Master of Science in Engineering

4D BIM-Based Workspace Planning Process for Building Construction

by

Byungjoo Choi

Department of Architecture & Architectural Engineering

The Graduate School

Seoul National University

February 2014

4D BIM-Based Workspace Planning Process for Building Construction

by

Byungjoo Choi

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Seoul National University

2014

Abstract

4D BIM-Based Workspace Planning Process for Building Construction

Byungjoo Choi
Department of Architecture and Architectural Engineering
The Graduate School
Seoul National University

Each participant in a building construction project requires their own workspace to execute their activities. In this environment, inappropriate workspace planning in a construction site causes workspace interferences, which results in a loss of productivity, safety hazards, and issues of poor quality. Therefore, the workspace should be considered one of the most important resources and constraints to manage at a construction site. However, the current construction planning techniques—such as Gantt Chart, Network Diagram, and Critical Path Method (CPM)—have proven to be insufficient for workspace planning because they do not account for the spatial feature of each activity. In order to establish a formalized workspace planning process, therefore, this paper categorizes workspace by its function and relocatability, and suggests a workspace planning process that contains five phases, including 4D Building Information Model (BIM) Generation, Workspace Requirement Identification, Workspace Occupation Representation, Workspace Interference Identification, and Workspace Interference Resolution. The proposed planning process in this paper can improve the accuracy of workspace status representation and workspace interference identification by introducing the workspace occupation concept and the integrated workspace planning process that considers characteristics of activity, workspace, and construction plan. In addition, this paper aims to ameliorate the workspace planning process through path analysis and a formalized workspace interference resolution process. In order to scrutinize the applicability of the proposed approach, a case project was tested. The result shows the applicability and effectiveness of the proposed method on improving the workspace planning process. Based on the result of this study, a project manager will be able to prevent possible workspace interferences and their negative effects on project performance by devising a pertinent workspace plan during the preconstruction phase.

Keywords: Workspace, 4D Building Information Model (BIM), Space Scheduling, Project Management

Student Number: 2012-20566

Contents

List of Tables

List of Figures

Chapter 1 Introduction

This chapter deals with the importance of the workspace and current practice of the workspace planning process in a construction project. To solve the problems, research objectives are established. Then, research process to attain the objectives is addressed.

1.1 Research Background and Objectives

One of the distinctive features in a building construction project is limited site space (Bansal 2011; Chua et al. 2010; Said and El-Rayes 2013). Regarding this constraint, each participant requires specific workspace for their resources—such as laborers, equipment, and materials—in order to execute their activities (Hammad et al. 2007; Riley and Sanvido 1997; Sadeghpour et al. 2006). Inappropriate workspace planning leads to workspace interferences, resulting in a loss of productivity, safety hazards, and issues of poor quality (Kaming et al. 1998, Oglesby et al. 1989; Zhang et al. 2007). For example, Riley and Sanvido (1997) detected 71 workspace conflicts between four participations during a two-month study period. Also empirical studies of factors affecting site productivity indicate that workspace interference cause decreasing of the productivity by 30% in a construction project (Kaming et al. 1998). As a result, a project manager should consider the workspace as one of the consequential resources and constraints to be managed at a construction site, alongside time, cost, laborer equipment, and material (Akinci et al. 2002a; Chavada et al 2012; Dawood and Mallasi 2006;

Tommelein et al. 1993).

Workspace for activity execution is differentiated from other resources. First the location and size of a workspace occupied by a specific activity at certain time is influenced by nature of the activity and its construction plan (Riley and Sanvido 1995). Second, workspace utilization by each activity shows dynamic changes in three dimensions in accordance with time flow in a construction project (Akinci et al. 2002b; Tommelein et al. 1993; Winch and North 2006). Therefore, an integrated approach embracing the dynamic and complex features of a workspace is required for a desirable workspace plan.

However, current construction planning techniques—such as Gantt Chart, Network Diagram, and Critical Path Method (CPM)—have limitations in that they cannot account for the spatial feature of each activity, and consider only construction schedules (Chau et al. 2004; Mallasi 2006; Wang et al. 2004). Due to the lack of a formalized process for workspace planning, current workspace planning at the construction site relies on planners' intuition and empirical knowledge (Akinci et al. 2002c; Sadeghpour et al. 2006). In this circumstance, even for experienced project managers, it is challenging to completely comprehend the complex and dynamic features of a workspace, thus mangers have experienced difficulties in proactively preventing workspace interferences and their negative effects (Guo 2002; Winch and North 2006). Moreover, recently increased requirements for a short duration schedule at large and complex projects in an urban area make it more difficult to design a fine workspace plan (Hammad et al. 2007; Said et al. 2013; Wang et al. 2004).

In recent years, there have been numerous efforts attempting to manage the dynamic and complicated feature of the building construction process. Among these efforts, a recent achievement in 4D Building Information Model (BIM), which links objects in 3D BIM and their corresponding activities in a project schedule, has demonstrated advances in efficiently handling dynamic and complicated changes during the construction process. Based on these achievements, this study proposes a 4D BIM-based workspace planning process, which integrates the characteristics of workspace, activity and construction plan, in order to proactively handle incidences of workspace interferences and to eliminate waste elements in a construction project.

1.2 Research Scope and Process

There are two branches in a space planning related research area, which are the space scheduling problem and the site layout problem. The space scheduling problem focuses on a workspace for the activity execution in a dynamic perspective and the site layout problems deals with a location of the temporary facilities in a static perspective (Winch and North 2006). Among these two branches, the scope of this study limited in a scheduling problem which treats planning the workspace for activity execution.

The suggested framework in this study is developed in the following process. First, this paper discusses critical reviews of previous related studies that investigate workspace planning process and workspace classification. Then, workspace is classified by its function and relocatability. Based on critical reviews on previous studies and workspace classification, this study proposes a workspace planning process using 4D BIM which contains 4D BIM Generation, Workspace Requirement Identification, Workspace Occupation Representation, Workspace Interference Identification, and Workspace Interference Resolution. Then, a case study applied with the suggested workspace planning process is presented. Finally, conclusions and recommendations for future research are offered. The entire research process of this paper is summarized in Figure 1-1.

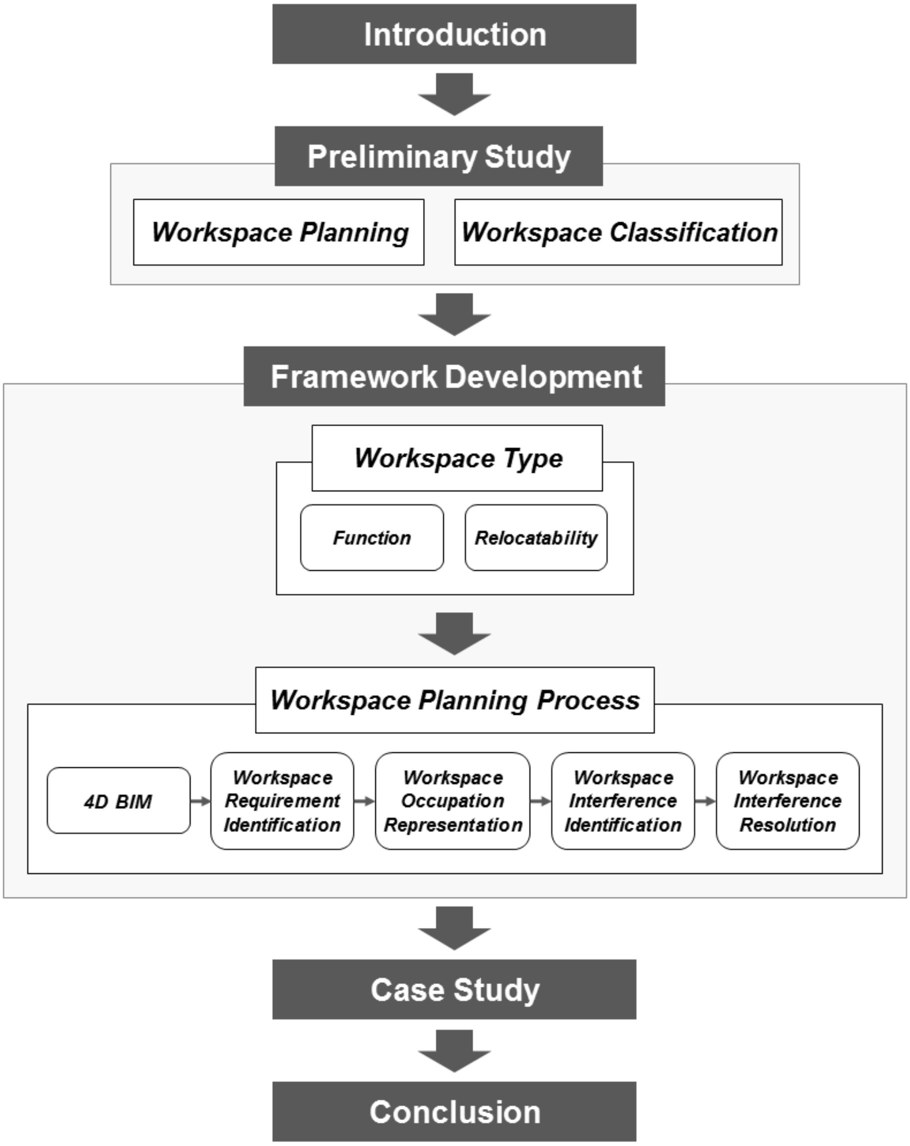


Figure 1-1. Research Process

Chapter 2 Preliminary Study

Prior to developing a framework for the workspace planning process in a construction project, this chapter reviews previous studies which deal with workspace planning process and workspace classification. This chapter also addresses this study’s strategies to overcome previous studies’ limitations.

2.1 Literature Review on Workspace Planning Process

The purpose of the workspace planning in a building construction project is to prevent workspace interferences and unnecessary wastes by predicting the workspace utilization status of each participant. Therefore, workspace planning includes a representation of workspace occupation status, workspace interference identification, and resolution. For an effective workspace planning process, diverse approaches have been suggested with regard to representing the state of workspace utilization and managing workspace interferences. Table 2-1 summarizes the major features of previous studies that investigate the workspace planning process as well as the improvements made by this study.

Thabet and Beliveau (1994) proposed a scheduling method that integrates space demand and space availability. To evaluate space availability, they first manually identified physical available space within the AutoCAD environment. They broke the available workspace into a number of work blocks and allocated activities to each work block. To describe productivity decrease due to the limited available workspace, they introduced a space capacity factor that is computed by the ratio of space demand to available workspace for the activity. In a follow-up study, Thabet and Beliveau (1997) developed a Space-Constrained and Resource-Constrained Scheduling system. However, their approach could not identify workspace conflict exactly because they were focus on congestion in the work block rather than interference between workspace for activities.

Guo (2002) attempted to identify workspace conflict in a construction project by manually overlapping workspace demands for each activity on a project's CAD drawings. He also introduced the concept of a path demand analysis which examines whether the plan provides sufficient path area for laborer and material movement. Their approach presents some important limitations in terms of manual execution of workspace conflict identification and path analysis and ambiguous method for representation of workspace demand for each activity.

