash with this activity, there would be instances generated from this clash, which number would be decided according to the number of windows. The conflict ratio manages to decreases the number of instances into only one, by summing up the conflicted volume and the space required at each instance, as long as they share the same pair of activities and the same type of space clash. After that, the clash ratio was mostly used to define the different levels of congestion, of the different types of equipment clashes.

The conflict ratio didn't account for the severity of the clashes and didn't account for the criticality of the activities, and hence the only acceptable optimization was the manual rescheduling. In the event that the conflict ratio detected more than one ratio for the same pair of activities, it identified the main conflict type through the following categorization shown in Figure 32 that depended on the type of trouble it would create:

Priority Rank	Conflict Type	Problem Created
1	Design Conflict	Design related constructability problem
2	Safety Hazard	Construction related constructability problem
3	Severe Congestion	Construction related constructability problem
4	Damage	Construction related quality problem
5	Medium Congestion	Significant productivity loss problem
6	Mild Congestion	Minimal productivity loss problem
7	No Impact	No problem created

Figure 32 Akinci et al Clash Ranking (2002)

2.5.2.3 Guo Model (2002)

This study used two equations to estimate the clashes: the Interference Space Percentage (ISP) in Equation 6 and the Interference Duration Percentage (IDP) in Equation 7:

$$ISP = \frac{interference\ space\ size}{original\ size} \times 100$$

Equation 6 Guo's Interference Space Percentage (2002)

$$IDP = \frac{interference\ duration}{original\ duration} \times 100$$

Equation 7 Guo's Interference Duration Percentage (2002)

Where the interference space size and duration are those of the clash between the activities and the original size and duration are those of the planned workspace of the activity. As explained above in section 2.4.1.3, Guo model considered the activity as the parent, from which hierarchies are broken down to reach to the space demanded. Therefore, these equations are calculated for each clash for each activity. This means that a single activity may have more than one ISP and IDP. As Akinci et al (2002), Guo's main focus was the resolution of the clash, and has not classified any types of clashes. Rather than that, a set of criteria were developed to aid to the decision of conflict resolution. The criteria covered items such as the logical sequence between the clashing activities, the criticality, the possibility of changing duration and the possibility of modifying the space demand.

In many situations, the Guo model was proven to be a good choice for conflict resolution as it not only monitored the clashes from workspaces, but also the paths they needed from and to the work area. However, the model didn't account for the variable severity that could be resulted from the different space clashes, which should have been one of the main criteria for the conflict resolution.

2.5.2.4 Winch and North Model (2006)

They developed a set of equations for the Critical Space Analysis (CSA) approach shown in Table 8:

Name	Equation
Spatial Loading	$S = \frac{r}{a} \times 100$
Spatial Overload	$S > 100$
Spatial Slack	$When\ S < 100, a - r$
Critical Space	$S = 100$

Table 8 Winch and North Spatial Loading Equations (2006)

Where S is the spatial loading factor for the activity, and r is the required space and a is the available space which is calculated according to Equation 8:

$$a = t - p - i$$

Equation 8 Winch and North Available Space Calculation (2006)

Where the t is the total space, the p is the product space and the i is the site installation space.

Similar to the Critical path method for calculating the time, the researchers developed the above set of measures to calculate the space status of the activity. The spatial loading is a ration between the required space and the available space. This technique was able to show when the activity was lacking the required space for execution (r > a, S > 100), or when the required space was mush less than the available space (r < a, S < 100) and thus more activities could be executed in the extra space (a-r) and the activity was critical and can't be modified any more (r = a).

However, this technique has failed to show the different clash types, of the severity of each clash as it only calculated the ration of the occupied space to the ration of the existing space. Moreover, the fact that the system works on the 2D scale has limited the ability to detect the vertical clashes that could occur.

2.5.2.5 Mallasi Model (2006)

The equation developed was the space criticality factor shown in Equation 9:

$$f_A(scr) = vw1.f_D\,(co) + vw2.f_D(r) + vw3.f_D(no) + vw4.f_D\,(st) + vw5.f_D(cr)$$

Equation 9 Mallasi's Space Criticality Factor (Mallasi 2006)

Where the f_A (scr) is the space criticality factor for A group of activities at D period of time, the f_D(co) is the ratio between the total of the conflicting volumes and the total of the occupied spaces, f_D(r) is the total of the clashes' severities based on the developed critical space-time analysis approach shown in Figure 33 below, the f_D(no) is the number of activities conflicting, f_D(st) is the number of workspaces conflicting and f_D(cr) is a measure for the activity criticality and has only two values, 1 for critical activities and 0 for non-critical activities. The vw_n are the weights determined by the user at the start of the study.

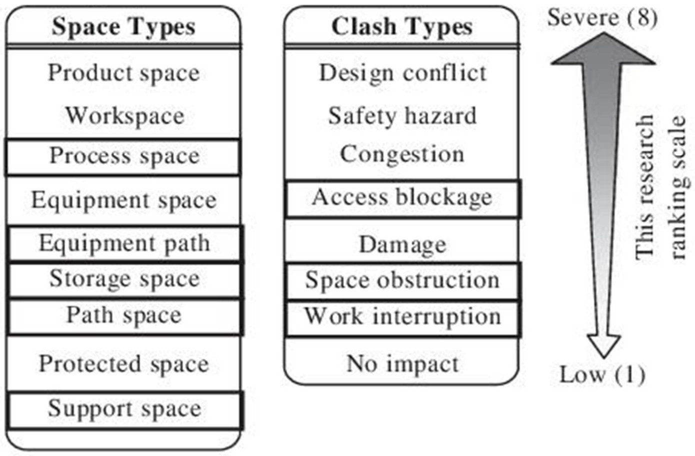


Figure 33 Mallasi's CSA Approach (Mallasi 2006)

Mallasi's model was the first to introduce the multi-criteria function to space-time analysis. It also accounts for the activities criticality, the types of workspaces and the clash types with different severities. Some would argue that this is the perfect method for clash estimation, but unfortunately there are some disadvantages to this system. One of the disadvantages is that the system can only evaluate a number of activities at the same time and not only one, which means that this study can't rank the activities based on their space criticality factor that would help planners greatly in their decision support system. Another disadvantage is the method of calculating the f_D(co) as the gathering and summation of all the conflicting volumes and the occupied spaces minimizes the f_D(co) value, which lowers its weight. Last but not least, many arguments could be raised about the importance of adding both the f_D(no) and f_D(st) to the equation, both represent factors of the same nature and thus having them both could be considered as double-counting and hence unbalance the system.

2.6 Summary of literature

Table 9 below shows the summary of the literature review. The models were investigated from the 3 main aspects mentioned in the scope of work: Workspace Generation, Clash Detection and Clash Evaluation. The basic conclusion was that the above researchers have demonstrated successful ways in generating workspaces detecting and evaluating clashes, however there were some handicaps in the following points:

- The focus on the process as a whole to deal with the challenge of automating the huge data needed for the workspace analysis
- The lack of the proper classification of the workspace types in some models, considering on the "Available Space" with reference to the "Required Space"
- The extra details of the classification of the workspace types in other studies considering the "Product Space" and the "Process Space", which was baffling to most users.
- The clear undervaluation of the clash impact in the studies. They tend to the measure the clash that happened in one of the activity to the overall workspace required of the activity for the entire duration. This gave a false indication to where the true problem was.

Author	Measurement	Different workspace types	Conflict volume analysis	Different clash types	Clash ranking	Account for activity criticality	Visualization medium	Optimization approach
Thabet and Beliveau (1994)	Space Capacity Factor	No	Yes	No	No	No	CAD	N.A
Akinci et al (2002)	Conflict Ratio + Clash Ranking	Yes	Yes	Yes	Yes	No	4D CAD	N.A
Guo (2002)	- Interference Space Percentage - Interference Duration Percentage	Yes	Yes	No	No	No	4D CAD	Manual Rescheduling
Song and Chua (2005)	Conflict Ratio	Yes	No	No	Yes	No	3D CAD	N.A
Winch and North (2006)	Spatial Loading	Yes	Yes	No	No	Yes	31 / 2D	Brute force Algorithm
Mallasi (2006)	Space Criticality Factor	Yes	Yes	Yes	Yes	Yes	4D CAD	Genetic Algorithm
Wu and Chiu	N.A	Yes	No	Yes	No	No	4D CAD	N.A

Table 9 Comparison of Previous Research

CHAPTER 3:

DEVELOPED FRAMEWORK

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Section 2 above has presented many of the past models and their techniques. The author's analysis has shown that till date, there is not a reliable model that can cover the whole process estimating the value of the space-time clashes and provide justifiable decision support mechanism to planners in the construction project. Therefore, the need still remains for a balanced decision support system that can estimate the severance of space-time clashes provide the planner with the enough information to optimize the situation. This section describes the developed framework in this study. As the literature review, the model framework will cover the following topics: the types and techniques to generate workspaces, the clash detection mechanism and the clash types resulting from the choice of workspaces. The framework will also cover the development of the "CME", which is a set of formulas used to help the planner estimate the clash severity. This framework mostly focuses on the micro-level workspaces, but allows the user to also check for some of the macro-level tasks. The framework will consist of 4 main modules:

1. 4D Model Generator
2. Workspace Generator
3. Clash Detector
4. Clash Evaluator

3.1 4D Model Generator Module

As mentioned before, one of the main problems with the calculation of the space-time clashes is the huge amount of input equation required. Thus, for the successful completion of this task, an automated method for generating the workspaces must be developed. The idea is to be able to formulate a sense of the proper size and behavior of the workspaces with the least amount possible from the planners. However, before moving to this step, one must ensure the availability of a constructible 4D model that answers the questions of What, Where, When and How the project is being built. This section presents the steps that are taken in order to generate 4D model. This study attempts to use the new concepts of Building Information Management (BIM) in its steps. The summary of this module is shown in Figure 34 below.

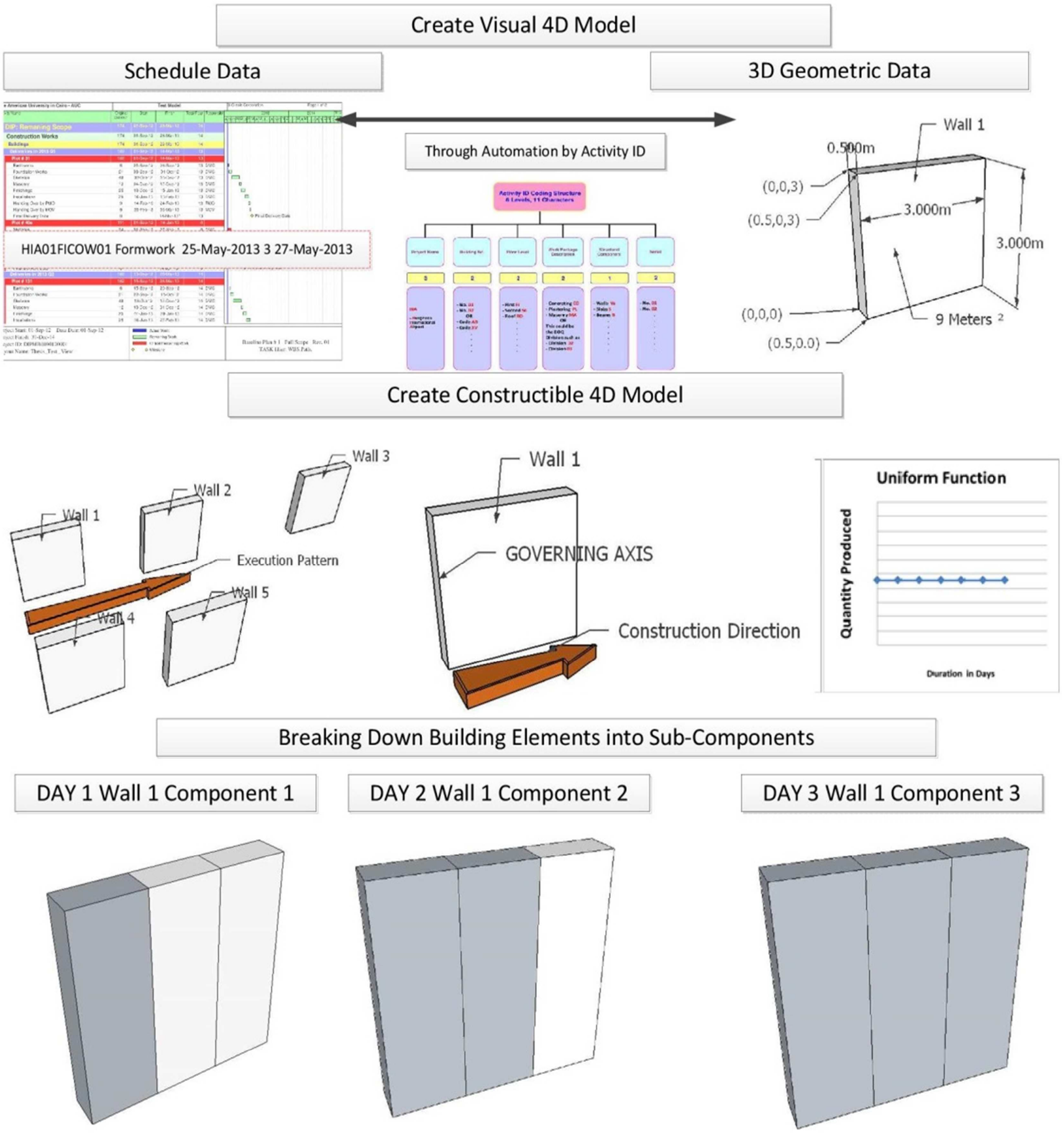


Figure 34 4D Model Generator Module

3.1.1 Creation of a Visual 4D model

This model depends mainly on the creation of the visual 4D model as the first step. This is created basically by connecting the tasks from the time schedule to the 3D building components. With the advancements of the BIM technology, it is easy to define a building component, its location dimensions, area and volume, and it is also possible to identify the orientation of the object, which face is north or south. Adding to that is the ability to assign each building component with a unique identification. In order to minimize the duration taken for linking the 3D model to the activities from the time schedule, this study suggests that creating unique identification factors to both the schedule activity and its corresponding building components so that they automatically are linked. The author has developed 2 steps to speed up the creation of the 4D model: an automatic step using the schedule Activity ID, and then manual selection.

The automated step is creating parameters in the Activity ID that can be translated and linked directly to the building component. The author has developed a coding sequence for the activity ID in the time schedule shown in Figure 35 below. The code consists of 6 levels with a total of 11 characters. By this code the 3D model is now categorized under the tasks planned. In the event that more than one activity will bear the same building objects, then manual selection would be used to categorize the conflicting objects.

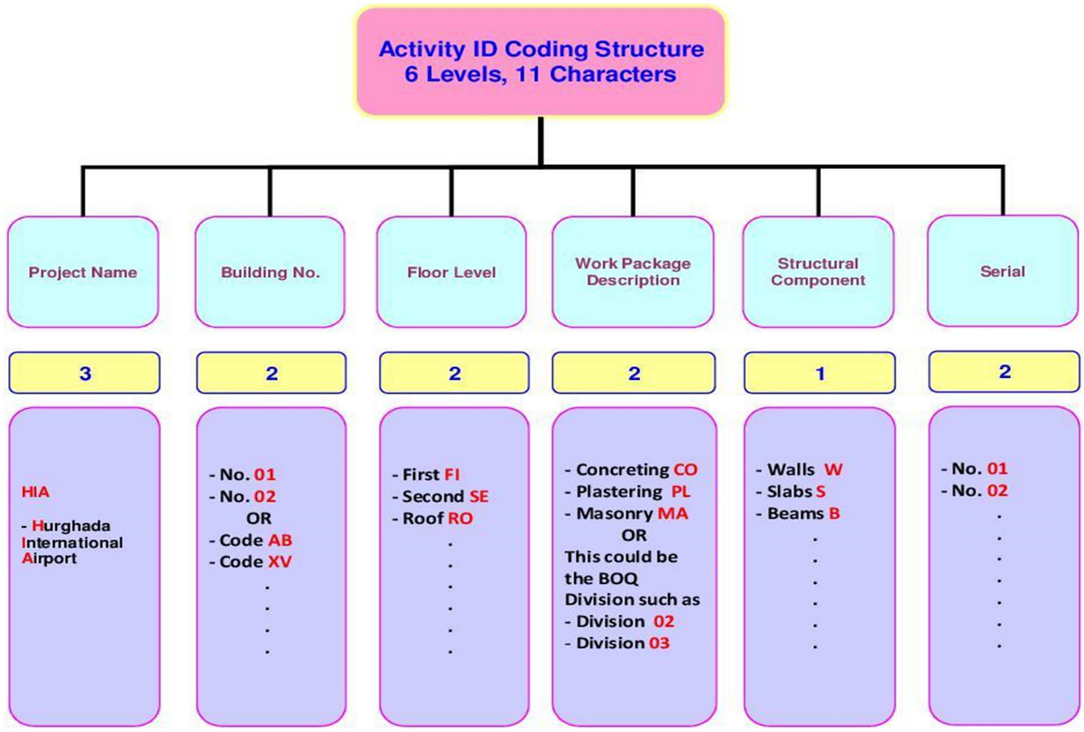


Figure 35 Activity ID Coding Structure

3.1.2 Generation of a Constructible 4D model

Most 4D models in the market are only visualization tools, and have not been used for projects control or workspace analysis. This means that the current tools cannot simulate the execution strategy resembled in the method statements for the building components (cannot build a constructible 4D model). In other words, the only important aspect about the building in the 4D model is the time, but now how or which first. Thus, this study presents the concepts needed for the creation of a "Constructible 4D model". There are 2 concepts for the study, the "Singular Construction Method, and the "Group Execution Strategy".

3.1.2.1 Singular Construction Method

The singular construction method deals with the way a single building component shall be constructed. It shall answer the question of "How is this built?" This data will be obtained from the construction method statements. Using the simple coordinate system (x,y,z), any planner will determine the direction of construction and the governing axis (terms explained before in section 2.4). The remaining issue will be the intended construction rate to answer the question of" how long and how fast is it built?" The best way to answer this is by having any statistical data from the market or previous projects that could explain the average produced quantity per day for each activity and the minimum allowable duration. Since at this moment the data is unavailable, this study has developed 3 types of quantity production simulation used in the study shown in Figure 36 below. But the planner will be asked to manually input the least allowable duration per activity

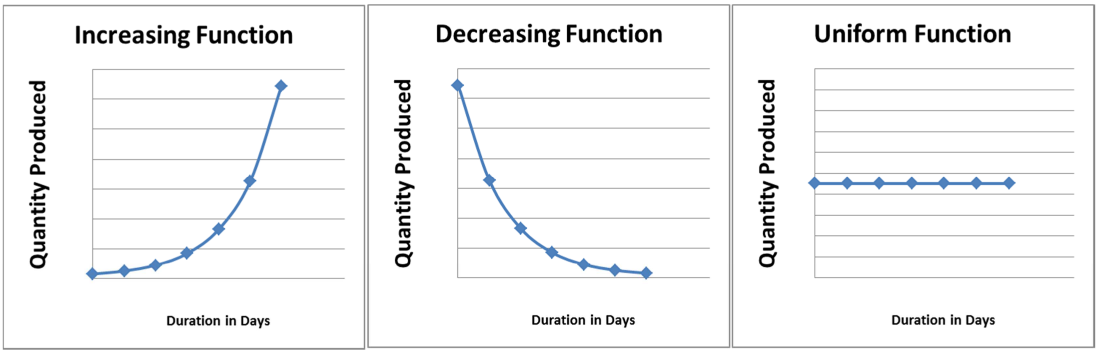


Figure 36 Completion Rates of Activities

3.1.2.2 Group Execution Strategy

The group execution strategy shall deal with the behavior of the mass. The common practice has shown that usually planners would link a group of building components to one activity, which duration would be estimated for the completion of all the components (example formwork of columns). Therefore, based on the minimum allowed duration per activity and the direction, the group execution strategy sequences the building components to simulate the construction process on site. This means that each building element can have different start and end date, provided that they all preserve the planned activity start and end dates. The sequence is identified by utilizing the cardinal category to create 4 directions: North-South, South to North, West to East and East to West. An extra direction is added "General" which explains the intention to work on all the elements at the same time. Since the study focuses mainly on the micro-level workspaces, these four construction directions will be enough to explain the site. In the event that the study includes macro-level details in the future, then the directions will need to be detailed more.

3.2 Workspace Generator Module

Having now a constructible 4D model, one can move to the next step, which would assigning the workspaces to the models to create a "Space-Loaded Model", which is a 4D model that accounts for the workspace assignments in the project.

3.2.1 Workspace Types

There are five different workspace types that are included in the study shown in Figure 37:

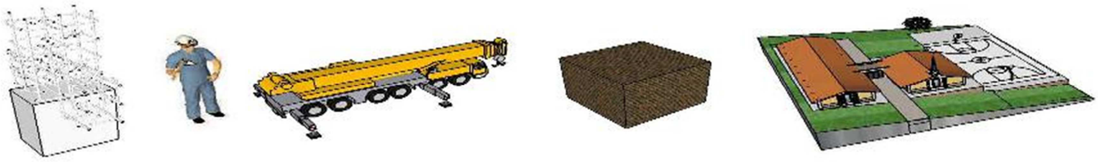


Figure 37 Workspace Types

- **Building workspace:** This workspace represents the physical dimensions of the actual building components of the project. They will be generated automatically once the building component is linked to the schedule activity. This workspace serves two purposes, the first is to help visualize the construction method based on the data from section 3.1.2 and to acknowledge the existence of this space in the model after the constriction is complete. The building workspace should be the size of the component itself in addition to a protected space to set a protection zone before causing damage. A protected space factor (PSF) was developed in this study to calculate the building workspace according to Equation 10:

$$Building\ Workspace = Actual\ Building\ component\ size * \left(1 + \frac{PSF}{100}\right)$$

Equation 10 Building Workspace Calculation

- **Labor workspace:** This workspace represents the space requirements of the labor crew in order to execute a certain activity at any building component. The dimensions of this work space are proportional to the dimensions of the building component and the crew size. Equation 11 determines the size of the workspace:

$$Labor\ workspace = (estimated\ size\ per\ one\ labor * number\ of\ labor) * maneuver\ factor$$

Equation 11 Labor Workspace Calculation

The maneuver factor must always be greater than 1, and is estimated based on the nature of the activity, the use of equipment, and the expected crew behavior. In most cases, the labor workspace will be ties to its object, thus this equation will mainly help identify the width only, since the length and the height will be that of the object itself. This workspace is always dynamic.

- **Equipment workspace:** this workspace can be used to describe two scenarios: the equipment path on the site and its operation radius. For example, if a concrete pump were to be used, then the planner would first select the workspace type as dynamic to resemble the path taken to reach the destination. Once the equipment is in position, the planner would select another workspace, but this time static to resemble the operation space around the equipment.
- **Material workspace:** Same as above for the equipment workspace, this workspace describes the material storage locations and the material paths.
- **Site workspace:** This workspace represents the site boundaries and any height limitations that could exist, such as working on a site near airports. This workspace is never linked to any activity and will always be static.

3.2.2 Automated generation of workspaces

Once the Constructible 4D model is created, objects are categorized below their tasks, and all the needed data regarding their construction is lined. At this level of detail, site engineers and superintendents through a series of qualitative data can automatically generate the workspace sizes and behavior. This data is then translated into geometrical displacements to be simulated. The data will cover:

- Workspace types used in the activity
- Workspace's relationship: whether they are directly linked to the building objects or just share the same duration. For example, the concrete pump is used for pouring the walls, but will be positioned away from them, whereas masons will work directly in front of the walls.

- Workspace location: if it is not related to building objects, then size and location will have to be manually drawn. But, if it is linked to the object, then Table 10 below shows the location options that the site engineers would use to describe it.

Location Option	Geometrical Translation
Around	Workspace will be along all faces of the object
Parallel	Workspace will be parallel the longest face of the object
Below	Workspace will be below the lowest z-component of the object
Above	Workspace will be above the highest z-component
Inwards	Workspace will be along the face connecting to the ceiling and floor
Outwards	Workspace will be along the face not connecting to the ceiling and floor
Perpendicular	Workspace will be parallel the shortest face of the object

Table 10 Geometry of Location Options

- Workspace size: the workspace size will be determined using the terms long, wide and high, to reflect the length, width and height respectively. If the workspace is linked to the object, then based on the Singular Construction Method in section 3.1.2.1 and the workspace location, defaults for the workspace size can be assumed. For example, if the workspace is parallel to the object, it will probably have the same length and height, and the planner would only need to input the width.
- Workspace behavior: whether it is a static workspace that would preserve the same dimensions and location throughout the planned duration, or it is a dynamic workspace that would change dimensions or location throughout the planned duration.

3.2.3 Workspace representation in 4D

This study shall use the cuboid (rectangular prism) same as the previous authors' choice in representing the geometrical data of the workspaces.

3.3 Clash Detector Module

At this stage the output of the 2 generator modules would be a matrix as shown in Figure 38 below, where each element has been linked to an activity, assigned a workspace, and has been decomposed into its sub-components to know exactly what is being done, when, where and how. So, this next section describes the clash detection mechanism of the framework.

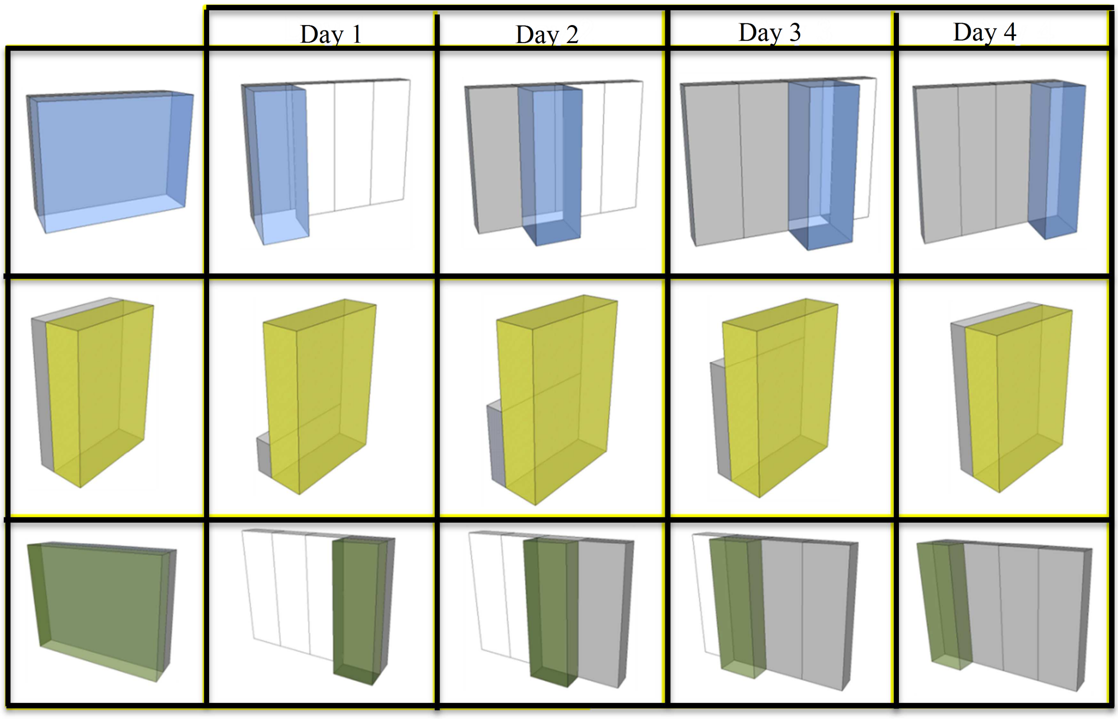


Figure 38 Outputs of the 2 Generator Modules

3.3.1 Relational Database Concept

Relational Database Concept means that any parameter is entered once, linked to all and used many. The database connects all the graphical data from the 3D model to the schedule data to the formulated 3D information of the workspaces. Figure 39 below shows the UML diagram to explain the relations built in the framework:

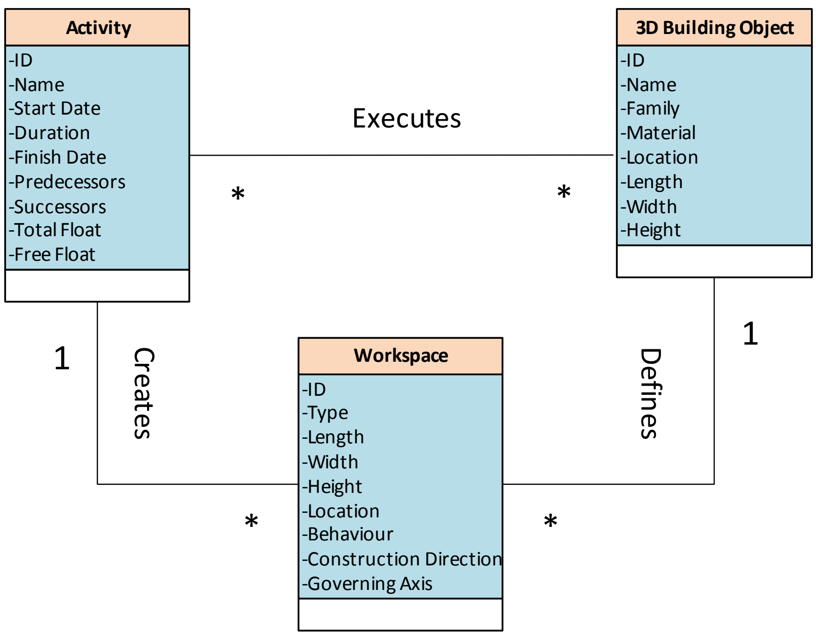


Figure 39 UML Diagram

3.3.2 Discrete Event Simulation

As explained before in literature, in order to capture any space-time conflicts in a 4D model loaded with the workspaces' properties, a discrete event must be produced. In this discrete event, the graphical properties of all the objects and their workspaces are fixed (the model works on the graphical information of the sub-components). By that method, the detection for clashes becomes and geometrical clash detection. The output from the 2 generator modules as shown in Figure 38 above, has considered each single day as a discrete event itself, from which clashes could be detected.