Akinci et al. (2002 a, b) developed a 4D WorkPlanner Space Generator that automatically generates the microlevel workspace requirement via incorporating the construction method for installment each product breakdown structure (PBS) and its' spatial requirement information in 4D CAD model. Then in Akinci et al. (2002 c) suggested a method for categorizing and prioritizing identified workspace conflicts. Their approach considered conflicting workspace's type and the properties which are defined by the ratio of conflicting volume to total volume of workspace requirement. In spite of substantial advancement than previous studies, they limited their analysis scope to microlevel space that excluded macrolevel workspace such as material storage area and path area for crew and material movement. Also their approach with direct relationship between workspace and building components rather than activity separated from general planning practice at construction site.

Dawood and Mallasi (2006) developed a PECASO 4D simulator introducing three work rate distribution types and twelve work execution patterns in order to identify workspace conflicts in a construction site. They also proposed the multi-criteria quantification function to assess criticality of workspace competition among the activities.

Chavada et al. (2012) presented methodology that integrates Critical Path Method and Building Information Modeling data for workspace management. They proposed workspace management process that includes workspace generation process, conflict detection process, congestion detection process and resolution process in 4D/5D environment. Moreover their approach to identify workspace conflicts has important limitation because they only identify workspace conflicts among the activities which have schedule conflicts.

Despite the number of previous studies that have considerably ameliorated the workspace planning process, these studies have several important limitations regarding workspace utilization status representation, workspace interference identification, and resolution. A majority of previous studies assume that resources for activity execution occupy their required workspace for the entire duration of the activity. However, this assumption fails to achieve an accurate representation of the workspace occupation since the activity is executed by utilizing a part of the entire workspace requirements repetitively and successively in the actual construction project. Moreover, the location and size of the workspace represented in the previous studies cannot be updated with modifications to the construction plan, such as an activity execution plan or a material management plan. Finally, relatively little attention has been paid to the formalized process for workspace interference resolution and path analysis in the previous studies. This study has attempted to further improve the previous studies' findings by: (1) differentiating the workspace requirement and workspace occupation for each activity in order to reflect the way of workspace utilization in an actual construction project; (2) integrating characteristics of the workspace, activity, and construction plan for representing workspace occupation; (3) including path analysis process which is overlooked in most of previous studies; and (4) presenting a formalized procedure for workspace interference resolution.

Table 2-1. Review on Related Studies and Improvement by this Study

Author (Year)	Workspace Interference Identification	Operating Environment	Activity execution Progress Representation	Integration of Construction Plan and Workspace	Workspace Interference Resolution
Thabet and Belilveau (1994)	Limited (Congestion)	CAD	Workspace occupies allocated areas for entire duration of activity	Not Mentioned	Not Mentioned
Guo (2002)	Yes	CAD		Manually reflect when construction plan changes	Criteria for workspace conflict resolution
Akinci et al. (2002)	Yes	4D CAD		Determination of workspace by construction methods	Prioritization of workspace conflict
Dawood and Mallasi (2006)	Yes	4D CAD	12 types of execution pattern and 3 types of work rate	Manually reflect when construction plan changes	Mentioned conflict resolution process in the case study
Chavada et al. (2012)	Yes	4D BIM	Required workspace occupies whole workspace during activity duration		Enumeration of possible solutions for workspace conflict
Choi et al. (2013)	Yes	4D BIM	Differentiated workspace requirement and workspace occupation	Integration of activity execution plan and material management plan	Formalized procedure for workspace conflict resolution

2.2 Literature Review on Workspace Classification

Before developing a workspace planning process, it is important to explain different types of workspace in related studies. Workspace classification helps to comprehend characteristics of workspace and to extend the comprehension to the workspace planning process.

Riley and Sanvido (1995) proposed a Construction Space Model that defines twelve construction workspace types and their behavior patterns in multi-story building using site visits, interviews, and document reviews for ten case project studies. Guo (2002) categorized workspace into four types of workspaces based on the user of each workspace—such as labor, equipment, material, and temporary facility—in order to represent status of workspace utilization. Mallasi (2006) introduced the concept of product and process for workspace classification and defined eight workspace types. Wu and Chiu (2010) regarded construction workspace as a combination of building component space, site layout space, human workspace, equipment space, and material space. Chavada et al. (2012) tried to classify workspace by adopting a terminology which distinguishes between value added and non-value added activities. Table 2 summarizes the previous studies' workspace classifications.

In spite of numerous efforts of the previous studies classifying workspace, these approaches have some limitations in the workspace planning process. Most of previous studies fail to integrate the characteristics of each workspace type and workspace planning process, since they only regard workspace classification as means of the workspace conflict categorization.

Furthermore, previous studies are not able to reflect the different nature of workspaces types since all types of workspaces are generated by the identical method regardless of the characteristics of each workspace type.

Table 2-2. Reviews on Previous Workspace Classification

Author (Year)	**Riely and Sandivo (1995)**	**Guo (2002)**	**Mallasi (2006)**	**Wu and Chiu (2010)**	**Chavada et al. (2012)**
Classification	Layout Area Unloading Area Material Path Staging Area Personnel Path Storage Area Prefabrication Area Work Area Tool/Equipment Area Debris Area Hazard Area Protected Area	Working Space Storage Space Waste Space Set-up Space Path Space	Product Space Workspace Equipment Space Equipment Path Storage Space Path Space Protected Space Support Space	Building Component Workspace Site layout Workspace Labor Workspace Equipment Workspace Material Workspace	Main Workspace Support Workspace Object Workspace Safety Workspace

2.3 Summary

The previous chapter reviewed limitations of the previous studies which investigate workspace planning process and workspace classification. In spite of considerable improvements by these studies, they are not able to represent the actual workspace utilization status in a construction project due to the insufficient assumptions. Moreover, they fail to integrate information related in workspace planning process.

In order to be an effective and applicable process, a workspace planning process should consider following requirements;

(1) Effective method for representing actual status of the workspace utilization
(2) Workspace classification for integrating with the workspace planning process
(3) Integration of characteristics of the workspace, activity, and construction plan in workspace planning process
(4) Formalized workspace interference resolution process

Chapter 3 Workspace Classification

Before suggesting a workspace planning process, characteristics of a workspace should be comprehended. In order to integrate the characteristics of a workspace with the workspace planning process, this study classified workspace by its function and relocatability. Classification by its function helps represent the whole workspace requirement without exception, and classification by relocatability is useful in identifying the cause of workspace interferences and providing a pertinent resolution strategy for each issue.

3.1 Workspace Classification by Function

The function of workspace explains why a specific workspace is required for the activity execution. Among several efforts to categorize workspace types, Riley and Sanvido (1995) classified workspaces into thirteen workspace types by observing the construction process. Based on Riley and Sanvido's (1995) classification, this study defines six functional workspace types by merging the workspace types that perform the same functions, as described in Figure 3-1.

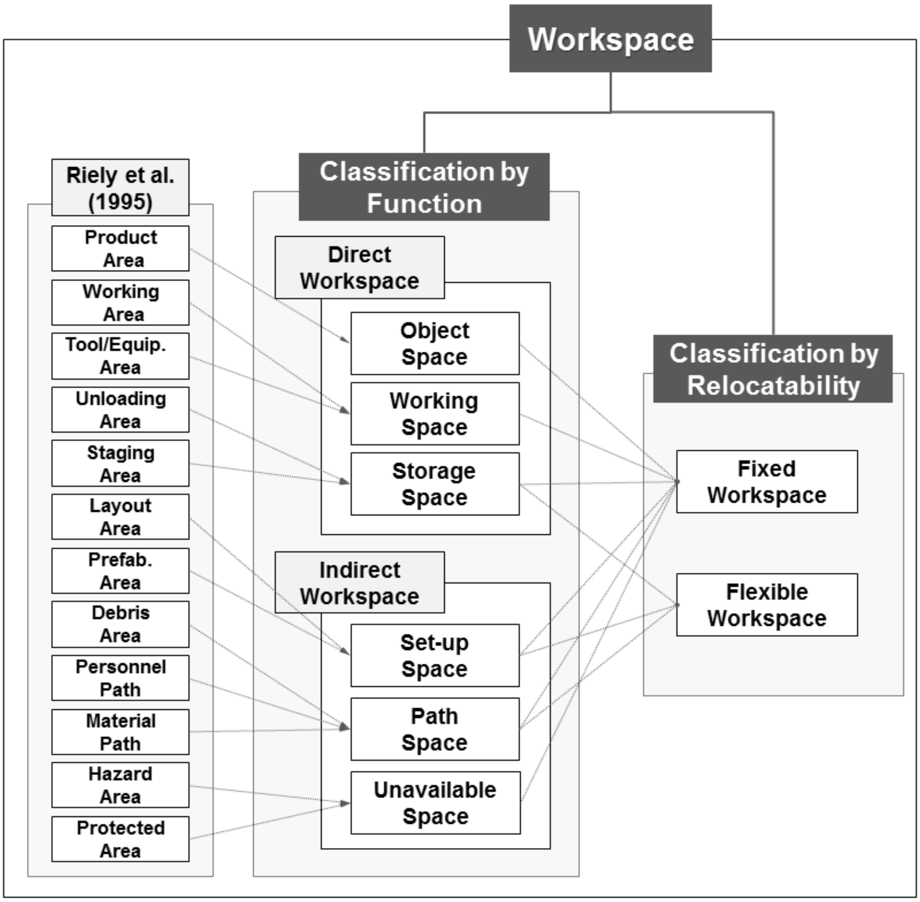


Figure 3-1. Workspace Classification Structure

Workspace in a construction project could be categorized as *direct workspace* or *indirect workspace* depending on its function. *Direct workspace* is associated with the execution of specific activity in a direct way, and the location and size of the workspace is determined by the geometric features of the related object or construction plan for the activity. *Direct workspace* includes: (1) *Object space* - the area occupied by a building component itself such as a wall, doors, or windows; (2) *Working space* - the area required for crews or equipment to execute a specific activity that contributes physical changes in a construction project; and (3) *Storage space* - the area for storing materials for each activity execution in a construction project.

Indirect workspace has either an indirect relationship with the execution of a specific activity or is associated with the execution of multiple activities. The location and size of an *indirect workspace* is determined by temporary facility layout plans or predefined spatial relations with the *direct workspace*. *Indirect workspace* includes: (4) *Set-up space* - the area for operating the overall construction project, such as a tower crane and lift car; (5) *Path space* - the area required for the movement of resources such as a laborer or equipment material; and (6) *Unavailable space* - unusable area due to the protection of established building components or safety issues caused by certain activity executions. Table 3-1 summarizes the definition and important attributes of each workspace type.

Table 3-1. Functional Workspace Classification

Workspace Type		Definition	Location and Size of Workspace	Generation and Expiration of Workspace
Direct Work-space	Object Space	Areas occupied by building components such as walls, doors, and windows.	Geometric features of building components determine the location and size of the space.	Object space is generated at starting point of linked activity and preserved until project completion.
	Working Space	Areas required for laborers, equipment, etc., required to execute each activity on the site.	Spatial relation with corresponding object defined by construction method determines the location and size of the space.	Working space is generated at starting point of the activity and expired at ending point of the activity.
	Storage Space	Areas required for materials storage before consuming them for executing each activity.	Geometric feature of material and quantity of corresponding activity determine size of the space. Material management plan determines location of the space.	Storage space is generated at starting point of the activity and expired at ending point of the activity.
Indirect Work-space	Set-up Space	Areas required to operate overall construction project (e.g., Tower crane, Scaffolding, Lift car, etc.).	Temporary facility layout determines the location and size of the space.	Set-up space is generated at starting point of independent activity or related activity and expired end point of the activity.
	Path Space	Areas required for movement of laborers, equipment, and materials in a construction project.	Construction method for the activity and geometric feature of materials determines the minimum path width and height.	Defined minimum path width and height is required during corresponding activity duration.
	Unavailable Space	Areas that are prohibited to use due to safety issue related to the execution of a specific activity and the protection of certain building components.	Hazardous condition defined by construction method and object protection condition determines the location and size of the space.	Unavailable space is preserved during corresponding activity duration or object protection duration determined by the object feature.

In this study, in order to represent the whole workspace without exception, requirements of the *direct workspace* are identified by integrating information about objects, construction methods, and materials. Then, the status of *direct workspace* occupation is represented by reflecting the activity execution plan and material management plan. Finally, the status of *indirect workspace* occupation is represented by referring to the occupied *direct workspace* and other construction plans. Through these processes, project managers are able to accurately predict the status of workspace utilization in a construction project and to identify all possible workspace interferences in advance.

3.2 Workspace Classification by Relocatability

Workspace classification by its attributes contributes to the effective enhancement of the comprehension and utilization of the workspace characteristics information. Among several workspace attributes, relocatability is one of the most paramount properties, since it assists in identifying the causes of workspace interferences and detects apposite resolution strategies for each issue. Therefore, this study classifies workspace into *fixed workspace* and *flexible workspace* by relocatability, as indicated in Figure 3-1.

Fixed workspace is a space that is not able to arbitrarily change its location. For instance, the location of *working space* is determined by a spatial relation with an object defined by a selected construction method. A project manager is not able to change the location of *working space* unless the construction method selection changes; thus, *working space* is categorized as *fixed workspace.* On the other hand, the location of *flexible workspace* varies by the modification of the construction plan. In general, a project manager plans how to distribute materials for a specific activity before the activity execution. The material distribution plan could be modified by a project manager's managerial decision, and thus the location of *storage space* for the materials would also change according to the revised plan. In this case, *storage space* is categorized as *flexible workspace*. However, not all *storage spaces* are categorized as *flexible workspace* because the relocatability of *storage space* is determined by the characteristics of the materials. For example, the *storage space* for plumbing and duct materials required by Mechanical Electrical Plumbing (MEP) work is *flexible workspace*, since those materials are stored at a specific assigned block at a site by the material distribution plan. On the other hand, due to the difficulty of movement, *storage space* for brick materials required for masonry work should be located adjacent to the *working space* for the activity. Therefore, *storage space* for a brick material is categorized as *flexible workspace.*

In *direct workspace*, *object space and working space* are classified as *fixed workspace.* In the case of *storage space*, workspace type based on relocatability is determined by the characteristics of the materials, as described above. *Unavailable space* is a type of *fixed workspace*, since *working space* and *object space*, which determine the location of the *unavailable space*, belong to *fixed workspace*. Finally workspace types by relocatability for *set-up space* and *path space* are determined by the flexibility of the construction plan that defines the location of the workspace.

3.3 Summary

Prior to developing a workspace planning process, a workspace classification structure is suggested in this chapter. Workspace is categorized as *direct workspace,* which contains *object space, working space,* and *storage space,* and *indirect workspace*, which includes *set-up space*, *path space,* and *unavailable space*, by its function. In addition, this study classifies workspace as *fixed workspace* and *flexible workspace* by whether or not the location of workspace can be changed arbitrarily.

Based on the functional classification of the workspace, the status of the workspace utilization in a construction project could be identified and represented without exception. Moreover, workspace classification by relocatability is used for identifying the cause of workspace interferences and finding pertinent resolution strategies for the identified workspace interferences in a suggested workspace planning process.

Chapter 4. Workspace Planning Process

Based on the previous workspace classification, this section discusses a workspace planning process that deals with the dynamic and complicated features of a workspace in a construction project. In general, a schedule plan in a construction project is established as follow: (1) creating baseline schedule using CPM algorithm; (2) identifying the restrictions and constraints on the baseline schedule and; (3) resolving the problems and modifying baseline schedule (Kenley and Seppanen 2010). This study follows this general planning process.

The workspace planning process proposed in this study consists of five phases: (1) 4D BIM, which is able to simulate changes in a construction project using linkages between objects in 3D BIM and corresponding activities in the project schedule plan, is generated; (2) the *working space* and *storage space* requirement for each activity is identified in light of information about construction methods and materials for the activity execution; (3) the status of workspace occupation for all types of workspace is represented by reflecting the construction plan, such as the activity execution plan or material management plan; (4) workspace interferences are identified thorough the spatial clash detection algorithm and wall follower algorithm; and (5) a pertinent solution for the identified workspace interference is presented by considering characteristics of the activity, workspace, and construction plan.

Figure 4-1 presents a schematic diagram for overall workspace planning process.

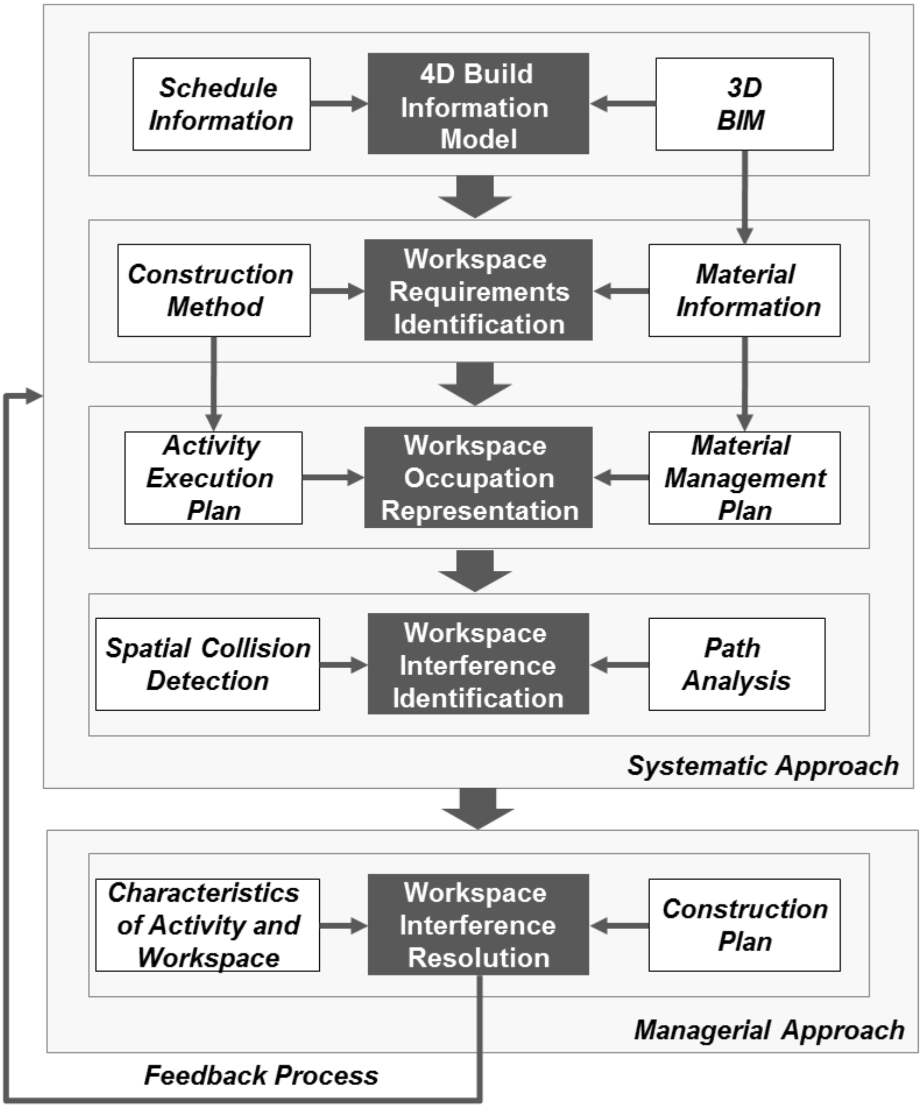


Figure 4-1 Workspace Planning Process

4.1 4D BIM Generation

The first task for workspace planning is to generate 4D BIM for a project. BIM is a digital representation of the physical and functional characteristics of a facility and the related project life cycle information; it uses the object-based parametric modeling method (Eastman et al. 2007; NBIS 2013). Each object in BIM is defined by parameters and relationships between parameters that determine geometric and additional properties of the object. 4D BIM is able to integrate information of building components and project schedule by linking between each object in 3D BIM and the corresponding activity in a schedule plan. 4D BIM can represent dynamic geometric changes in a building construction project, and is useful in identifying workspace changes in accordance with the construction process. In order to represent the status of workspace occupation and to identify workspace-related problems, this study utilized information about activity schedule, object quantity, and the geometric properties of the project that were contained in 4D BIM.

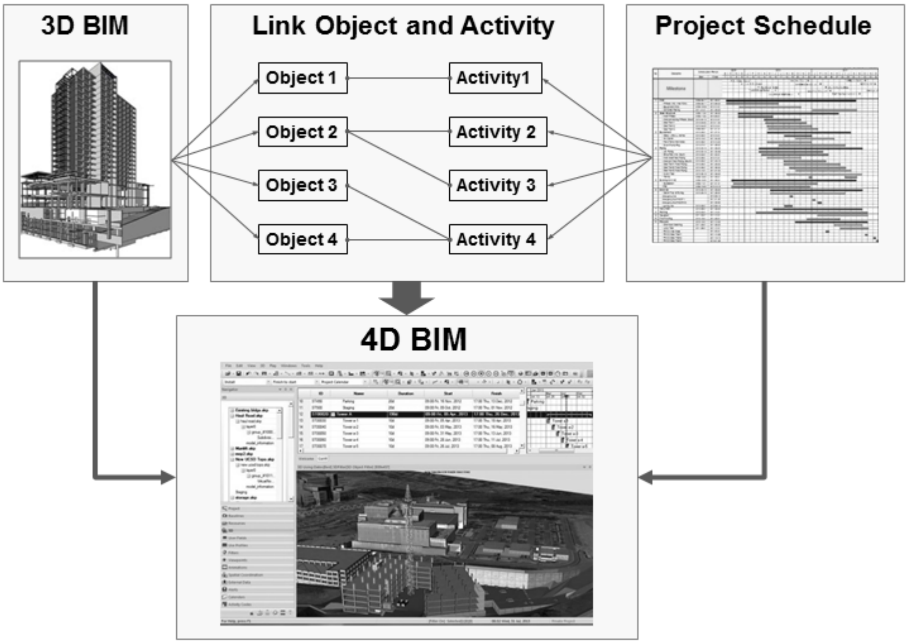


Figure 4-2. 4D BIM Generation

4.2 Workspace Requirement Identification

The *workspace requirement identification* phase is a process to identify the entire *working space* and *storage space* requirement for the execution of a specific activity. The detailed process for this phase is shown in Figure 4-3.