3.3.3 Trial Period

The trial period is the duration at which the discrete events are formed. Each discrete event in this model is 1 day. Based on the desired accuracy of the planner, the discrete events could be daily, weekly or monthly. The TP would define the duration between the events. It is recommended the TP is 1. Discrete events will be formulated at the following days using Equation 12:

$$Day_{i+1} = Day_i + TP$$

Equation 12 Determining the Dates of the Des

Where Day_i starts with the value of the Project Start Date and the maximum Day_{i+1} is less than or equal the Project End Date

For example, if the TP = 7 then the discrete events would be taken at Day 1, Day 8, Day 15, etc.

3.3.4 Pair-wise Detection Concept

After choosing the targeted days for investigation through the trial period, this section describes how it would check for the clashes. The model adopts the pair-wise system, which means that it chooses one of the objects and pairs it up with other objects to check for any geometrical clashes. Once the object is has been paired with the rest, it is removed from the calculations and the process is repeated until all objects have been checked. So for example, if A, B and C clash at the same time, then the model would record 3 clashes, A with B, A with C and B with C. The number of checks that is performed at each discrete event is calculated according to Equation 13:

$$Number\ of\ Checks = \frac{n!}{(n-r)! \times (r!)}$$

Equation 13 Number of Checks per Discrete Event

Where n = the number of workspaces in the discrete event and r = 2 (pair-wise concept).

3.3.5 Clash Types

Although the common practice before is to describe the clash based on the physical impact it would have on a site (for example when a building component interferes with an equipment component, this could be a damage clash), the study describes them as the workspaces that have interfered. So for example, an equipment-labor clash is the clash type that occurs from a labor workspace interfering with an equipment workspace. Since the model adopts the pair-wise system, as explained above in section 3.3.4, the clash type will not have more than 2 workspaces. Accordingly, the number of clashes in the model would be given by Equation 14:

$$NCT = \frac{(n + r - 1)!}{r!\,(n - 1)!}$$

Equation 14 Number of Clash Types Equation

Where NCT = the number of clash types (workspace combinations), N = the number of workspaces (in our case 5) and R = the combination between the workspaces which will always be 2 (pair-wise). So, in the model with 5 workspace types, there are 15 different clash types as shown in Figure 40.

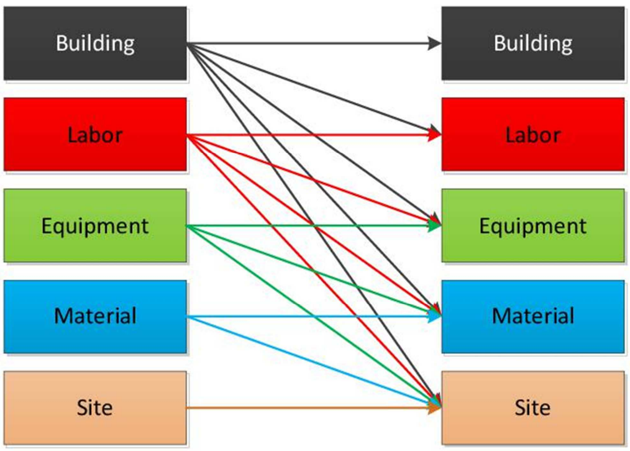


Figure 40 Workspace Combinations (Clash Types)

3.3.6 Severity of Clashes

There are some main points that any planner should investigate in order to help in identify and clash a clash:

- The complexity of the construction: simple structural system, choice of mechanical an electrical systems, etc.

- The site possession situation: whether it’s partial or full site possession.
- The type of equipment being used and their proximity to the building according to the site layout plan.
- The number of access points in the project.
- The possible work conditions for labor: compact spaces, high-rise structures, etc.
- The resource histograms to speculate the average ratio of labor to equipment on a daily basis.
- The criticality factor in the time schedule to determine the allowable tolerance.
- The strategic priorities of the project, should the focus be more on quality, or on safety or time?

This study considers three main clash categories: High, Medium and Low. The reason of this choice is the variable nature of the construction projects that two workspaces interfering could have more than one impact. Taking the interference between a building component clash and an equipment clash, it would usually be considered as a damage clash, since it is assumed that the equipment would damage part of the existing structure (Akinci, Fischer, and Kunz 306-315; Mallasi 2006; Akinci et al. 2002). But, what if the project nature was a partial handover to the contractor, and the equipment interfering with the structure had working offices? Then this clash would automatically be a safety hazard clash and not just damage.

Similarly, some researchers considered the clashes between the equipment workspaces as congestion, which is not always the case (Wu and Chiu 2010). It is granted that some of the clashes by equipment workspaces could be considered as congestion, such as two trucks competing on the same access point, but what if there was a more serious case? If the workspace interference were between two cranes due to poor site planning, then the clash cannot be considered as congestion, but should be damage, as certainly this clash would damage the cranes and would cause a serious productivity problem to the site; crossing one’s finger together that it doesn’t become a safety hazard and casualties are suffered.

There are some clash impacts that all could agree upon, which are the building vs. building and the site vs. site as a “no impact” clash. If the definition for the workspace types above is revised, then the building vs. building clash type would be between the protection spaces and hence has no impact. This is of course assuming that the 3D model is free from any design conflicts and there many tools in the market now to do so. On the other hand, the site vs. site clash is just a programming clash and has no physical meaning and thus can be considered as no impact.

The severity of the clash may vary from one case to the other. Thus, this model utilizes the Monte Carlo simulation in predicting the values High, Medium and Low categories. Future study is needed in this area to be able to formulate the correct probability distribution for each category. Till then, the model assumes a uniform probability distribution with the values of 0.85, 0.5, and 0.25 for the High, Medium and Low respectively. For the no impact clashes the value would be zero.

3.3.7 Clash Detection Constraints

The model enforces some hard constraints that prevent the unbalancing or the over-estimation of clashes. The first hard rule prohibits the assigning of the same workspace to the same object of the same activity more than once. In other words, a wall undergoing the masonry activity cannot have two labor workspaces, but can have a labor and material workspace. The other constraint is that the interferences between the workspaces of the same object of the same activity are not considered a clash. It is assumed that the different workspaces built for one object linked to a certain activity work in harmony and must interfere in order to get the job done. Hence, the model neglects any interferences happening between the workspaces of the same activity of the same object.

3.4 Clash Estimator Module

This study developed a new multi-criterion function named the Clash Magnitude Estimator "CME" that would assist planners in qualitatively estimating the impact of the different clashes in a construction project and provide the enough analysis in order to decide on the preferable optimization. This section presents the findings and introduces the new equation. In order to minimize the computational effort and ensure receiving the results in a timely acceptable manner, the CME was designed to work on two levels. Figure 41 shows the flowchart for the clash detection and evaluation

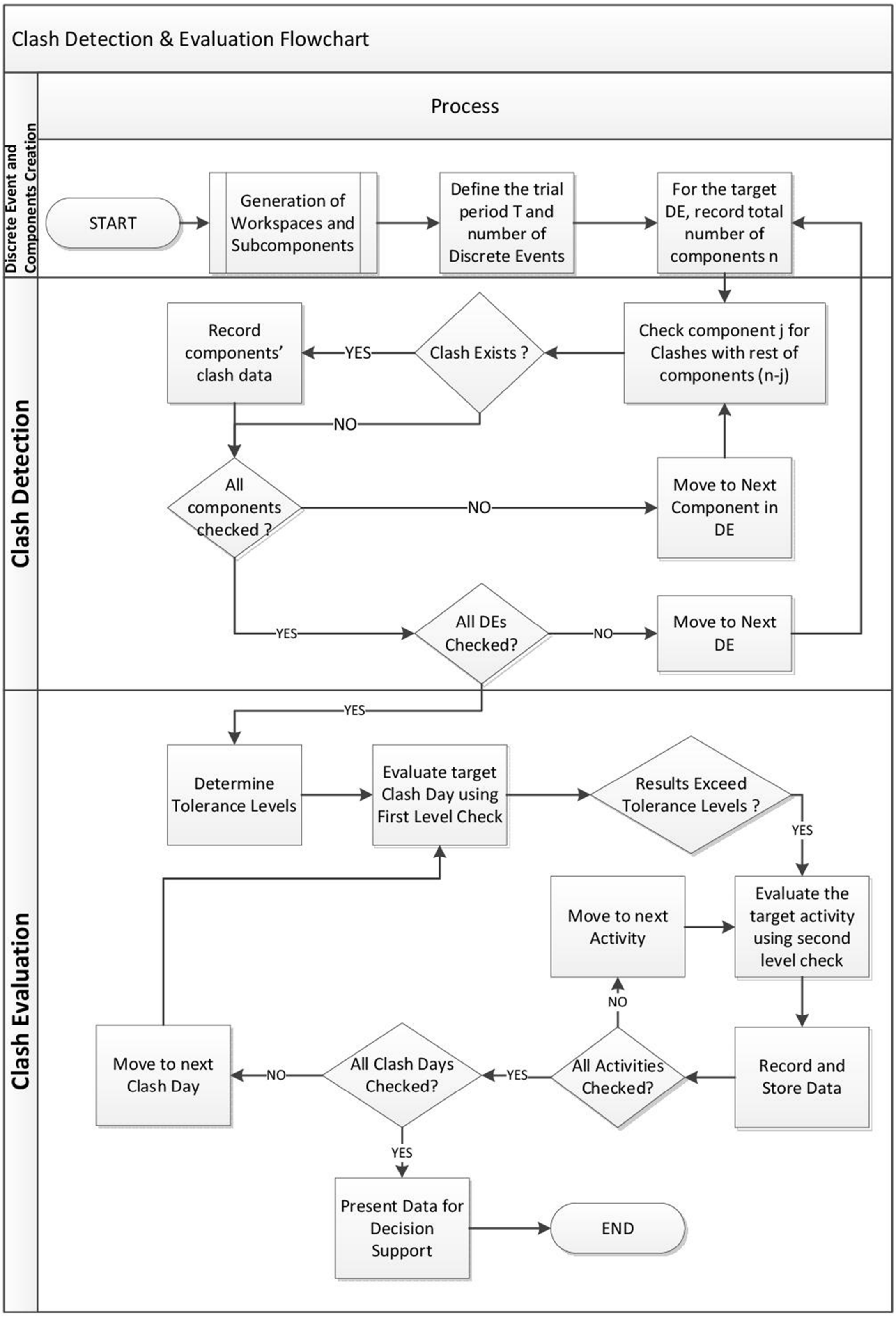


Figure 41 Clash Detection and Evaluation Flowchart

3.4.1 First Level Check: The Space-Time Criticality Factor

The first check's idea is similar to that of the planner's criticality factor. Here, the idea is to set the project's tolerance level for the allowable clashes per day. The system then checks for the days which are out of those tolerance levels, and would need extra investigation. The equation for the first level check for a given day *n* is as follows in Equation 15:

$$Day_n = \sum_{i=1}^{i=NC} w_1.\frac{V_{ci}}{V_{pi}} + w_2.SFi$$

Equation 15 First Level Check: Space-Time Criticality Factor

Where NC = the number of clashes at that day, V_c = The volume of the conflicting space between the two workspace types, V_p = The planned volume required by both workspaces at that day, SF = The value of the severity of the clash, and w_1, w_2 = User-defined weights that are decided upon the start of the project. However in this check, it is recommended that the weight for the severity factor be greater than that of the volume ratio, since the clashes with the bigger severity should be the top priority. Here the target is to prioritize the problems in the project, starting with the days with highest space-time clashes and then working down the line.

3.4.2 Second Level Check: Clash Magnitude Estimator

At this point, the system has identified the critical days with the highest space-time clashes. Accordingly, the second level of investigation will start, which will be conducted on the activities that are working in these days. The target from this check is to pinpoint the activity with the highest space-time clashes, which when modified would enhance the project behavior. Also, this check provides the user with the prioritization of the activities, which are the most causing space-time clashes and which are the least. The equation that is used to evaluate the activity's behavior is as follows in Equation 16:

$$CME_{Activities} = \sum_{n=1}^{n=CN} w_1.\frac{V_{cn}}{V_{Apn}} + w_2.\frac{D_{cn}}{D_{Apn}} + w_3.CFn + w_4.SFn$$

Equation 16 Second Level Check: Clash Magnitude Estimator

Where V_c = The volume conflicting between 2 workspaces, V_{ap} = Planned workspace volume of the activity, D_c = the length of the clash in days, D_{ap} = the planned duration of the activity, CF = a measure to indicate the criticality of the activity in question, SF

= the quantification of the clash type based on the workspaces, and CN is the total number of clashes that the activity is suffering.

CHAPTER 4:

IMPLEMENTATION OF THE DEVELOPED FRAMEWORK

CHAPTER 4: IMPLEMENTATION OF THE DEVELOPED FRAMEWORK

This chapter describes the tools developed in order to test the developed framework in Chapter 3. It describes to main parts: first the software tool used for inputting and processing the data for workspace generation, and second a test model to display the analysis techniques of the resulting data.

4.1 Development of the software tools

The tool needed for this study can be categorized into 3 main parts: a planning tool, a 3D graphical tool, and a tool for workspace generation. The planning and 3D graphical tools are common and any type could be used in this study. However, a software tool for workspace generation has been developed specifically since there was no tool in the market to do so.

The software tool developed is called the "Activity Workspace Generator (AWG)". The AWG utilizes the GUI of the Blender software, which is 3D software using the python programming language with an open-source license (Blender Organization). Being an open-source license has allowed the developers to modify the software to collect and process the data needed for defining the workspaces, detecting and calculating the clash volumes. Figure 42 below describes the main components in the user interface that help in gathering the data.