The construction method and material information databases are necessary for *workspace requirement identification*. The construction method database contains information about construction method selection criteria for each activity type and the spatial relationship between the object and *working space* that each construction method requires. The material information

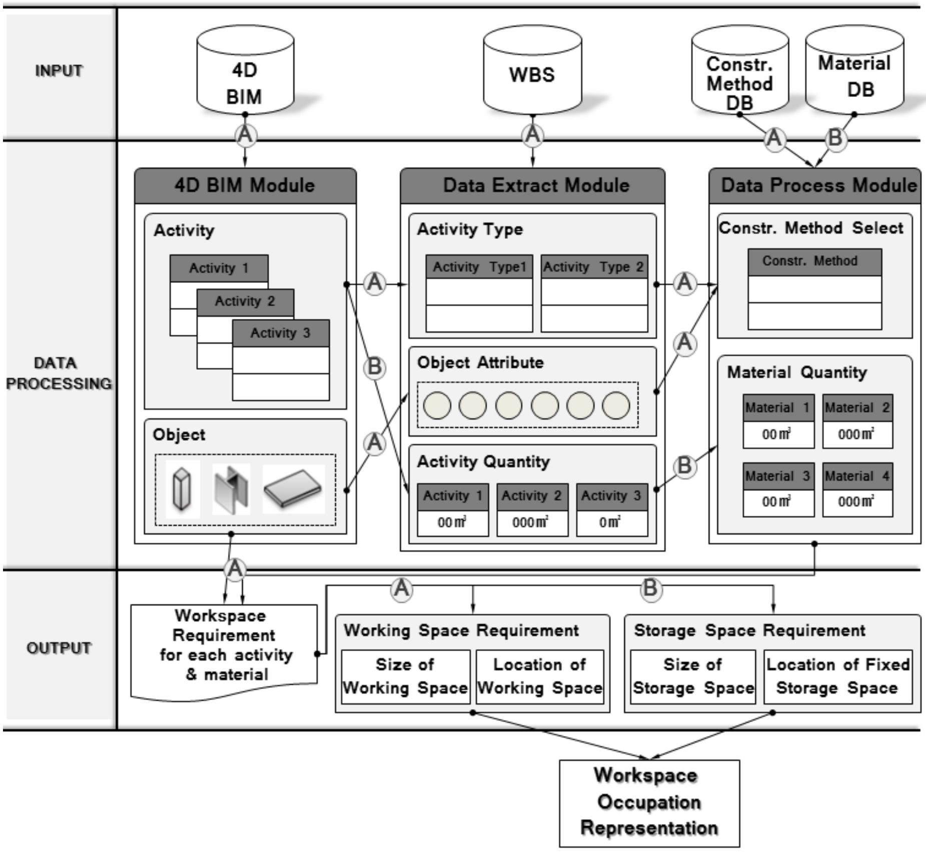


Figure 4-3. Workspace Requirement Identification

database includes information about the physical features of each material, as well as the quantitative relationship between activities and materials.

In order to identify the *working space* requirement, each activity extracted from 4D BIM is classified as an activity type through the work breakdown structure (WBS). A construction method for each activity is selected from possible construction methods for the activity type by considering the corresponding object's properties in 4D BIM. Afterward, the *working space* requirement for the activity execution is identified using the spatial relationship between *working space* and an object predefined in the construction method database (A in Figure 4). Akinci et al. (2002a) suggested a method to generate the workspace for each object using the spatial relationship between an object and the workspace, presented in the form of a transformation matrix. Based on this method, the whole requirement of *working space* for each activity could be identified.

To determine the *storage space* requirement, the quantities of each material needed to perform an activity are calculated by the quantity of the activity in 4D BIM and the quantitative relationship between the activity and the material in the material information database. The total size of the *storage space* for the material is established using geometric information of the materials found in the material information database. Then, the location of the fixed *storage space,* which should be adjacent to the *working space* owing to the nature of the material, is determined using the predefined spatial relationship between the *working space* and *storage space* (B in Figure 4-3).

Figure 4-4 depicts the detailed process of *storage space* requirement identification for a brick material example.

Most of the approaches for workspace planning developed in the previous studies identify workspace conflicts based on workspace requirements, which are assumed to occupy the whole required space for the entire activity duration (Akinci et al. 2002b; Chavada et al. 2012; Guo 2002; Winch and North 2006). However, in a real construction process, the activity is executed by successive and repetitive occupation as part of the workspace requirements (Riley and Sanvido 1995). Therefore, the pertinent methods for the representation of workspace occupation status are necessary to predict the actual workspace interferences.

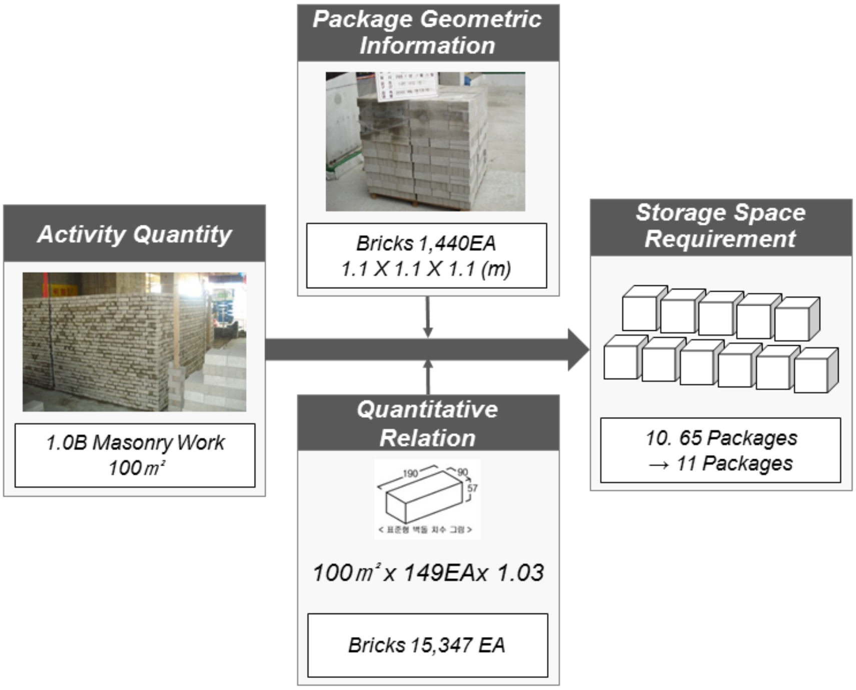


Figure 4-4. Example of Brick Material Storage Space Identification

4.3 Workspace Occupation Representation

Workspace occupation representation is a phase that describes the state of the workspace utilization for all types of workspace by reflecting the construction plan, such as activity execution plan and material management plan. The detailed process of this stage is delineated in Figure 4-5.

The activity execution plan explains the performance of an activity, and contains the number of work units for each activity and activity execution pattern of each work unit. This study adopts Riley and Sanvido's (1995) workspace pattern analysis in order to define the activity execution pattern of

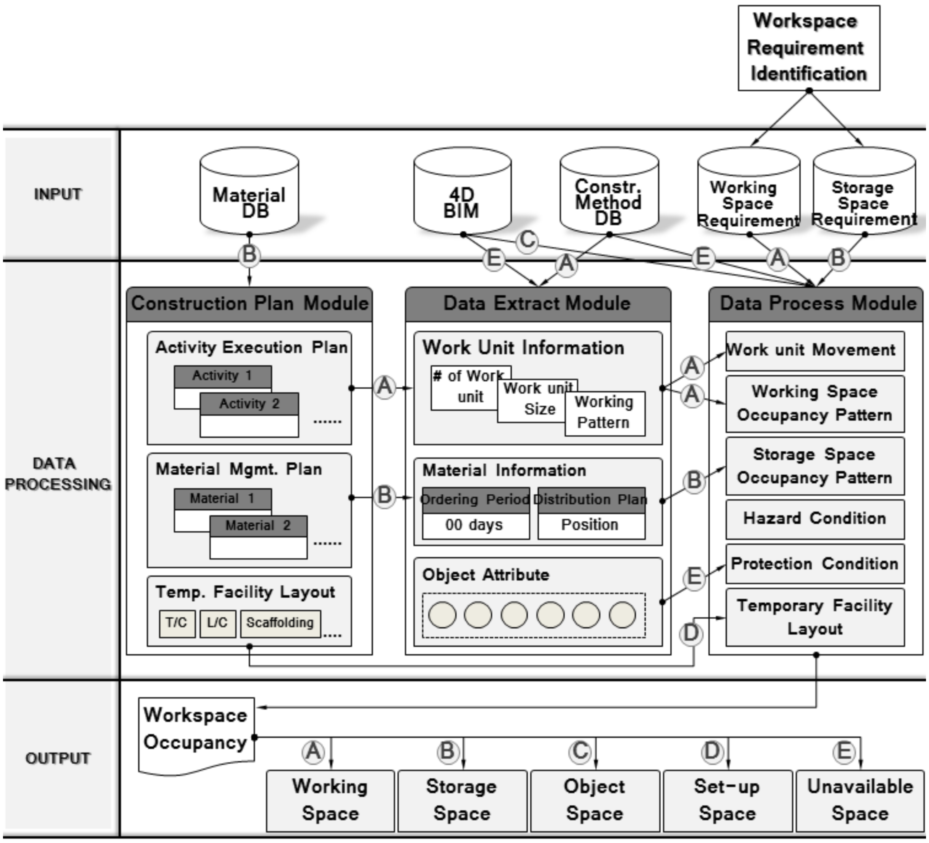


Figure 4-5. Workspace Occupation Representation

each work unit. The material management plan includes a material procurement plan that defines the quantity and period of material ordered and a material distribution plan that determines the layout for the materials imported to the construction site.

In order to represent the *working space* occupation, a *working space* occupation pattern is identified based on the size of each work unit defined in the construction method database, and the number of work units and the activity execution pattern are defined in the activity execution plan. Then, the velocity of each work unit passing along with the identified pattern is established by the activity quantity and duration derived from 4D BIM; the *working space* occupied by work units during a specific time period is represented based on the velocity (A in Figure 4-5).

The location and size of the *storage space* occupied by each material is determined by the material procurement plan and distribution plan. First, the total size of the *storage space* occupation at a specific time is calculated by dividing the size of the *storage space* requirement by the number of ordering times defined in the material procurement plan. Then, the location and size of the *storage space* occupation for imported material are represented by utilizing the material distribution plan. In the case of fixed *storage space*, location is determined using a predefined spatial relationship between *storage space* and *working space* (B in Figure 4-5).

Object space occupation would be perceived by the result of 4D BIM simulation (C in Figure 4-5), and the location and size of the *set-up space* are determined using the project manager's temporary facility layout plan (D in

Figure 4-5). Finally, *unavailable space* is represented using a spatial relation with the *object space,* which is defined by the protection condition in the object property, or using a spatial relationship with the *working space,* which is defined by the hazardous condition in the construction method database (E in Figure 4-5).

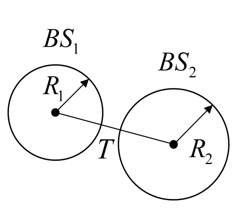
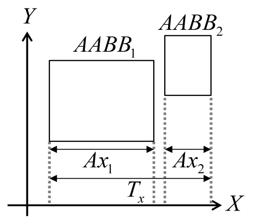
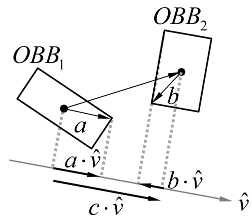
4.4 Workspace Interference Identification

In this study, the workspace interference is defined as a situation when the workspace for conducting an activity is not available. This situation can occur when different activities are required to occupy a specific space during the same time period, or when resources for activity execution cannot be accessed at their workspace due to obstructions created by other workspaces. Therefore, the *workspace interference identification* should include detecting not only workspace conflicts but also blocked paths.

Virtual spatial collisions in a 3D model are detected by the algorithm that generates minimized bounding volumes of the objects and identifies the conflict between each bounding volume. A 3D bounding volume is categorized by its shape into Bounding Spheres (BS), Axis-Aligned Bounding Boxes (AABB), or Oriented Bounding Boxes (OBB), as described in Table 4-1. BS identifies a spatial collision by comparing the sum of two bounding spheres' radii and the distance between the centers of two spheres. AABB detects a spatial collision by comparing the minimum and maximum values of the two bounding boxes that are parallel to their coordinate axes. OBB generates minimized bounding boxes around objects regardless of the objects' axis orientations, and determines a spatial collision between the two bounding boxes by identifying the existence of a separating axis (DeLoura et al. 2000; Moller and Haines 2002). When most objects at a job site are located parallel to a certain axis in a typical form, such as a box shape, AABB is the desirable method for identifying a spatial collision, but OBB is more pertinent to the emerging irregular-shaped building project, which contains numerous atypical objects.

Path analysis is a process that investigates the existence of available *path space* for all of the necessary resources in a construction project. For path analysis, the wall follower algorithm—which is one of the best-known rules for a maze problem—was adopted in this study (Madhavan et al. 2009). The wall follower algorithm finds an available path using the following steps: (1) it creates a straight line from a starting point to a destination point; and (2) when the line encounters an obstacle, the line moves along the surface of the obstacle until it meets the predefined straight line again. As described in Figure 4-6, the algorithm determines that a path does not exist when a moving line spins around at the same place or when the line reaches the boundary of the map (Sedgewick 2001).

Table 4-1. Spatial Collision Detection Algorithm (DeLoura et al. 2000; Moller and Haines 2002)

	Bounding Sphere	**Axis-Aligned Bounding Box**	**Oriented Bounding Box**
Diagram			
Collision Condition	$T < R_1 + R_2$	$T_x < Ax_1 + Ax_2$	$\lvert c \cdot \hat{v} \rvert < \lvert a \cdot \hat{v} + b \cdot \hat{v} \rvert$

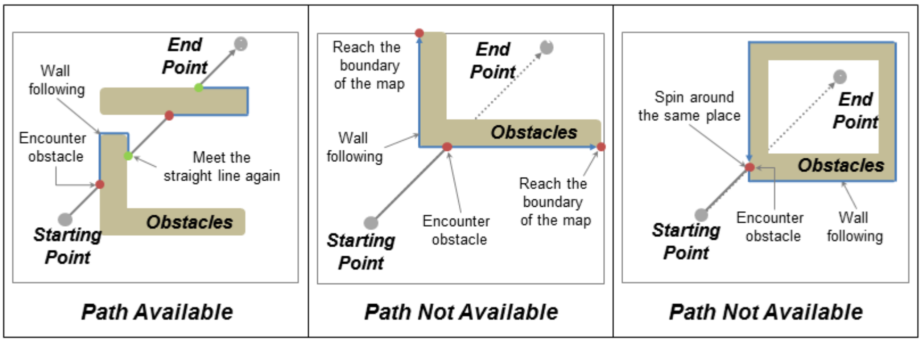


Figure 4-6. Wall Follower Algorithm (Sedgewick 2001)

Since diverse paths can be necessary at a construction site, path analysis should be conducted for every type of path required to execute an activity. Therefore, path analysis should include: (1) a laborer's path from an entrance to the *working space*, (2) a work unit's path from a *working space* to the next *working space*, (3) a material distribution path from an entrance to the *storage space,* and (4) a material transportation path from a *storage space* to the *working space*. The width of a straight line in the wall follower algorithm, which defines the minimum wideness of the necessary *path space*, is determined by the physical feature of the resource for the associated space. The detailed criteria of the minimum size of path space are described in Table 4-2.

Table 4-2. Detailed Criteria for Determining Minimum Size of Path Space

Path	Reference for the straight line size
Laborer's path	Size of Laborer
Work unit's path	Size of Laborer and Work unit in construction method DB
Material distribution path	Size of Laborer and material package in material information DB
Material transportation path	Size of Laborer and material unit in material information DB

The project manager can obtain the information of characteristics of activity and workspace at the location where workspace interferences possibly happen through a systematic approach from the *4D BIM generation* phase to the *workspace interference identification* phase. In addition to the systematic approach that helps to get objective information about the workspace interference, a managerial approach for the whole project perspective that considers a relationship with other activities is also required.

4.5 Workspace Interference Resolution

In the *workspace interference resolution* phase, pertinent strategies are devised for the identified workspace interferences by considering characteristics of an activity, workspace, and construction plans. In other words, the project manager should consider the relocatability of the workspace, the criticality of the activity, the activity execution plan, and the material management plan in order to resolve the workspace interferences as described in Figure 4-7.

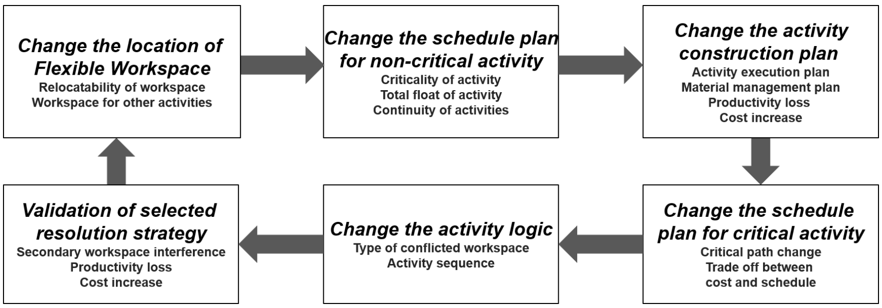


Figure 4-7. Workspace Interference Resolution Process

(1) Change the location of *flexible workspace*

If there is a *flexible workspace* among conflicted workspaces, the workspace interference could be resolved by changing the workspace location. When determining the location of the changed workspace, the project manager should consider not only the location of the conflicted workspace but also the location of other workspaces that are occupied by other activities at the same time.

(2) Change the schedule plan for non-critical activity

In the case where every conflicted workspace is a *fixed workspace*, the workspace interferences could be resolved by deferring a start date or changing the duration of the non-critical activity among the problematic activities. In order not to affect the total duration of the project, the schedule change for non-critical activity should be designed within the total float of the activity. The continuity of the activity should also be considered.

(3) Change the activity construction plan

The activity execution plan and the material management plan are factors that determine the final status of workspace utilization in the *workspace occupation representation* phase. Therefore, the project manager can change the location of the *working space* and the related *indirect workspace* through the modification of the activity execution pattern. Moreover, workspace interference could be solved by revising the material procurement plan and the distribution plan. When planning to change the construction plan, the project manager should consider the possible productivity loss and cost increase caused by the change.

(4) Change the schedule plan for critical activity

The workspace interference that cannot be resolved by methods 1–3 is resolved by changing a schedule plan for a critical activity. Although the schedule plan change for the critical activity can cause a project delay, it can prevent further damages caused by negative project management issues—such as unnecessary rework, safety hazard, and issues of poor quality—due to the interference of the workspace. When changing the schedule plan for critical activities, the project manager should examine whether or not the critical path is changed due to the schedule plan change.

(5) Change the activity logic

Some workspace interferences between *object space* and *fixed workspace* may not be resolved by methods 1–4. This type of workspace interference occurs when the project manager fails to consider the workspace for an activity when he/she determines the activity sequence. Therefore, this type of workspace interference could be prevented by changing an activity performing logic with the consideration of the workspace.

(6) Validation of selected resolution strategy

Finally, the validation of the selected workspace interference resolution strategy from the process described above is examined by again inputting the strategy into the workspace planning process. In this process, the project manager can confirm the validity of the selected strategy through the identification of secondary workspace interferences by the selected strategy

4.6 Summary

Based on the review on previous studies in chapter 2, and workspace classification in chapter 3, formalized workspace planning process is proposed in this chapter. The workspace planning process suggested in this study consists of five following phases.

(1) *4D BIM generation*, which is able to simulate changes in a construction project by linking between objects in 3D BIM and corresponding activities in the project schedule plan;

(2) *Workspace requirement identification* that identifies entire *working space* and *storage space* requirement for the execution of a specific activity by considering construction methods and materials for the activity execution;

(3) *Workspace occupation representation* which describes the state of the workspace utilization for all types of workspace by reflecting the construction plan, such as activity execution plan and material management plan;

(4) *Workspace interference identification* that detects potential workspace interferences in a construction project by the spatial clash detection algorithm and wall follower algorithm; and

(5) *Workspace interference resolution* which suggests pertinent solutions for identified workspace interferences by integrating consideration for characteristics of the activity and workspace and construction plan.

Chapter 5 Case Study

This chapter scrutinizes the applicability of the suggested workspace planning process in real world setting with an application example. The case project was a one floor finish work of the 1,850 m^2 floor research building construction project in Seoul National University.

5.1 Workspace Planning Process for Case Project

The case project was to take 90 days and be composed of 23 activities, including vertical piping and floor finishing work. Figure 5-1 displays *4D BIM generation* phase combined 3D BIM and an initial construction schedule.

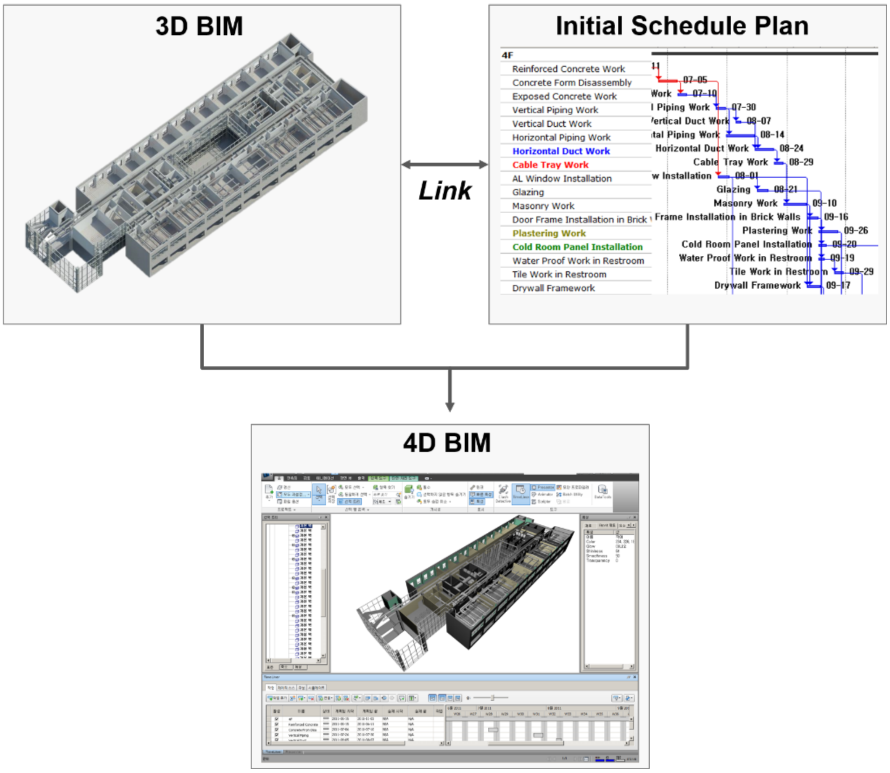


Figure 5-1. 4D BIM for the Case Project

A required workspace for each activity was identified based on the attributes of the object in 4D BIM, construction methods, and materials for activity execution. The AABB method was used to identify the workspace requirement as most objects in the case project were located parallel to the BIM's local axes in a box shape. Figure 8 explains an example of the workspace identification for a drywall framework activity. The rolling scaffolding was determined as a construction method for framing drywall because the height of the wall objects associated with the activity was consistently more than 3.0m but less than 5.0m; thus, the entire workspace requirement of the drywall framework activity was identified by replicating the unit workspace for a rolling scaffolding work to all of the associated objects, as described in Figure 5-2.