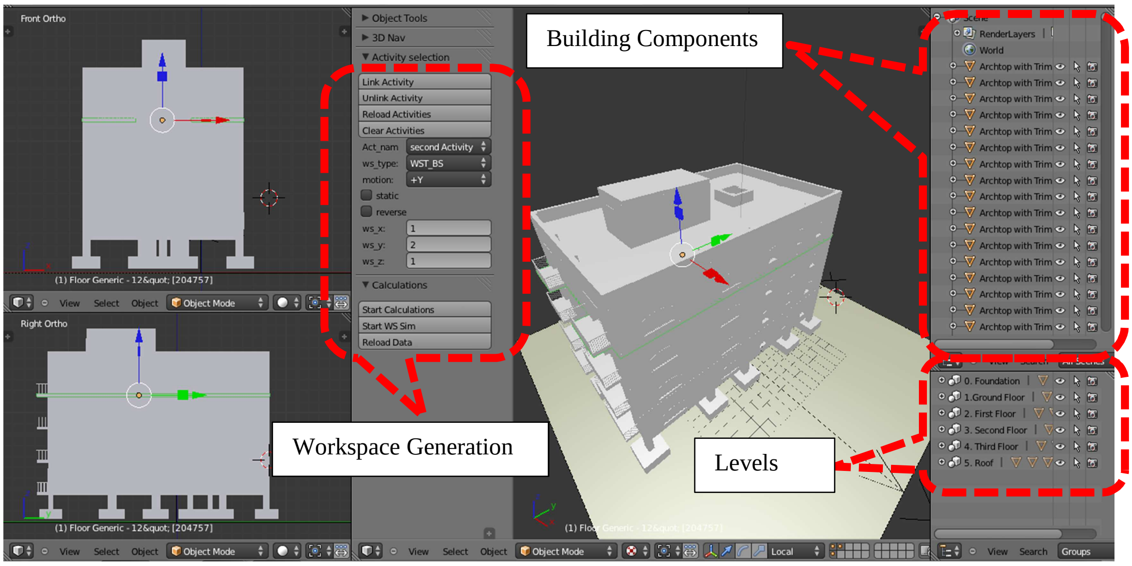


Figure 42 User Interface of the AWG

The Blender accepts the Film Box (FBX) format from any drawing software, which captures the graphical data and the IDs of the building components. The data from the planning software is inputted into the blender using the Comma-Separated Values (CSV) format. Figure 43 explains the functions in the Workspace generation component that is used after the object is selected to create the 4D schedule and input the workspaces. For the simplicity of the data entry, each object's orientation is according to its local axes, rather than providing one global set of axes for all.

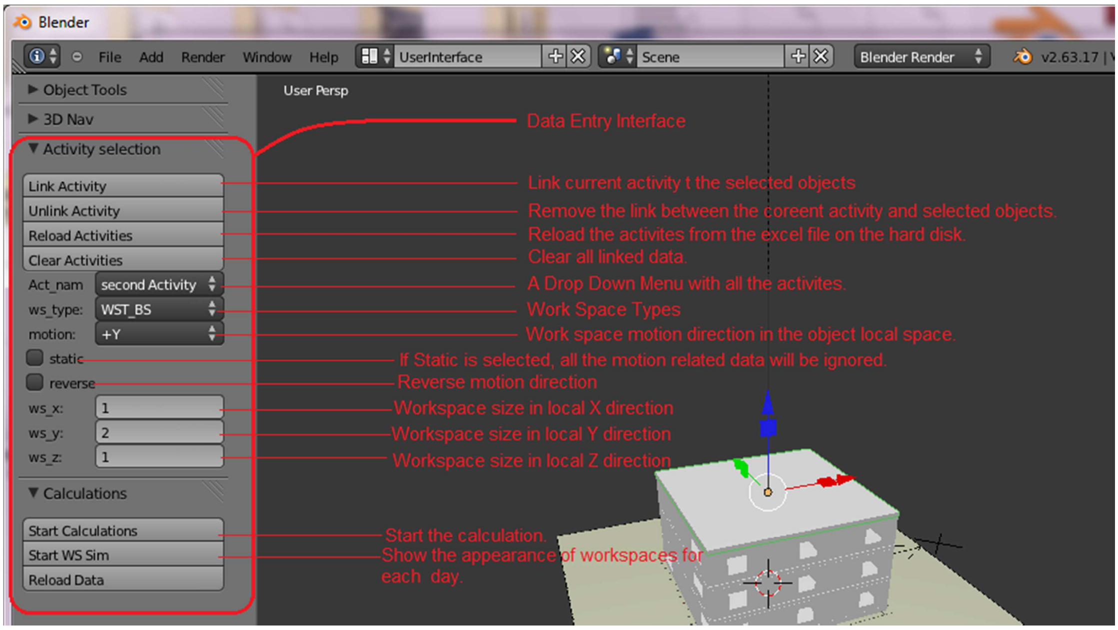


Figure 43 Workspace Generation Component

Once all the workspace data for the objects is inputted in the software, it starts to create the properties for each building object as a set of decision in a singly array. The trial period is set to 1, the PSF is 0 and the assumed quantity production simulation is uniform. The AWG ends with the calculation of the clashes' volumes and the rest of the analysis is done using the Microsoft Office Excel tool.

4.1.1 Clash Detection and Volume Estimation

Since the software is originally a 3D model, it is capable of determining the center point of each building element. The clash detection mechanism depends on measuring the ratio between the distances of 2 elements' center points and their dimensions. If the ratio is less than 1, then a clash exists and will start calculating its volume. This is done in two steps: first the blender has already a built-in algorithm that can formulate the shape of the intersection clashing between 2 objects, and then the developers have added another algorithm for calculating the volume. Since, the intersection output is not always a regular shape, so the calculation of the volume is done by slicing the shape from any assumed center to tetrahedrons and then calculating the summation of their volumes (Zhang and Chen 2013). For example if we have a 4 vertices shape such as a cube, it has six faces, each face consists of two triangles, so we take each triangle 3 vertices and connect it to the assumed center to form a tetrahedron and calculate its volume and do the same for the other triangles. So, if we have the assumed center point O= (0, 0, 0) and a triangle ABC where A=(x1, y1, z1), B=(x2, y2, z2), C=(x3, y3, z3), the volume of tetrahedron OACB is according to Equation 17:

$$|V_{OACB}|=\left|\frac{1}{6}(-x3y2z1 + x2y3z1 + x3y1z2 - x1y3z2 - x2y1z3 + x1y2z3)\right|$$

Equation 17 Volume of Tetrahedron (Zhang and Chen 2013)

4.2 Design of the test model

A test model was designed for two main reasons: first is to provide an illustrative example of the calculations done for the clash evaluation adopted in this study and to verify the developed “AWG”.

4.2.1 Test Model to Measure the CME effectiveness

Figure 44 shows the dimensions of the test model, it consists of five walls each with the thickness of 0.5 m. Two scenarios of the construction execution on the model were tested.

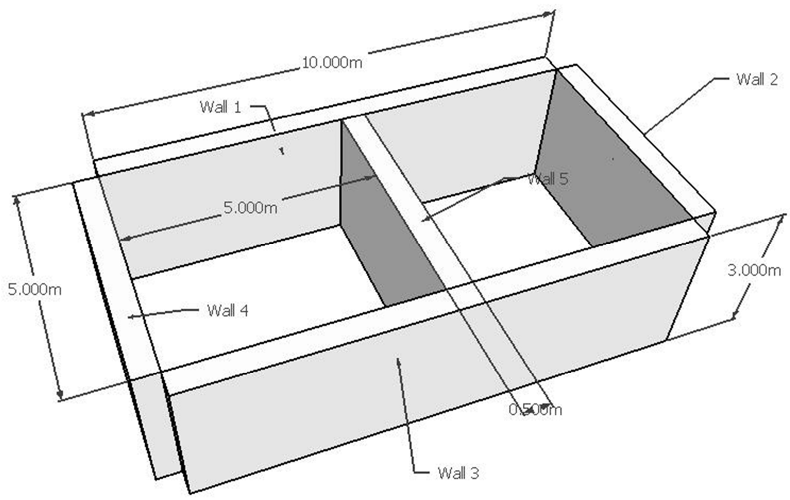
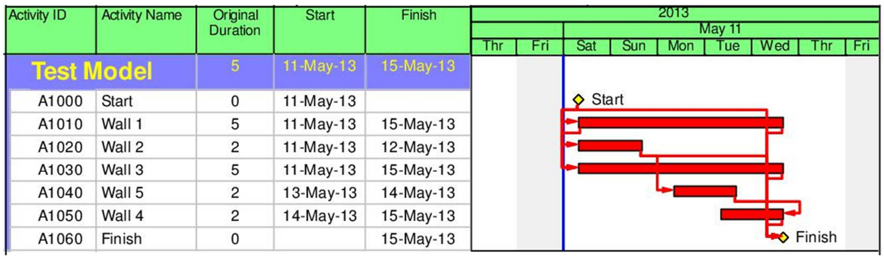


Figure 44 Test Model Design

For simplicity, the wall will only have one type of workspace which is the labor workspace. The planned schedule is shown in Figure 45. The workspaces for the walls and the intended construction direction are shown in Figure 46. The governing axis for the walls is assumed to be perpendicular to the construction direction.



Activity ID	Activity Name	Original Duration	Start	Finish
Test Model		5	11-May-13	15-May-13
A1000	Start	0	11-May-13	
A1010	Wall 1	5	11-May-13	15-May-13
A1020	Wall 2	2	11-May-13	12-May-13
A1030	Wall 3	5	11-May-13	15-May-13
A1040	Wall 5	2	13-May-13	14-May-13
A1050	Wall 4	2	14-May-13	15-May-13
A1060	Finish	0		15-May-13

Figure 45 Test Model Schedule

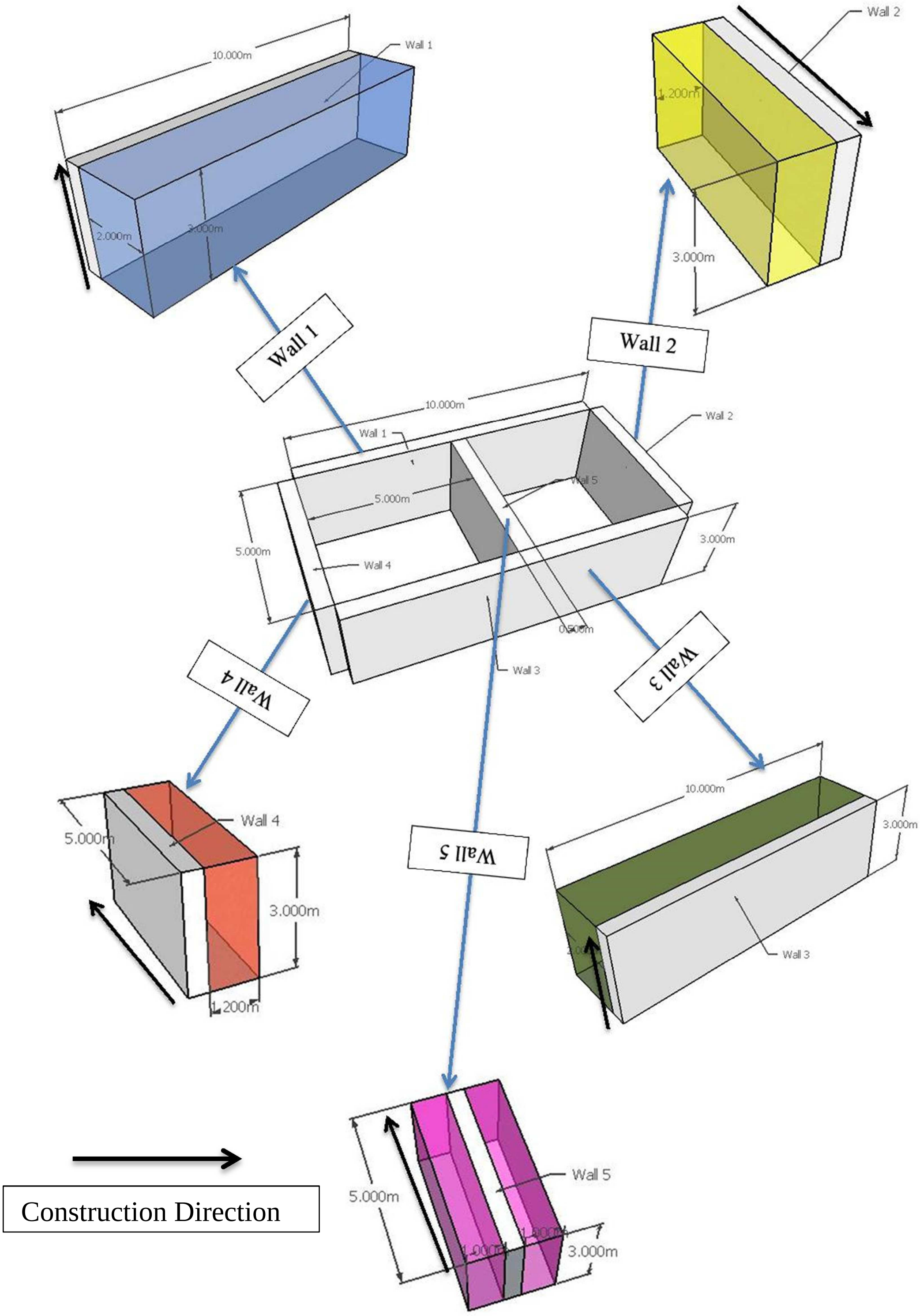


Figure 46 Workspaces for Scenario 1 in Test Model

Different colors have been given to the labor workspace of each wall in Figure 46 to ease the simulation process. Table 11 below shows the simulation of scenario 1 based on the same assumptions that the AWG has.