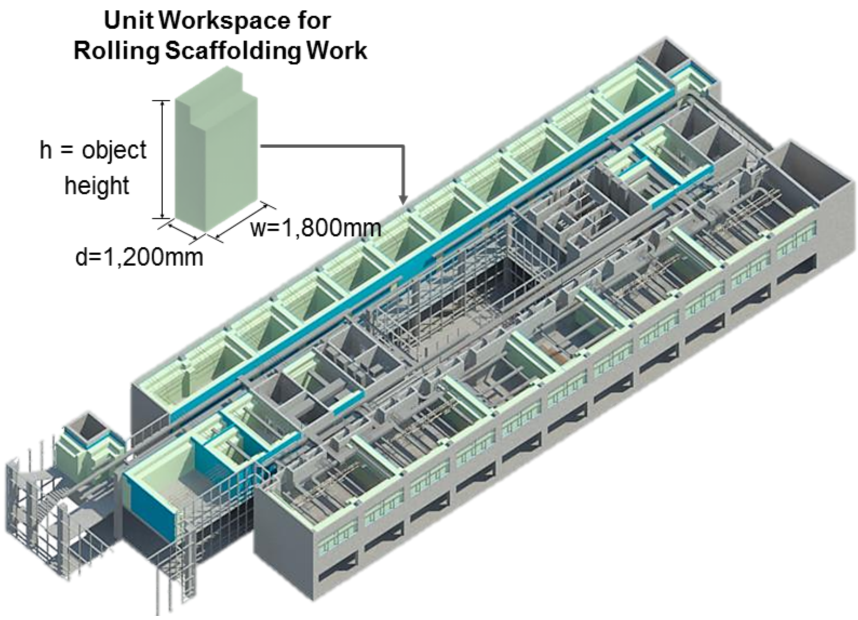


Figure 5-2. Workspace Requirement Identification for Drywall Framework

The project manager in the case project devised an activity execution plan, which divided the entire floor into three work zones—classroom zone (left), corridor zone (center), and laboratory zone (right)—that consider the schedule plans and quantity of the activity, as described in 5-3.

The size of each work unit was the same as the one for the rolling scaffolding (1,800mm x 1,200mm). Based on this process, a daily occupation status of *working space* for the activity could be represented as Figure 5-4. Through the process from *4D BIM generation* to *workspace occupation representation* as explained with the example of drywall framework activity, the workspace occupation status for all 23 activities could be represented. Table 5-1 shows the detailed information on *workspace occupation representation* for several activities of the case project.

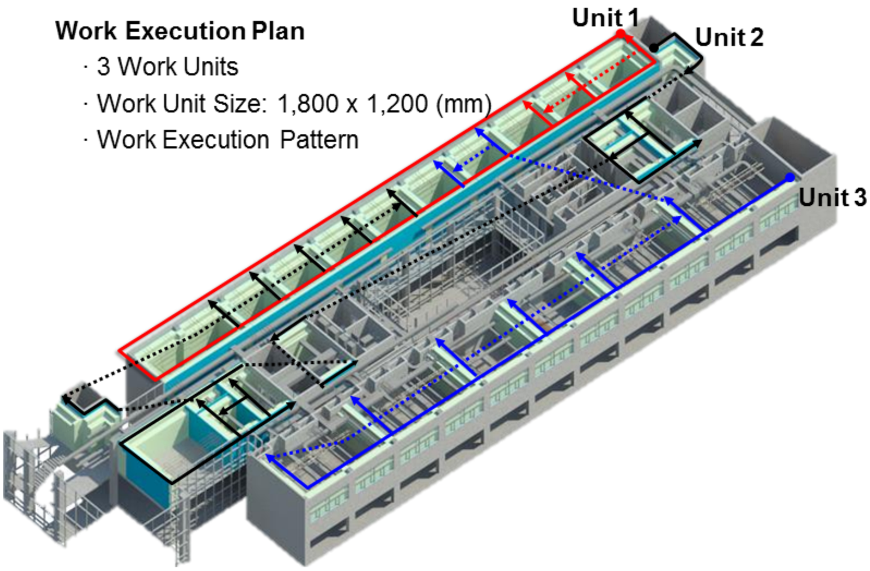


Figure 5-3. Activity Execution Plan for Drywall Framework

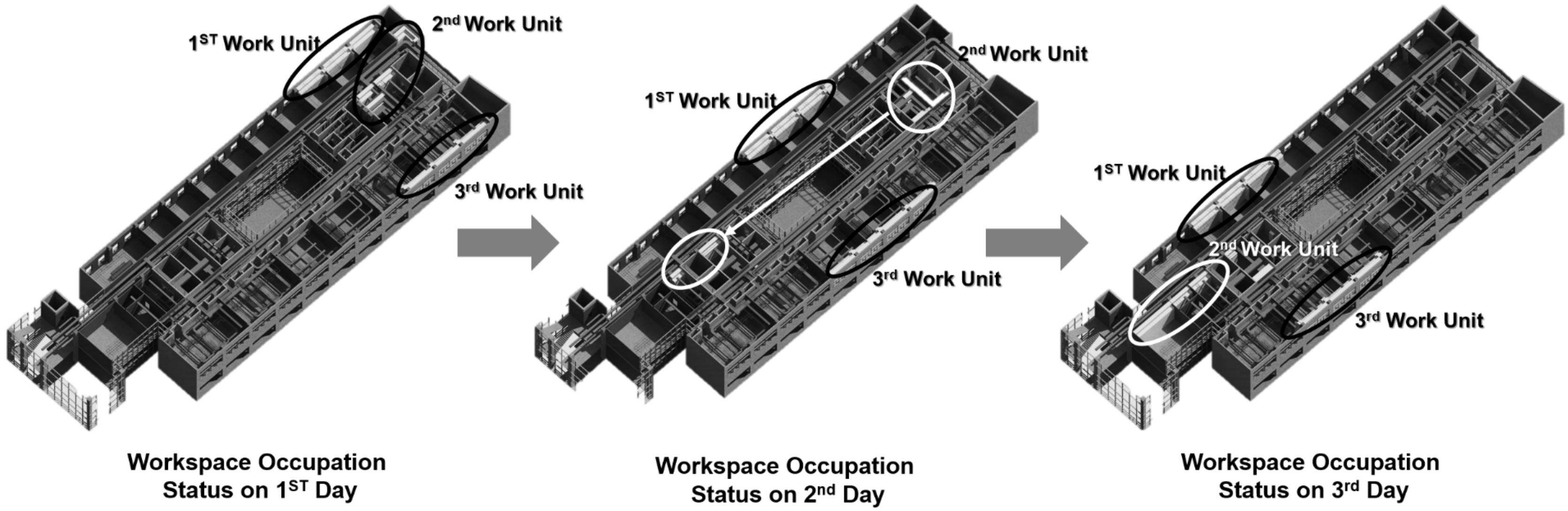


Figure 5-4. Workspace Occupation Representation for Drywall Framework>

Table 5-1. Information for Workspace Occupation Representation in the Case Project

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
1	Vertical Piping Work	5 days	4D BIM Simulation	Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 Places	-	-
2	AL Window Installation	6 days		Rolling Scaffolding	2 Units	Horizontal Unit	Ordering whole quantity at one time	Adjacent to Working Space	-	-
3	Glazing	6 days		Rolling Scaffolding	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Adjacent to Working Space	-	-
4	Horizontal Piping Work	15 days		Table Lift	3 Units	Linear	7 days	Distribute in 5 places	-	-
5	Vertical Duct Work	3 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 3 places	Prefabrication Area	
6	Atrium Curtain Wall installation	10 days		Car Gondola	2 Units	Vertical Unit	Ordering whole quantity at one time	Distribute in 6 places	-	Hazardous Area beneath Working Space
7	Atrium Glazing	5 days		Car Gondola	2 Units	Vertical Unit	Ordering whole quantity at one time	Distribute in 3 places	-	Hazardous Area beneath Working Space
8	Horizontal Duct Work	10 days		Table Lift	3 Units	Linear	5 days	Distribute in 4 places	Prefabrication Area	-

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
9	Cable Tray Work	5 days		Table Lift	2 Units	Linear	Ordering whole quantity at one time	Distribute in 3 places	-	-
10	Masonry Work	12 days		Rolling Scaffolding	3 Units	Linear	6 days	Adjacent to Working Space	-	-
11	Door Frame Installation in Brick Walls	6 days		Step Ladder	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 5 places	-	-
12	Plaster Work	10 days		Step Ladder	4 Units	Repeated Linear	5 days	Distribute in 5 places	-	-
13	Cold Room Panel Installation	4 days	4D BIM Simulation	Pipe scaffold	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 places	-	-
14	Water Proof Work in Restroom	3 days		Stand-up work	1 Unit	Horizontal Unit	-		-	Protection for 5 days
15	Tile Work in Restroom	5 days		Step Ladder	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 places	-	-
16	Drywall Frame Work	7 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 3 places		
17	Door Frame Installation in Drywalls	2 days		Step Ladder	1 Unit	Linear	Ordering whole quantity at one time	Distribute in 2 places		

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
18	Drywall Finish Work	7 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 19 places		
19	Handrail Installation	6 days		Stand-up work	1 Unit	Linear	Ordering whole quantity at one time	Distribute in 1 place	Prefabrication Area	-
20	Base Painting Work	5 days		Stand-up work	1 Unit	Linear	-		-	-
21	Ceiling Work	14 days		Pipe Scaffold	2 Units	Horizontal Unit	7 days	Distribute in 2 place	-	-
22	Finish Painting Work	7days		Stand-up work	2 Units	Linear	-		-	-
23	Floor Finish Work	3 days		Stand-up work	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 place	-	Protection for 3 days
24	Temporarily Work		Temporarily Facility Layout	-	-	-	-	-	Lift Car T/C and etc.	-

After representing the workspace occupation for all activities, possible workspace interferences could be identified using spatial collision detection and path analysis. For example, Figure 5-5 displays the spatial conflict between the *working spaces* for drywall framework activity and *object space* for cable tray. This workspace interference could be resolved by changing the schedule of cable tray work execution, which was originally scheduled for execution before the drywall framework activity for the convenience of table lift movement. By putting the cable tray work execution after the drywall finish work activity, the productivity was somewhat lowered by the inconvenience of table lift movement during the cable tray work, but it actually prevented a delay of the project by avoiding more serious rework problems due to workspace interferences.

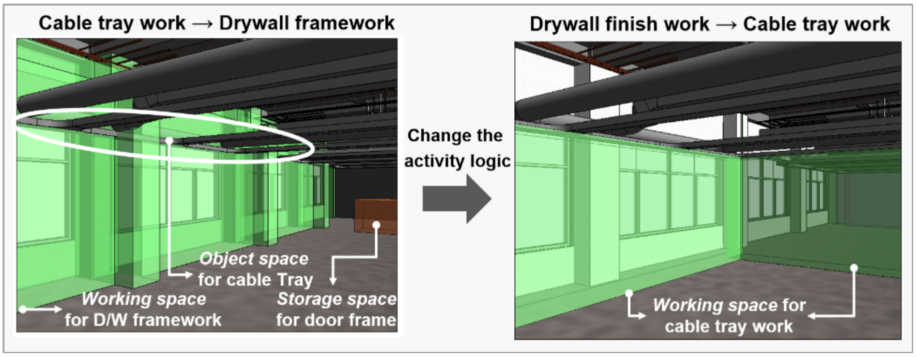


Figure 5-5. Workspace Interference Identification and Resolution Example

5.2 Results of Case Study

A total of 37 workspace interferences were identified by spatial collision detection (31 problems) and path analysis (6 problems) from the case study, and Table 6 summarizes a part of the identified workspace interferences. The correct location of the workspace interference was perceived by the values in the workspace interference location information boxes in Table 5-2, which indicates the maximum and minimum X, Y, and Z coordinate values for the conflicted rectangular space identified by the AABB algorithm. This study improved the accuracy of workspace status representation by introducing the workspace occupation concept. Moreover, it also improved the accuracy of workspace interference identification by removing 40 unrealistic workspace conflicts among 71 workspace conflicts that were identified using existing methods that could not distinguish workspace requirement from workspace occupation.

Table 5-2. Example of Identified Workspace Interferences in the Case Project

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A01	7/28	M210401	Vertical Piping Work	Storage Space	Flexible workspace	F210401	AL Window Installation	Working Space	Fixed workspace	25,180	65,150	16,900	26,320	69,800	17,000
A02	7/30	M210401	Vertical Piping Work	Storage Space	Flexible workspace	F210401	AL Window Installation	Working Space	Fixed workspace	25,180	39,800	16,900	26,320	35,150	17,000
A03	8/2	M210402	Horizontal Piping Work	Working Space	Fixed workspace	F219901	Atrium Curtain Wall Work	Working Space	Fixed workspace	15,425	50,900	16,900	16,625	55,760	20,800
A04	9/4	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	19,805	68,000	19,925	20,820	70,575	20,625
A05	9/5	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	19,300	62,000	19,500	19,700	64,900	19,600
A06	9/7	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	12,595	29,700	19,750	14,450	28,500	20,050
A07	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	15,490	32,500	20,300	15,890	37,725	20,600
A08	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,600	59,930	20,350	9,000	60,230	20,550
A09	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	6,695	25,950	19,950	7,095	27,900	20,250
A10	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	13,265	31,715	19,925	15,375	32,215	20,375

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A11	9/9	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	6,400	25,950	19,950	6,520	27,900	20,050
A12	9/10	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	12,035	24,645	20,350	12,800	28,300	20,950
A13	9/10	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	16,060	24,200	19,950	16,585	28,300	20,050
A14	9/11	F210409	Drywall Framework	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	24,870	71,785	19,500	25,120	80,715	19,600
A15	9/12	F210409	Drywall Framework	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	8,690	74,770	20,300	14,370	74,370	20,600
A16	9/11	F210409	Drywall Framework	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	25,625	70,670	20,925	25,650	82,050	20,950
A17	9/14	F210409	Drywall Framework	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	23,455	16,315	20,275	25,540	16,915	20,975
A18	9/16	F210409	Drywall Framework	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	19,135	57,270	19,455	24,645	58,020	19,855
A19	9/17	F210405	Plastering Work	Working Space	Fixed workspace	F210406	Cold Room Panel Installation	Storage Space	Fixed workspace	10,445	77,030	16,900	12,820	77,580	18,250
A20	9/17	F210406	Cold Room Panel Installation	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	10,250	77,030	16,900	11,250	78,230	18,700

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A21	9/17	F210407	Water Proof Work in Restroom	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	9,480	64,130	16,900	9,980	65,130	18,700
A22	9/18	F210407	Water Proof Work in Restroom	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	13,880	63,130	16,900	13,380	64,130	18,700
A23	9/20	F210405	Plastering Work	Storage Space	Flexible workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	5,580	78,290	16,900	6,395	80,490	18,000
A24	9/20	F210405	Plastering Work	Working Space	Fixed workspace	F210406	Cold Room Panel Installation	Storage Space	Fixed workspace	10,445	22,980	16,900	12,820	23,580	18,250
A25	9/20	F210406	Cold Room Panel Installation	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	10,250	22,980	16,900	11,250	24,180	18,700
A26	9/21	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	5,500	28,710	19,405	6,395	62,600	20,055
A27	9/22	F210412	Drywall Finish Work	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	17,180	54,400	16,900	17,680	55,400	18,700
A28	9/23	F210412	Drywall Finish Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	25,000	29,670	18,955	25,270	38,825	19,055
A29	9/24	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	14,055	31,280	16,900	15,255	32,480	20,500
A30	9/24	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	25,145	28,675	20,255	25,540	39,975	20,355

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A31	9/24	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	15,505	18,335	19,755	15,905	24,200	20,055
A32	9/24	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	18920	16,200	16,900	20,120	17,400	21,000
A33	9/25	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	14,055	28,570	16,900	15,255	29,770	20,500
A34	9/25	F210412	Drywall Finish Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	15,590	70100	19,750	16,340	78,200	19,850
A35	9/25	F210405	Plastering Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,180	82,690	19,900	15,395	83,140	20,200
A36	9/25	F210405	Plastering Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,180	82,690	19,900	15,395	83,140	20,200
A37	9/25	F210405	Plastering Work	Path Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	15395	28600	16900	16595	29600	18700

Identified workspace interferences were resolved by changing the location of *storage space* for plastering work and vertical piping work (changing the location of *flexible workspace*), delaying the start date of the cold room panel installation (changing the schedule plan for non-critical activity), modifying the activity execution plan for horizontal piping work and plastering work (changing the activity construction plan), dividing horizontal duct work into two phases, and changing the sequence of the cable tray work (changing the activity logic).

The revised schedule plan by workspace interference resolution strategies mentioned above indicated a schedule delay due to productivity decrease and other problems. Such delay implies that the project manager failed to properly consider workspace for activity execution during the scheduling of the project. In order to complete the project without workspace interferences, the project manager therefore should have modified the schedule plan for critical activities based on the revised schedule plan. In this case project, the project manager planned to implement the crashing strategy for ceiling work, which was one of the critical activities, in order to catch up on the two-day delay caused by workspace interference resolution strategies. Although this crashing plan was expected to decrease unit productivity due to additional resource input, it contributed to the improvement of the project performance by reducing the uncertainty of the project by preventing the workspace interferences.

5.3 Summary

This chapter presents a process of the application for the suggested workspace planning process in an actual construction project. The finish work for one floor of a research building construction project in Seoul National University is served as a test bed. The purpose of the case study is to examine the effectiveness and applicability of the suggested process.

In the case study, 37 potential workspace interferences are identified and resolved in advance, throughout the suggested workspace planning process from *4D BIM generation* to *workspace interference resolution*. In addition, project manager in a case project can proactively prevent side effect of the workspace interferences resolution strategies by modifying the established schedule plan.

Chapter 6 Conclusion

This chapter summarizes the results obtained from the suggested process in this study and addresses the possible contributions that this study makes for the construction industry. In addition, the limitations of the study and areas for future related studies have been identified.

6.1 Result and Discussion

Workspace interferences would result in significant problems in a construction project such as a loss of productivity, safety hazards, and issues of poor quality. In order to prevent such negative impact of the workspace interference, this study presented a formalized workspace planning process using 4D BIM for building construction as follow;

(1) Studying on Previous Studies

There have been a number of efforts to address the status of workspace utilization and identify workspace related problems in a construction projects. Along with substantial achievements by previous studies, however, they still have some limitations in the representation of workspace occupation status, workspace interferences identification and resolution. Previous studies rely on the inaccurate assumptions about the workspace utilization and they also fail to integrate information about the characteristics of workspace and activity together with construction plan.

(2) Classifying Workspace by its Function and Relocatability

In order to integrate the characteristics of workspace and workspace planning process, this study classified workspace by its function and relocatability. Based on the functional classification of the workspace, the status of the workspace utilization would be represented without exception. Workspace classification by its relocatability is used for finding pertinent resolution strategies for the identified workspace interferences in a suggested workspace planning process.

(3) Suggesting a Workspace Planning Process

Based on the workspace classification, a formalized workspace planning process is proposed. Suggested process in this study improves the accuracy of workspace status prediction and workspace interference identification by introducing the workspace occupation concept. It also contributes to effective workspace planning process by integrating construction plan, characteristics of workspace types, and activity. Moreover, this study can help to ameliorate workspace planning process by including the path analysis process and workspace interference resolution phase that is overlooked in the most of previous studies.

(4) Practical Utilization

In order to examine the applicability of the proposed approach, a case project was tested. The result of the case study shows the applicability and effectiveness of the proposed process on enhancing the workspace planning process.

6.2 Contributions and Further Study

In spite of the significance of the workspace, current construction planning process fails to consider workspace for the activity properly in a building construction project due to its dynamic and complex nature. This study integrates the characteristics of workspace and workspace planning process. The contributions of this research are as follow;

(1) Improving Workspace Planning Process

The developed workspace planning process in this study can help the project manager prepare construction plans that are free of workspace interferences. A construction plan that properly considers workspace can help avoid severe problems in a construction project—such as rework, a decrease in productivity, safety hazards, and issues of poor quality—all of which are caused by workspace interferences. In addition, the suggested process in this study also contributes to cultivate the collaborative culture in a construction project since it prevents strife among the project participants due to workspace interruptions. All of this features of the suggested workspace planning process would be beneficial for planning of construction projects, in particular whey they are performed in cramped conditions.

(2) Expanding the Scope of BIM Application

This study's 4D BIM–based approach for workspace planning shows that the application scope of BIM can expand into diverse and contextual information that is generated during the construction process from the simple information that occurs as a consequence of the construction project.

Although the study work presented thus far hold a good promise by showing that the suggested workspace planning process can help enhance planning capabilities, the study needs to be further related studies in order to get more refined workspace planning process.

(1) Collecting Related Data

As mentioned, the suggested workspace planning process requires numerous types of database such as construction method database and material information database. When there is not abundant data source enormous efforts are required to prepare these data. Therefore, developing database for these types of data should be implemented before the suggested workspace planning process.

(2) Developing Construction Process Reflecting BIM

Construction process reflecting BIM is an indispensable component of the suggested process in this study. However, it is also true that numerous efforts are required for the generation of construction process reflecting BIM. Therefore, additional studies for effective BIM generation process are able to contribute to ameliorate effectiveness and applicability of the suggested workspace planning process.