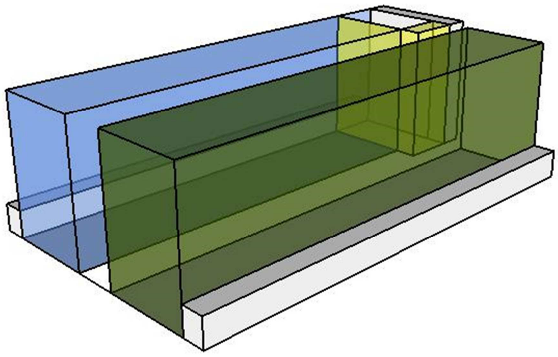
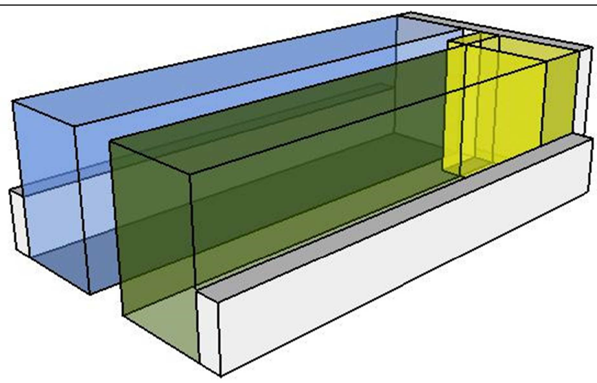
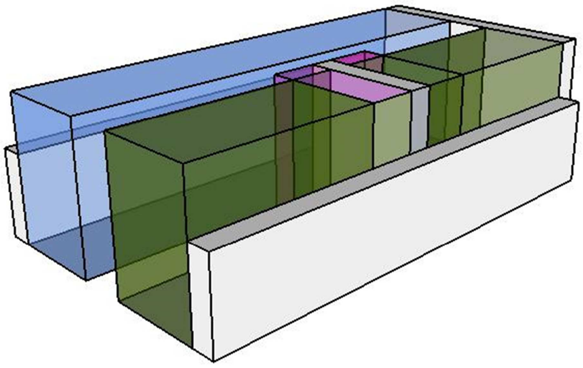
Day	3D Simulation
11-May-13	
12-May-13	
13-May-13	

Table 11 Scenario 1 Simulation

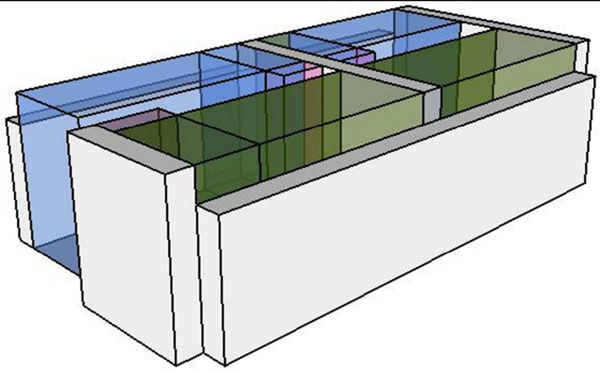
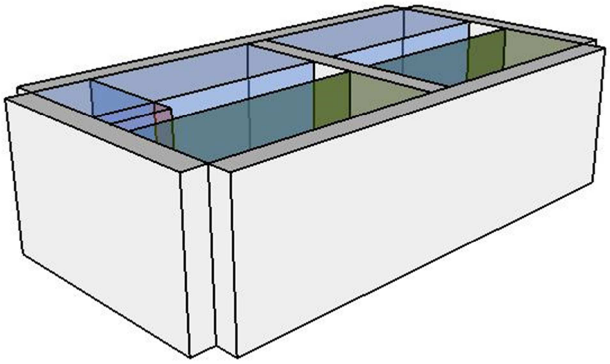
14-May-13	
15-May-13	

Table 12 Scenario 1 Continued

Table 13 presents the clashes arising in the model based on the simulation Table 11:

#	Clash Date	Activity ID	Activity Name	Workspace	Planned Workspace Volume (m^3)				Activity ID	Activity Name	Workspace	Planned Workspace Volume (m^3)				Clash Dimensions			
					Length (m)	Width (m)	Height (m)	Volume (m^3)				Length (m)	Width (m)	Height (m)	Volume (m^3)	Length (m)	Width (m)	Height (m)	Volume (m^3)
1	11-05-2013	A1010	Wall 1	Labor	10	2	3	60	A1020	Wall 2	Labor	2.5	1.2	3	9	2	1.2	3	7.2
2	12-05-2013	A1020	Wall 2	Labor	2.5	1.2	3	9	A1030	Wall 3	Labor	10	2	3	60	2	1.2	3	7.2
3	13-05-2013	A1030	Wall 3	Labor	10	2	3	60	A1040	Wall 5	Labor	2.5	2	3	15	2	2	3	12
4	14-05-2013	A1040	Wall 5	Labor	2.5	2	3	15	A1010	Wall 1	Labor	10	2	3	60	2	2	3	12
5	14-05-2013	A1050	Wall 4	Labor	2.5	1.2	3	9	A1030	Wall 3	Labor	10	2	3	60	2	1.2	3	7.2
6	15-05-2013	A1050	Wall 4	Labor	2.5	1.2	3	9	A1010	Wall 1	Labor	10	2	3	60	2	1.2	3	7.2
7	15-05-2013		Wall 5	Building	5	0.5	3	7.5	A1010	Wall 1	Labor	10	2	3	60	2	0.5	3	3
8	15-05-2013		Wall 5	Building	5	0.5	3	7.5	A1030	Wall 3	Labor	10	2	3	60	2	0.5	3	3

Table 13 Clashes Resulting from Scenario 1

Table 14 below shows the calculation of the first level check using Equation 15:

#	Clash Date	Workspace Type 1	Workspace Type 2	Vp			Vc (m^3)	W1	W2	Severity Factor	First Level Check
				Vp 1 (m^3)	Vp 2 (m^3)	Vp Total (m^3)					
1	11-May-13	Labor	Labor	60	9	69	7.2	0.4	0.6	0.5	0.342
11-May-13 Total											0.342
2	12-May-13	Labor	Labor	9	60	69	7.2	0.4	0.6	0.5	0.342
12-May-13 Total											0.342
3	13-May-13	Labor	Labor	60	15	75	12	0.4	0.6	0.5	0.364
13-May-13 Total											0.364
4	14-May-13	Labor	Labor	15	60	75	12	0.4	0.6	0.5	0.364
5	14-May-13	Labor	Labor	9	60	69	7.2	0.4	0.6	0.5	0.342
14-May-13 Total											0.706
6	15-May-13	Labor	Labor	9	60	69	7.2	0.4	0.6	0.5	0.342
7	15-May-13	Building	Labor	7.5	60	67.5	3	0.4	0.6	0.85	0.528
8	15-May-13	Building	Labor	7.5	60	67.5	3	0.4	0.6	0.85	0.528
15-May-13 Total											1.397

Table 14 First Level Check Calculations

The values for the severity factor and the weights are shown in Table 15

Severity Factors		
Workspace	Workspace	Value
Labor	Labor	0.5
Building	Labor	0.85

Weights	
W1	0.4
W2	0.6

Table 15 Severity Factor and Weights Values

Graphing the results of the First Level check and considering the tolerance to have a maximum value of 0.75, then Figure 47 below shows the problem in day 15-May-2013

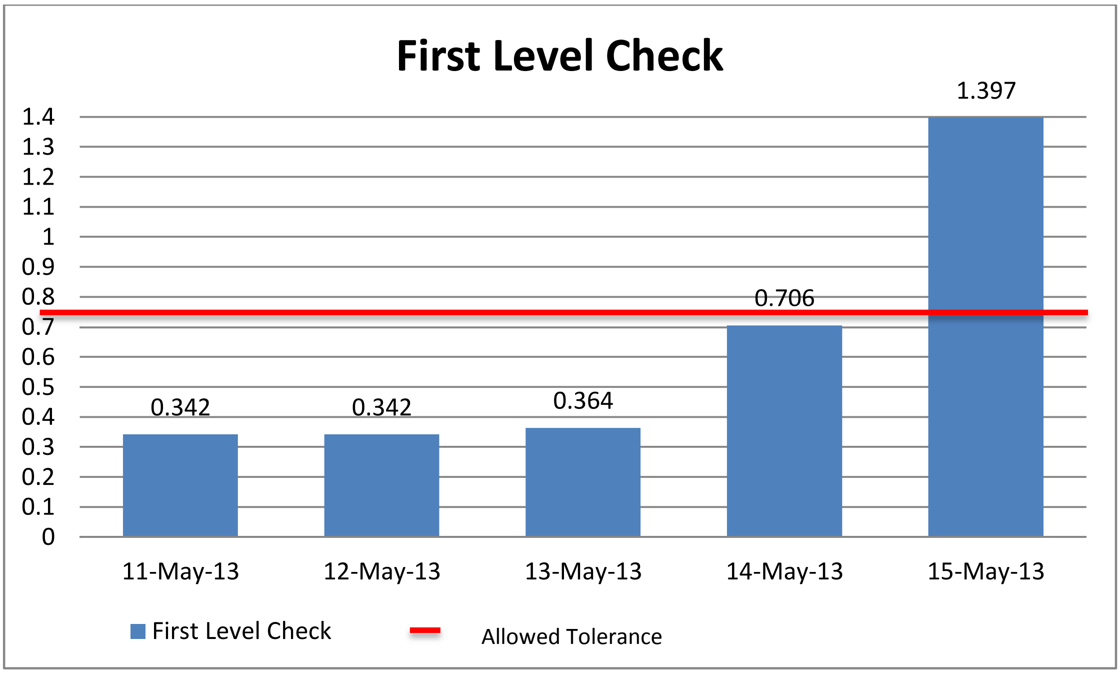


Figure 47 First Level Check Results

Therefore the second level check is applied to the activities in 15-May-2013 which are Wall 1, Wall 3 and Wall 4, whose calculations are shown in Table 16 below:

Activity Name	Clash Dates	Workspace Type	Planned Workspace Volume (m^3)	Clashed With: Activity Name / Object Name	Clashed With: Workspace Type	Clashed With: Clash Volume (m^3)	Total Float	W1	Vc (m^3)	Vp (m^3)	W2	Dc (days)	Dp (days)	W3	CF	W4	SF	CME Value
Wall 1	11-May-13	Labor	60	Wall 2	Labor	7.2	0	0.3	7.2	60	0.1	1	5	0.1	0.9	0.5	0.5	0.396
Wall 1	14-May-13	Labor	60	Wall 5	Labor	12	0	0.3	12	60	0.1	1	5	0.1	0.9	0.5	0.5	0.42
Wall 1	15-May-13	Labor	60	Wall 4	Labor	7.2	0	0.3	7.2	60	0.1	1	5	0.1	0.9	0.5	0.5	0.396
Wall 1	15-May-13	Labor	60	Wall 5	Building	3	0	0.3	3	60	0.1	1	5	0.1	0.9	0.5	0.85	0.55
Wall 1 Total																		1.762
Wall 3	12-May-13	Labor	60	Wall 2	Labor	7.2	0	0.3	7.2	60	0.1	1	5	0.1	0.9	0.5	0.5	0.396
Wall 3	13-May-13	Labor	60	Wall 5	Labor	12	0	0.3	12	60	0.1	1	5	0.1	0.9	0.5	0.5	0.42
Wall 3	14-May-13	Labor	60	Wall 4	Labor	7.2	0	0.3	7.2	60	0.1	1	5	0.1	0.9	0.5	0.5	0.396
Wall 3	15-May-13	Labor	60	Wall 5	Building	3	0	0.3	3	60	0.1	1	5	0.1	0.9	0.5	0.85	0.55
Wall 3 Total																		1.762
Wall 4	14-May-13	Labor	9	Wall 3	Labor	7.2	0	0.3	7.2	9	0.1	1	2	0.1	0.9	0.5	0.5	0.63
Wall 4	15-May-13	Labor	9	Wall 1	Labor	7.2	0	0.3	7.2	9	0.1	1	2	0.1	0.9	0.5	0.5	0.63
Wall 4 Total																		1.26

Weights	Values
W1	0.3
W2	0.1
W3	0.1
W4	0.5

Severity Factors		
Workspace	Workspace	Value
Labor	Labor	0.5
Building	Labor	0.85

Criticality Factors	
T.F Range	Value
0≤x<20	0.9

Table 16 Second Level Clash Results

The results show that Wall 1 and Wall 3 have a CME value of 1.762 each where Wall 4 has lesser value of 1.26. This indicates that the choices made for Wall 1 and 3 ought to be revised. Accordingly, Scenario 2 was designed with changes applied to the workspaces of Walls 1 and 3 only as shown in below in Table 17:

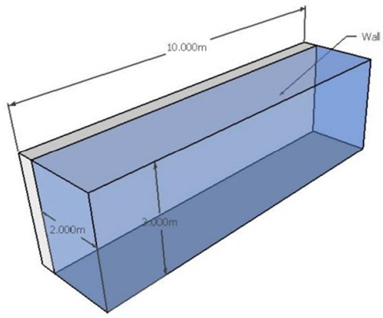
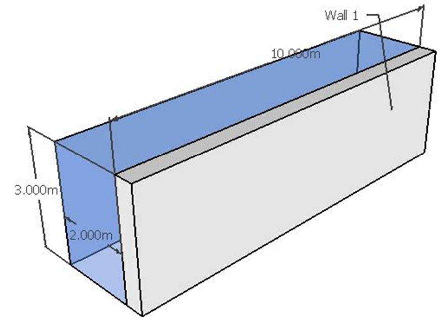
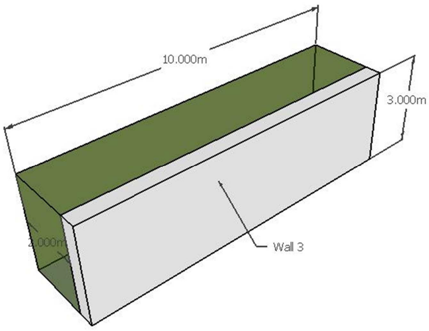
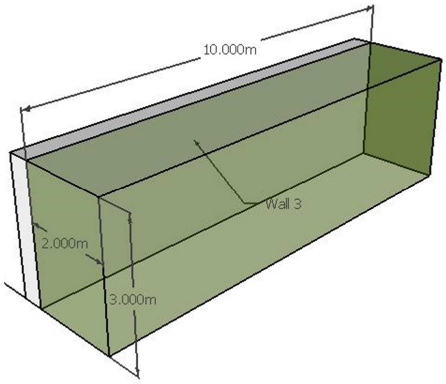
Wall #	Scenario 1 Workspace	Scenario 2 Workspace
1		
3		

Table 17 Workspaces Changes for Scenario 2

Thus, the simulation for scenario 2 is shown in Table 18:

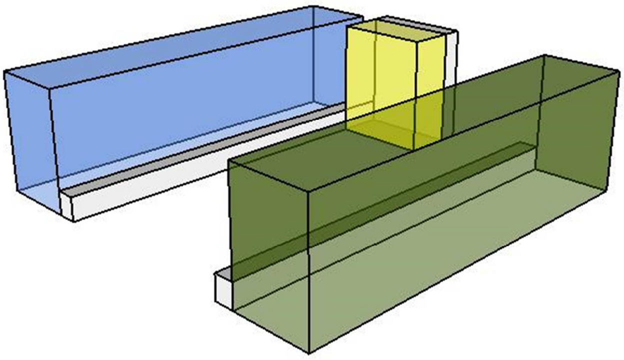
Day	3D Simulation
11-May-13	

Table 18 Simulation of Scenario 2

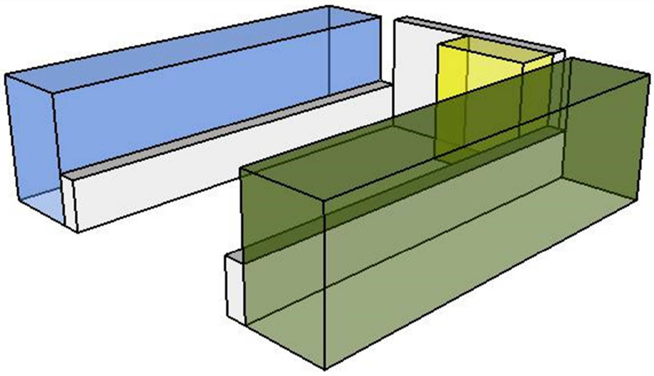
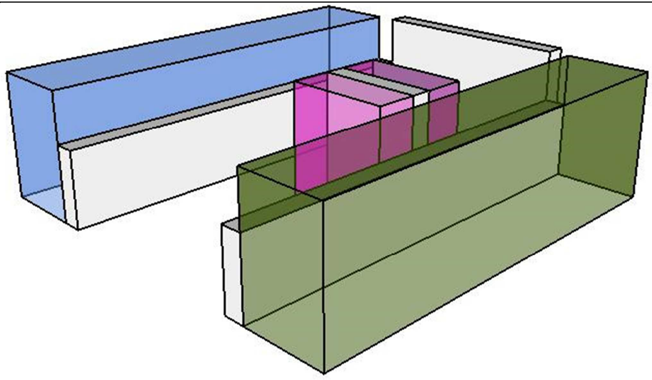
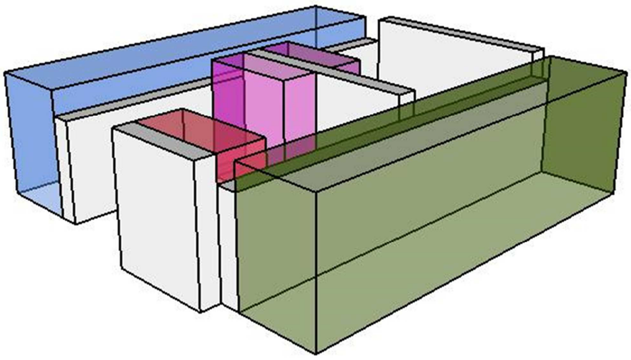
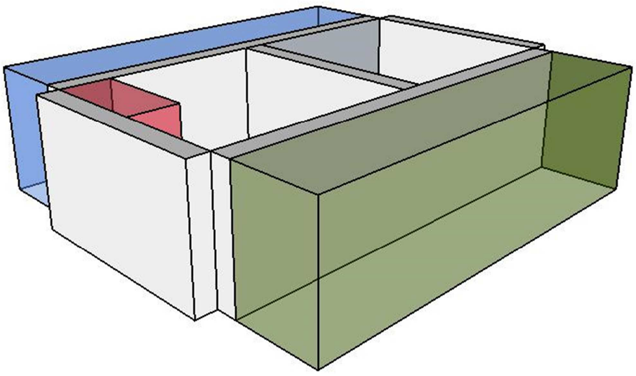
12-May-13	
13-May-13	
14-May-13	
15-May-13	

Table 19 Scenario 2 Continued

The simulation shows that there are no clashes, which proves that the results of the clash evaluation mechanism were successful in pinpointing the preferable optimization solution.

4.2.2 Verification of the AWG

Since the AWG's main task is to estimate the clash volume arising from any space-loaded model, Scenario 1 was repeated using the AWG and the results were compared. This section also provides the user with the method for inputting the data into the AWG. Figure 48 shows a snapshot of the model

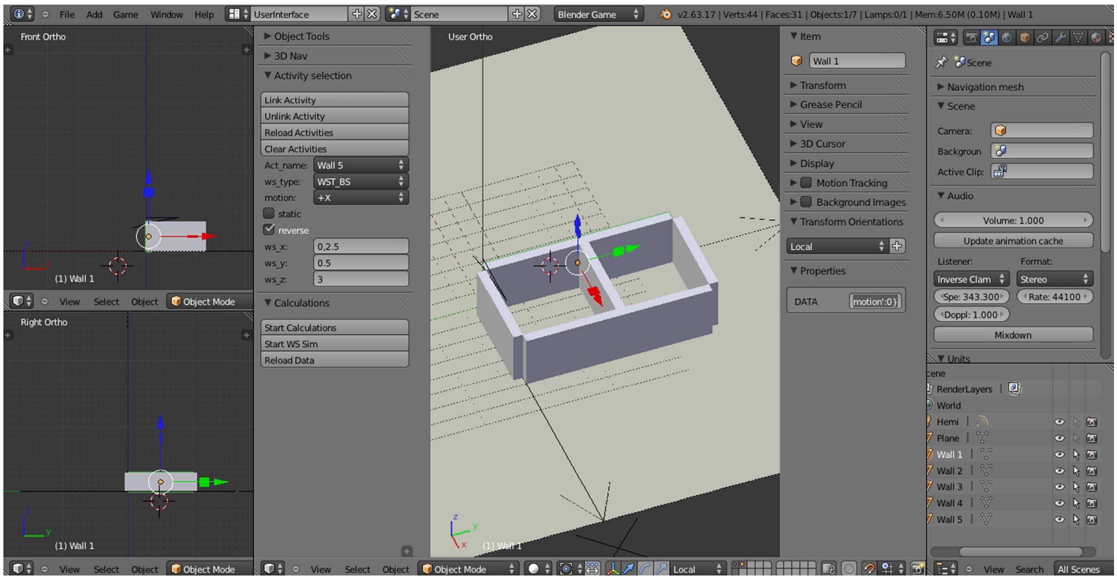


Figure 48 Application of AWG to Scenario 1

Table 20 shows the workspace calculations inputted for Scenario 1 in the AWG

Activity Name	Object Name	Workspace Type	Motion	Static	Reverse	WS_x (+x,-x)	WS_y (+y,-y)	WS_z (+z,z)
Wall 1	Wall 1	Labor	+X	Yes	No	(2.25,-0.25)	10	3
Wall 2	Wall 2	Labor	+X	No	No	(2.5,0)	(-0.25,1.45)	3
Wall 3	Wall 3	Labor	+X	Yes	No	(-0.25,2.25)	10	3
Wall 4	Wall 4	Labor	+X	No	Yes	(0,2.5)	(1.45,-0.25)	3
Wall 5	Wall 5	Labor	+X	No	Yes	(0,2.5)	2.5	3

Table 20 Choices for Workspaces of Scenario 1 in AWG

The AWG calculates the workspace sizes from the center point of the object, thus the negative inputs are to account for the workspace area inside the object itself. The AWG also accepts values in both directions of any axis, but in the event that only one value is placed (such case for the z in wall 1), then the AWG consider the workspace equally distributed in both directions (+z = -z = 1.5 in Wall 1). Table 21 shows the comparison between the clash results of the Manual calculation and the AWG.

Clash #	Clash Date	Clash Between		Clash Volume		Variance	Variance %
		Activity	Activity	Manually	Using AWG		
1	11-May-13	A1010	A1020	7.2	7.20000	-0.000004	0.000%
2	12-May-13	A1020	A1030	7.2	7.20000	-0.000005	0.000%
3	13-May-13	A1030	A1040	12	12.00037	-0.000365	-0.003%
4	14-May-13	A1040	A1010	12	11.99867	0.001327	0.011%
5	14-May-13	A1050	A1030	7.2	7.20000	0.000000	0.000%
6	15-May-13	A1050	A1010	7.2	7.20000	0.000000	0.000%
7	15-May-13		A1010	3	3.00000	0.000000	0.000%
8	15-May-13		A1030	3	3.00000	0.000000	0.000%

Table 21 Results Comparison between Manual Calculations and AWG

CHAPTER 5: CASE STUDY

CHAPTER 5: CASE STUDY

5.1 Case Study Description

After verifying the AWG and proving the effectiveness of the clash evaluation mechanism, it was tested on a live case study. Since the framework developed works best at the micro-level workspaces, a residential project was chosen as the case study. The project consists of one residential building, ground floor, 3 typical floors and a roof as shown in Figure 49 and Figure 50. The dimensions for the ground and typical floor are shown in Figure 51 and Figure 52. The height of each floor is set to 3 meters. The 3D model was developed using the Autodesk Revit Architecture. The time schedule was prepared using the Primavera Project Planner P6 version 7.

Figure 49 Residential Building for Case Study

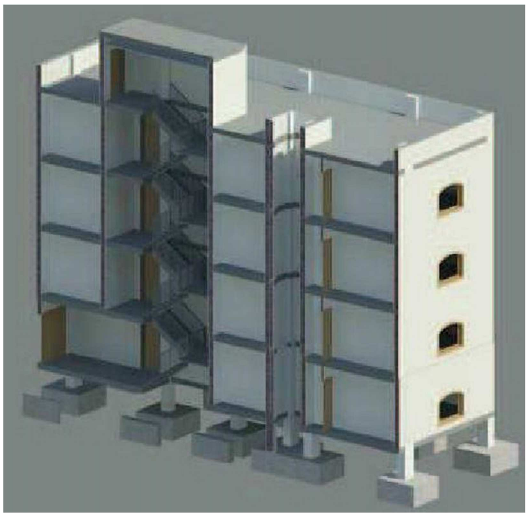


Figure 50 Section of the Residential Building

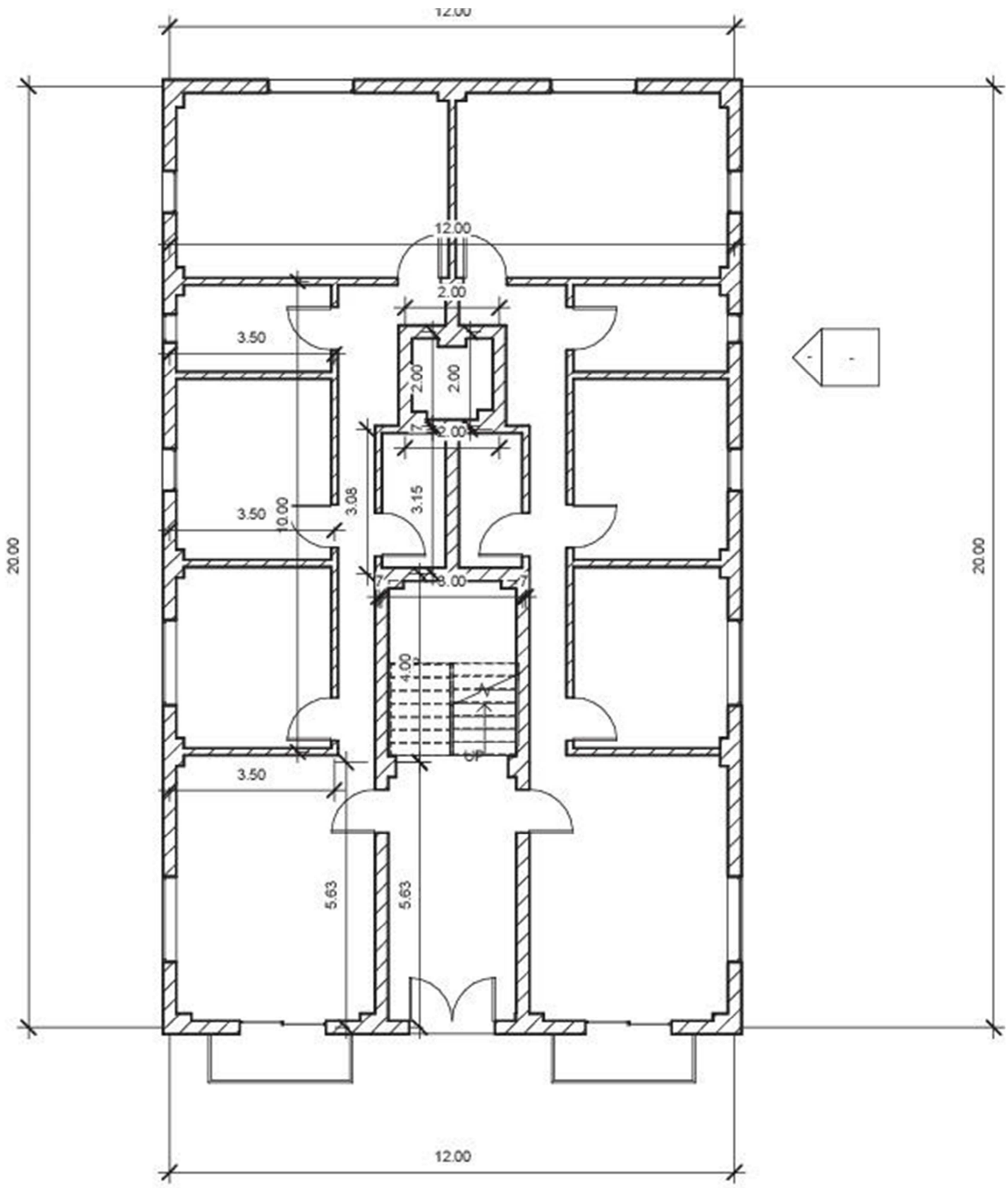


Figure 51 Ground Floor Plan

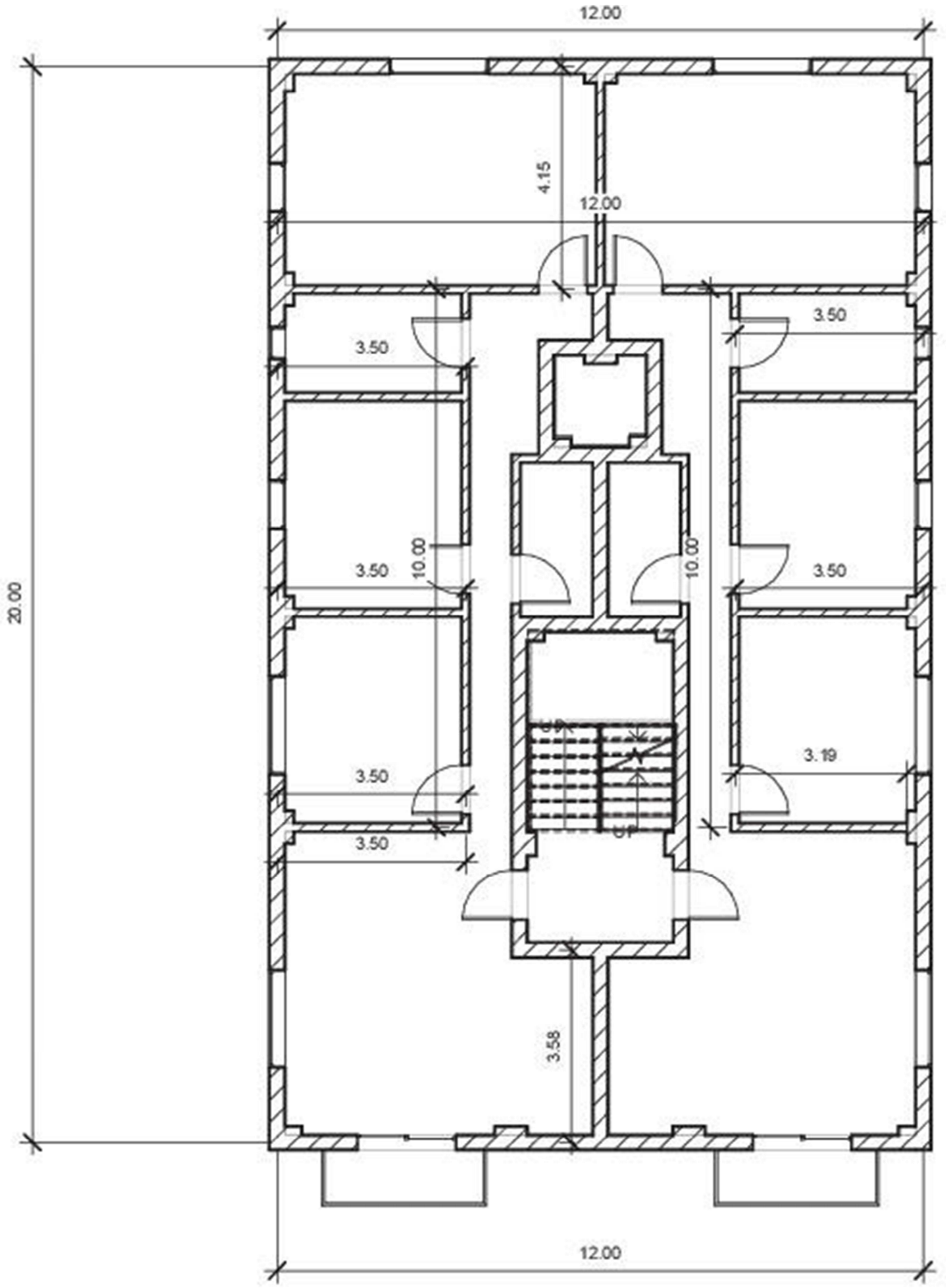


Figure 52 Typical Floor Plan

The works that were tested in this study were the concreting works, masonry and plastering works. The first floor was extracted from the case study and tested. Two Scenarios were tested.

5.2 Scenario 1 Calculation and Results

For Scenario 1, the proposed time schedule is shown in Figure 54. A snapshot of the workspaces assigned is shown in Figure 55.

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
Residential Building		152	01-May-13	30-Sep-13	0
Contractual Milestones		152	01-May-13	30-Sep-13	0
A1000	Start	0	01-May-13		0
A1570	Finish	0		30-Sep-13	0
Project Summary		152	01-May-13	30-Sep-13	0
A1580	Foundation Level	13	01-May-13	14-May-13	0
A1590	Ground Floor	49	14-May-13	02-Jul-13	82
A1600	First Floor	59	29-May-13	27-Jul-13	59
A1610	Second Floor	59	24-Jun-13	22-Aug-13	35
A1620	Third Floor	59	20-Jul-13	17-Sep-13	12
A1630	Roof	46	14-Aug-13	30-Sep-13	0
Construction Schedule		152	01-May-13	30-Sep-13	0
Foundation Level		13	01-May-13	14-May-13	0
Concrete Works		13	01-May-13	14-May-13	0
A1010	Formwork for PC Concrete	3	01-May-13	03-May-13	0
A1020	Pouring PC	1	03-May-13	04-May-13	0
A1030	Formwork for RC and Smells	5	04-May-13	09-May-13	0
A1040	Reinforcement for RC and S	3	09-May-13	11-May-13	0
A1050	Pouring RC and Smells	1	11-May-13	12-May-13	0
A1160	Deshuttering	2	12-May-13	14-May-13	0
Ground Floor		49	14-May-13	02-Jul-13	82
Concrete Works		32	14-May-13	15-Jun-13	0
A1060	Formwork Columns	3	14-May-13	17-May-13	0
A1070	Reinforcement Columns	3	17-May-13	19-May-13	0
A1080	Pouring Columns	1	19-May-13	20-May-13	0
A1090	Formwork Slab	5	20-May-13	26-May-13	0
A1100	Reinforcement Slab	3	26-May-13	28-May-13	0
A1110	Pouring Slab	1	28-May-13	29-May-13	0
A1120	Deshuttering	3	12-Jun-13	15-Jun-13	0
Masonry Works		9	15-Jun-13	24-Jun-13	62
A1130	Masonry	9	15-Jun-13	24-Jun-13	62
Plaster Works		8	24-Jun-13	02-Jul-13	82
A1140	Plastering Walls	5	24-Jun-13	29-Jun-13	73
A1150	Plastering Ceiling	2	29-Jun-13	02-Jul-13	82
First Floor		59	29-May-13	27-Jul-13	59
Concrete Works		42	29-May-13	11-Jul-13	0
A1170	Formwork Columns	3	29-May-13	01-Jun-13	10
A1180	Reinforcement Columns	3	01-Jun-13	04-Jun-13	10
A1190	Pouring Columns	1	04-Jun-13	05-Jun-13	10
A1200	Formwork Slab	5	15-Jun-13	20-Jun-13	0
A1210	Reinforcement Slab	3	20-Jun-13	23-Jun-13	0
A1220	Pouring Slab	1	23-Jun-13	24-Jun-13	0
A1230	Deshuttering	3	08-Jul-13	11-Jul-13	0
Masonry Works		9	11-Jul-13	20-Jul-13	45
A1240	Masonry	9	11-Jul-13	20-Jul-13	45
Plaster Works		8	20-Jul-13	27-Jul-13	59
A1250	Plastering Walls	5	20-Jul-13	25-Jul-13	52

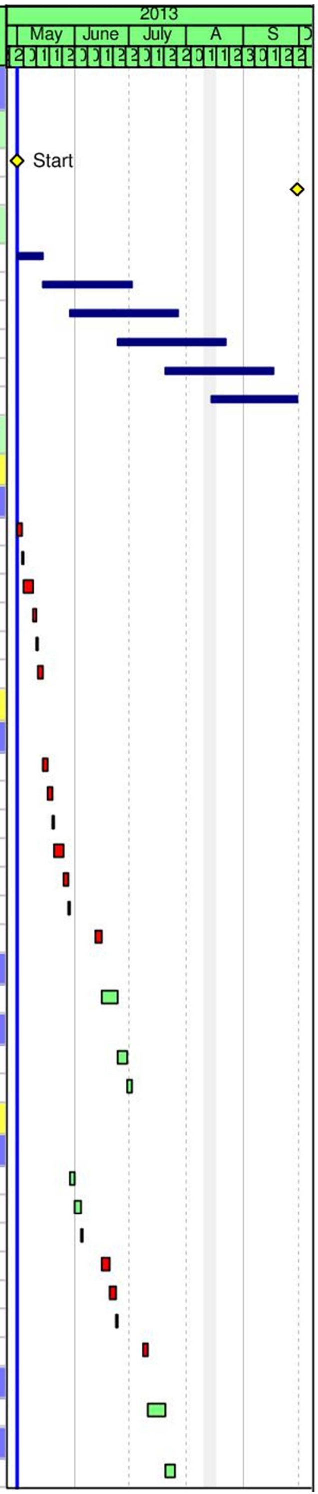


Figure 53 Proposed Time Schedule

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
A1260	Plastering Ceiling	2	25-Jul-13	27-Jul-13	59
Second Floor		59	24-Jun-13	22-Aug-13	35
Concrete Works		42	24-Jun-13	05-Aug-13	0
A1270	Formwork Columns	3	24-Jun-13	27-Jun-13	10
A1280	Reinforcement Columns	3	27-Jun-13	29-Jun-13	10
A1290	Pouring Columns	1	29-Jun-13	30-Jun-13	10
A1300	Formwork Slab	5	11-Jul-13	16-Jul-13	0
A1310	Reinforcement Slab	3	16-Jul-13	19-Jul-13	0
A1320	Pouring Slab	1	19-Jul-13	20-Jul-13	0
A1330	Deshuttering	3	03-Aug-13	05-Aug-13	0
Masonry Works		9	05-Aug-13	14-Aug-13	28
A1340	Masonry	9	05-Aug-13	14-Aug-13	28
Plaster Works		8	14-Aug-13	22-Aug-13	35
A1350	Plastering Walls	5	14-Aug-13	20-Aug-13	32
A1360	Plastering Ceiling	2	20-Aug-13	22-Aug-13	35
Third Floor		59	20-Jul-13	17-Sep-13	12
Concrete Works		42	20-Jul-13	31-Aug-13	0
A1370	Formwork Columns	3	20-Jul-13	22-Jul-13	10
A1380	Reinforcement Columns	3	22-Jul-13	25-Jul-13	10
A1390	Pouring Columns	1	25-Jul-13	26-Jul-13	10
A1400	Formwork Slab	5	05-Aug-13	11-Aug-13	0
A1410	Reinforcement Slab	3	11-Aug-13	13-Aug-13	0
A1420	Pouring Slab	1	13-Aug-13	14-Aug-13	0
A1430	Deshuttering	3	28-Aug-13	31-Aug-13	0
Masonry Works		9	31-Aug-13	09-Sep-13	12
A1440	Masonry	9	31-Aug-13	09-Sep-13	12
Plaster Works		8	09-Sep-13	17-Sep-13	12
A1450	Plastering Walls	5	09-Sep-13	14-Sep-13	12
A1460	Plastering Ceiling	2	14-Sep-13	17-Sep-13	12
Roof		46	14-Aug-13	30-Sep-13	0
Concrete Works		37	14-Aug-13	21-Sep-13	0
A1470	Formwork Columns	2	14-Aug-13	16-Aug-13	13
A1480	Reinforcement Columns	2	16-Aug-13	18-Aug-13	13
A1490	Pouring Columns	1	18-Aug-13	19-Aug-13	13
A1500	Formwork Slab	3	31-Aug-13	03-Sep-13	0
A1510	Reinforcement Slab	2	03-Sep-13	04-Sep-13	0
A1520	Pouring Slab	1	04-Sep-13	05-Sep-13	0
A1530	Deshuttering	2	19-Sep-13	21-Sep-13	0
Masonry Works		5	21-Sep-13	26-Sep-13	0
A1540	Masonry	5	21-Sep-13	26-Sep-13	0
Plaster Works		4	26-Sep-13	30-Sep-13	0
A1550	Plastering Walls	3	26-Sep-13	29-Sep-13	0
A1560	Plastering Ceiling	1	29-Sep-13	30-Sep-13	0

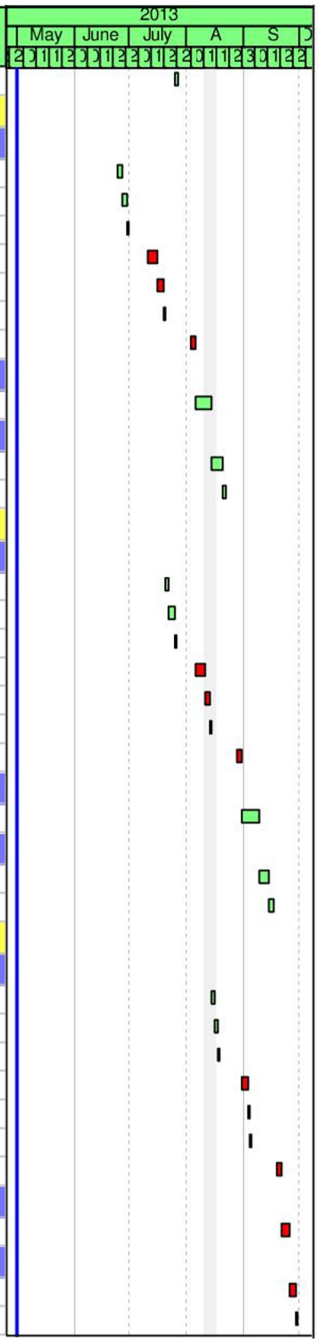


Figure 54 Time Schedule Continued

Activity Name	Object Name	WS Type	Motion	Static	Ws X(+&-)	Ws Y(+&-)	Ws Z(+&-)
A1090.Case Study.CN.GR.CO.Formwork Slab	Slab - Ground Floor	WST_LS	+Y	False	12.29	4.258:0	2.125:3.125
A1100.Case Study.CN.GR.CO.Reinforcement Slab	Slab - Ground Floor	WST_LS	+Y	False	12.29	4.258:0	2.125:3.125
A1110.Case Study.CN.GR.CO.Pouring Slab	Slab - Ground Floor	WST_BS	+Y	False	12.29	21.29	0.25
A1110.Case Study.CN.GR.CO.Pouring Slab	Slab - Ground Floor	WST_LS	+Y	False	12.29	4.258:0	2.125:3.125
A1150.Case Study.CN.GR.PS.Plastering Ceiling	Slab - Ground Floor	WST_LS	+X	False	6.145:0	21.29	-0.125:3.125
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-01	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-02	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-03	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-04	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-05	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-06	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-07	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-08	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-09	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-10	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-11	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-12	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-13	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-14	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-15	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-16	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-17	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-18	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-19	WST_LS	+X	True	1.5	1.5	3
A1170.Case Study.CN.FR.CO.Formwork Columns	Column FF-20	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-01	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-02	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-03	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-04	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-05	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-06	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-07	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-08	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-09	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-10	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-11	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-12	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-13	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-14	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-15	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-16	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-17	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-18	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-19	WST_LS	+X	True	1.5	1.5	3
A1180.Case Study.CN.FR.CO.Reinforcement Columns	Column FF-20	WST_LS	+X	True	1.5	1.5	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-01	WST_BS	+Z	False	0.167	0.457	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-02	WST_BS	+Z	False	0.167	0.457	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-03	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-04	WST_BS	+Z	False	0.167	0.32	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-05	WST_BS	+Z	False	0.61	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-06	WST_BS	+Z	False	0.167	0.32	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-07	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-08	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-09	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-10	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-11	WST_BS	+Z	False	0.167	0.61	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-12	WST_BS	+Z	False	0.32	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-13	WST_BS	+Z	False	0.32	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-14	WST_BS	+Z	False	0.61	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-15	WST_BS	+Z	False	0.61	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-16	WST_BS	+Z	False	0.32	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-17	WST_BS	+Z	False	0.32	0.204	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-18	WST_BS	+Z	False	0.61	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-19	WST_BS	+Z	False	0.32	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-20	WST_BS	+Z	False	0.32	0.167	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-01	WST_LS	+X	False	1.5	1.5	3
A1190.Case Study.CN.FR.CO.Pouring Columns	Column FF-02	WST_LS	+X	False	1.5	1.5	3

Figure 55 Snapshot of Workspaces for Scenario 1

The graph for the first level check is shown in Figure 56. From the 59 days for the first floor, 36 days had clashes, 10 of them were above the tolerance level of 60.

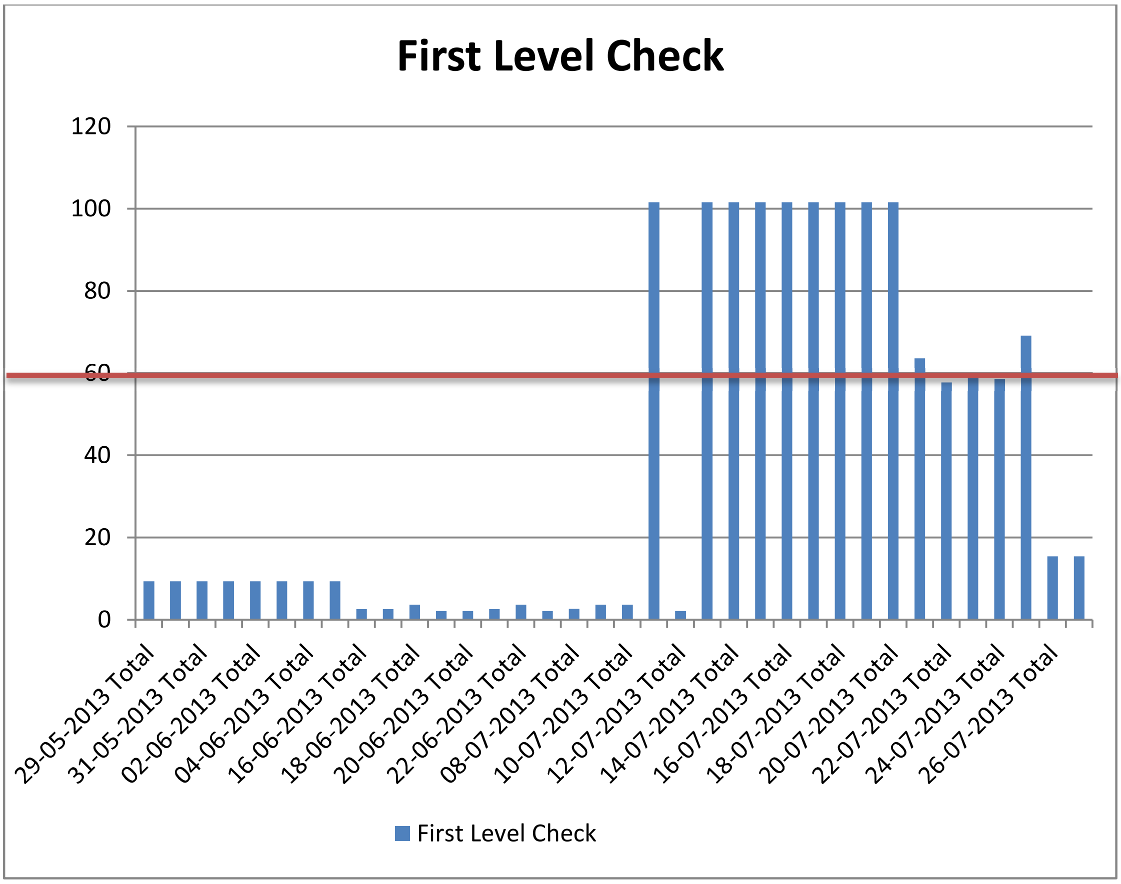


Figure 56 First Level Check Results for Case Study Scenario 1

The severity values and weights for the first level check are shown below in Table 22 below:

Workspace Type	Workspace Type	Value
Labor Space	Building Space	0.85
Building Space	Labor Space	0.85
Labor Space	Labor Space	0.5
Building Space	Building Space	0.25

W1	0.4
W2	0.6

Table 22 Weights and Severity Values for Case Study

The days above the tolerance level were the dates from 11-July-2013 to 20-July-2013 and 24-July-2013. When these dates were investigated, it was found that the activities of de-shuttering, masonry and plastering walls were in question. The results of the second level check are presented in Figure 57.

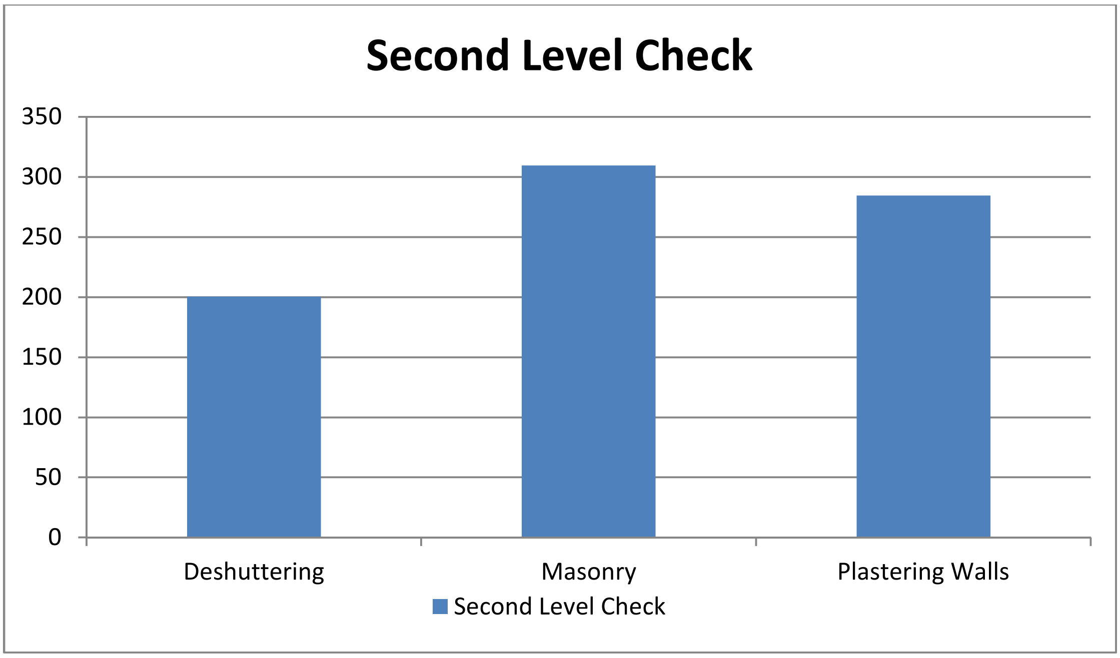


Figure 57 Case Study Second Level Results

5.3 Scenario 2 Calculation and Results

Based on the findings of the second level check of Scenario 1, the masonry and plastering activities were readjusted by only modifying their workspace assignments and orientations without any schedule adjustments as a first attempt. The results showed improvement in the ranges an average of 20%. However the results still showed some critical days above the tolerance, which shows the need for an automated optimization tool as an addition to this software in the future.

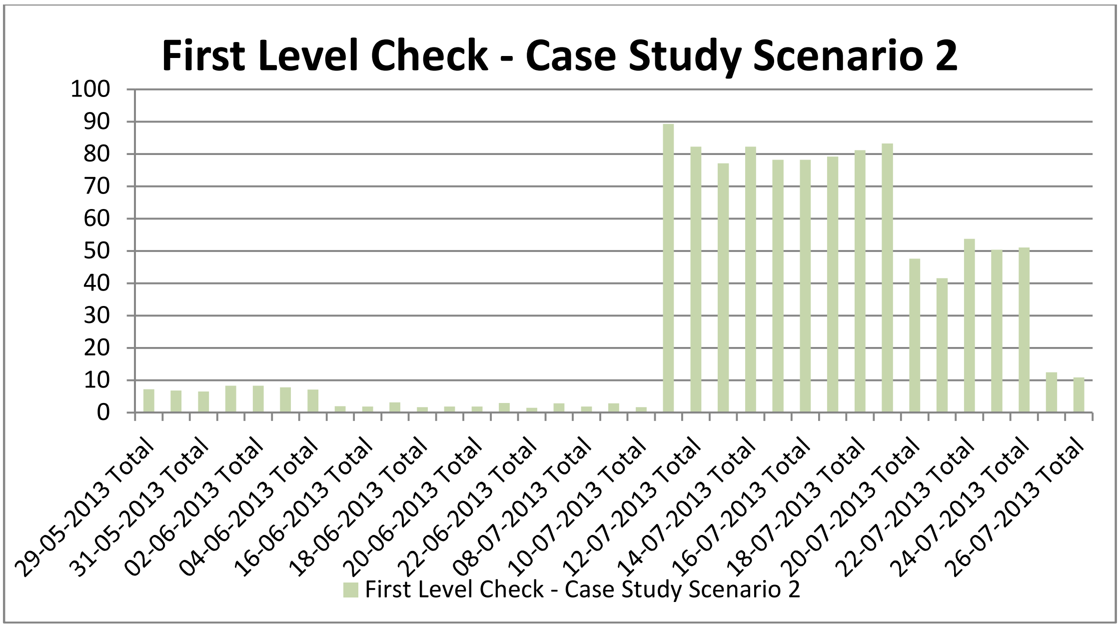


Figure 58 First Level Check - Scenario 2

5.4 Validation and Discussion

The above results were presented to 6 lead experts in the construction field through short informal sessions. Each session lasted 1.5 hours, covering the following topics:

- The problem statement of the research and the proposed framework
- The case study and the choices of input
- The results of the case study

The profiles of the evaluators are shown below in Table 23:

No.	Participant Type	Experience Years	Participant Profile
1	Projects Control Director	26	Leading architectural engineer in an Egyptian consultancy firm with planning and costing roles
2	Two Senior Planners	Average 10	Civil engineers in an Egyptian contracting firm with planning and costing roles
3	Three Project Managers	Average 13	Civil engineers with planning experience in Egyptian contracting firms working in the Middle East

Table 23 Profiles of Evaluators

Since the topic was still considered new to the Egyptian market, the discussions at the start of the sessions generally tangled the question of when would it be best to use this model, and who is benefiting the most out of it, the contractor or the client? What would be the easiest method to attain the data from the site engineers? Etc...

The overall agreement was that it was preferred to use the model at the end of the planning stage by the contractor, once the detailed level 4 schedule has been prepared. This is to ensure the adequate available data to trace the workspaces on site and detect the clashes. It was also found that it is preferable to conduct the study on the whole schedule as the first trial in order to capture any critical activities (space-wise) that would appear at the end of the project.

The rest of the feedback from the sessions was the content and acknowledgement of such useful data in the market. The main benefits highlighted were:

- The use of the 4D as a visualization medium which has eased the estimation and analysis stages
- The variable productivity rates and their link to the market norms

- The automaton attempts of the workspaces
- The 2 level check of the clash evaluation mechanism to be used as a comparison tool between schedule alternatives

There were some critics to the model also which highlighted the following points:

- The output was not still refined enough for direct use in the site, which needed more work
- The fact that there was not yet an automated optimization tool to the model forced the users into manual optimization which made the process longer.
- The absence translation of the clash evaluator results to the impacts on the time, cost and quality and hence the inability to optimize through these factors.

CHAPTER 6:
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusion

The study has presented a complete coherent framework for the detection, analysis and evaluation of clashes. The research started by identifying the handicaps that were available in the previous studies. Then, it began to design the road map from the start of the problem which is the automated generation of the different workspace types based on the least data possible. As this has been one of the main problems in the past due to the large amount of input data required. The automated generation dealt with three main topics

- The creation of the 4D model through utilizing the Activity ID.
- The definition of the inputs for the singular component through the construction direction and the different quantity rates.
- Dealing with the behavior of the mass components through defining the different execution strategies.

The next step the research presented was the clash detection mechanism which for the first time ever was done on two steps:

- Step One targeted the days to quickly identify the critical days beyond the tolerance levels, focusing on the activities of these days
- The results of step one led to the second step of evaluating the performance of these activities, to determine which are the most troublesome and ought to be modified.

Not only that, but the research also presented a proof-of-concept illustrative test model to demonstrate the framework in action, and to show the effectiveness of the two level check.

The framework was also tested on an actual case study, by developing a software tool to ease and structure the workspace assignment data, where the first floor was extracted and workspaces were assigned to the concreting, masonry and plastering works. The results showed massive clashes which were analyzed. A modified plan was then tested again based on the analysis from the first scenario which showed an average optimization of 20% in the clash results. The finding were presented to construction experts in the field whom acknowledged the usefulness of the results and recommended extra output for better practical use.

6.2 Recommendations for Future Work

The future work will be focusing on the following:

- Modifying the singular direction construction assumption: In order to mimic the actual execution behavior of any element, it must be assumed that the building rate of the element is variable in each direction (coordinate).
- Adding factors to the CME: Some factors could be added to the CME to provide the user with a better estimation. Examples of these factors could be the cost weight of the building component or the BOQ division it follows, or could be a quality factor to reflect on the design complexity of the building element.
- Introducing uncertainty software such as Monte-Carlo simulation: For the clash quantification area, a simulation like Monte-Carlo simulation may be added to provide the users with confidence levels.
- Quantify CME results: Utilizing the BIM technology, the CME results will be linked with parameters as the resources' cost to and the time schedule to quantify them into estimates that could be considered in contingencies.
- Prediction tool: The current output of the model is the CME results in addition to some analysis. The future hope is to expand the tool into a complete prediction model which could estimate the new project end date and expected cost. For that to happen, the author will attempt to create algorithm to import more schedule data such as the relations. Most 4D mechanisms in the market relate the building components to the start and end of the activity and do not respect the activity relations.
- Automatic optimization of the presented model and the output of the re-modified construction method and sequence through the following parameters:
    - Delaying the start of certain components in each activity, by utilizing the total and free floats (adopting the same concepts of resources leveling.
    - Allowing for the automatic breaking down of activities into smaller sections, to allow for the interrupted flow of work.
    - Optimizing the results based on the time delay caused or the cost incurred rather than the CME value only.

- Setting a priority mechanism to eliminate clash types before others based on the project type. For example, when working in nuclear plants, not building clashes can be allowed.
- Introducing evolutionary algorithms as Genetic algorithms to enhance the optimization process.

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