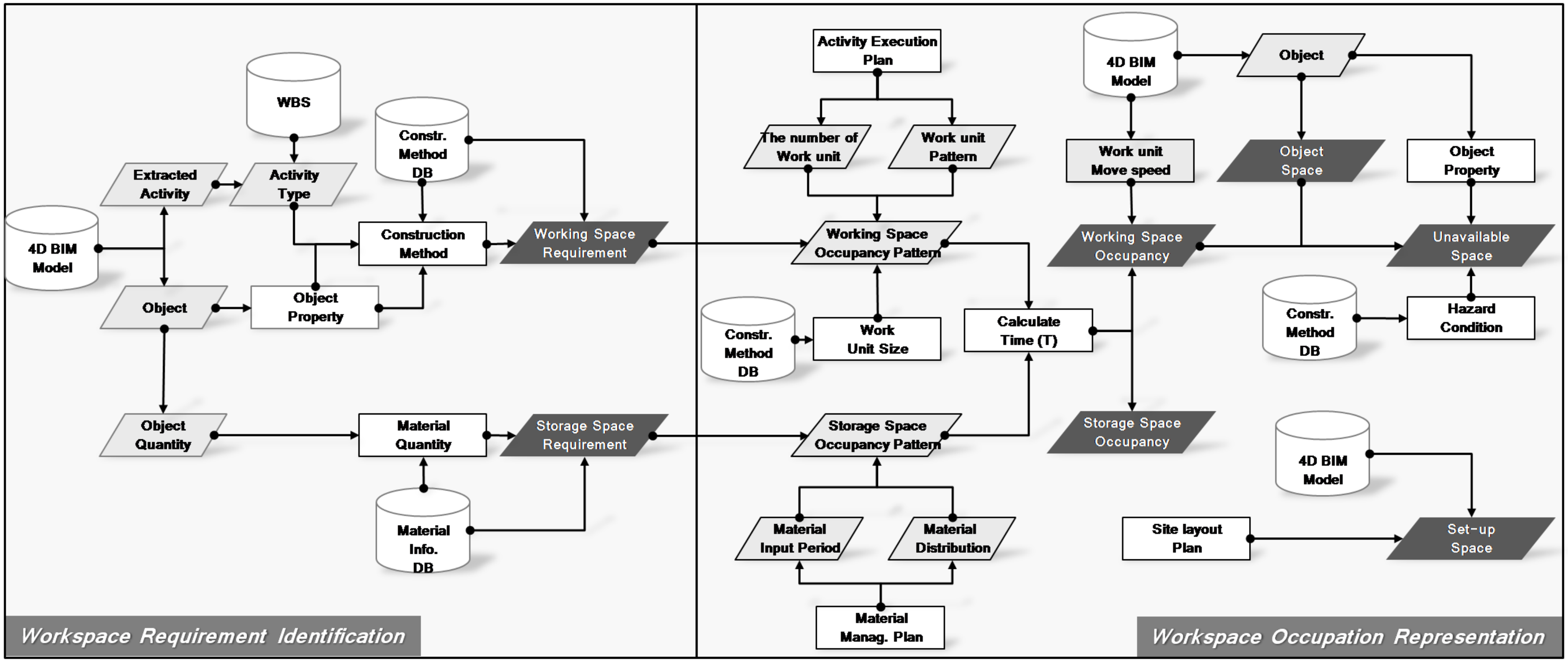
Appendices

Appendix A. Floor Chart for Workspace Requirement Identification and Workspace Occupation Representation

Appendix B. Selected Resolution Strategies for Identified Workspace Interferences in Case Project

Appendix C. Schedule plan for Case Project (Before & After Workspace Planning Process)

Appendix A. Flow Chart for Workspace Requirement Identification and Workspace Occupation Representation



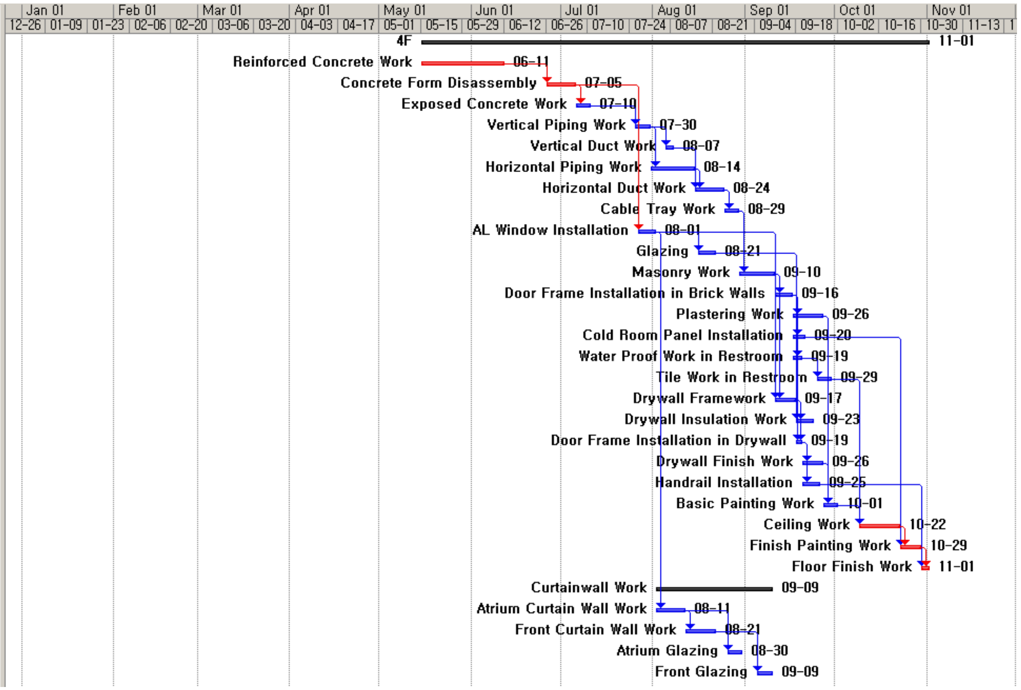
Appendix B. Selected Strategies for Identified Workspace Interferences in Case Project

No.	Date	Workspace 1		Workspace 2		Resolution Strategy
		Activity Name	Workspace type	Activity Name	Workspace type	
A01	7/28	Vertical Piping Work	Storage Space	AL Window Installation	Working Space	Change the location of Workspace 1
A02	7/30	Vertical Piping Work	Storage Space	AL Window Installation	Working Space	Change the location of Workspace 1
A03	8/2	Horizontal Piping Work	Working Space	Atrium Curtain Wall Work	Working Space	Change the activity execution plan for Workspace 1
A04	9/4	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A05	9/5	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A06	9/7	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A07	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A08	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A09	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A10	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A11	9/9	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A12	9/10	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A13	9/10	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A14	9/11	Drywall Framework	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A15	9/12	Drywall Framework	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A16	9/11	Drywall Framework	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A17	9/14	Drywall Framework	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A18	9/16	Drywall Framework	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2

No.	Date	Workspace 1		Workspace 2		Resolution Strategy
		Activity Name	Workspace type	Activity Name	Workspace type	
A19	9/17	Plastering Work	Working Space	Cold Room Panel Installation	Storage Space	Change the Schedule plan for Workspace 2
A20	9/17	Cold Room Panel Installation	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A21	9/17	Water Proof Work in Restroom	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A22	9/18	Water Proof Work in Restroom	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A23	9/20	Plastering Work	Storage Space	Drywall Finish Work	Working Space	Change the location of Workspace 1
A24	9/20	Plastering Work	Working Space	Cold Room Panel Installation	Storage Space	Change the Schedule plan for Workspace 2
A25	9/20	Cold Room Panel Installation	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A26	9/21	Drywall Finish Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A27	9/22	Drywall Finish Work	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A28	9/23	Drywall Finish Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A29	9/24	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A30	9/24	Drywall Finish Work	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A31	9/24	Drywall Finish Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A32	9/24	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A33	9/25	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A34	9/25	Drywall Finish Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A35	9/25	Plastering Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A36	9/25	Plastering Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A37	9/25	Plastering Work	Path Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1

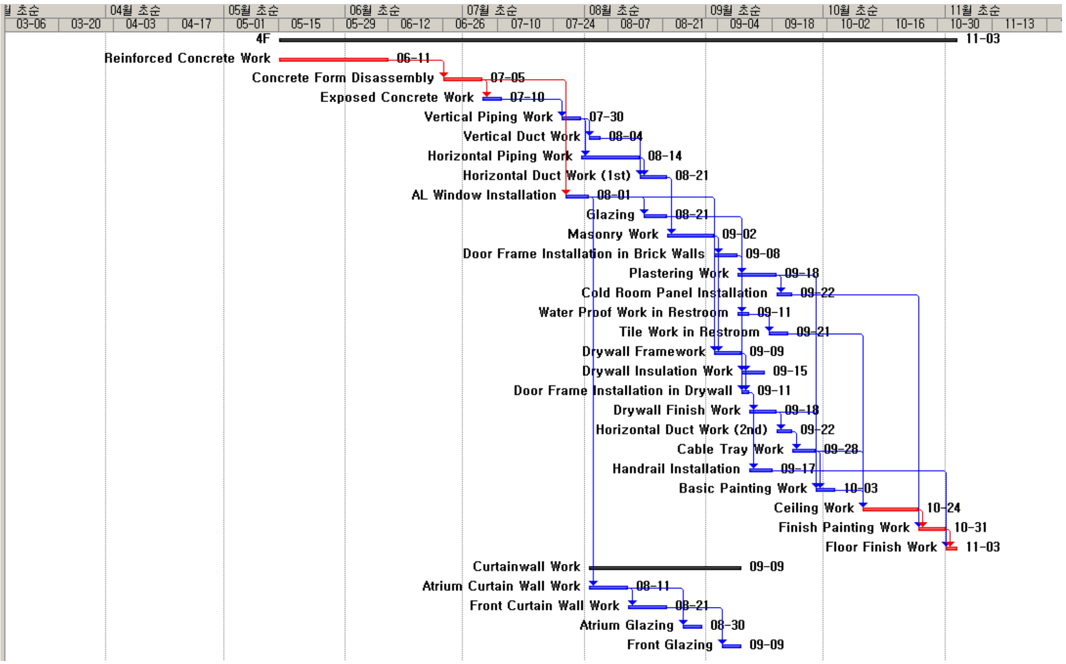
Appendix C-1 Schedule Plan for Case Project before Workspace Planning Process

	작업 이름	기간	시작 날짜	완료 날짜
55	**4F**	**171 일**	**11-05-15 (일)**	**11-11-01 (화)**
56	Reinforced Concrete Work	28 일	11-05-15 (일)	11-06-11 (토)
57	Concrete Form Disassembly	10 일	11-06-26 (일)	11-07-05 (화)
58	Exposed Concrete Work	5 일	11-07-06 (수)	11-07-10 (일)
59	Vertical Piping Work	5 일	11-07-26 (화)	11-07-30 (토)
60	Vertical Duct Work	3 일	11-08-05 (금)	11-08-07 (일)
61	Horizontal Piping Work	15 일	11-07-31 (일)	11-08-14 (일)
62	**Horizontal Duct Work**	**10 일**	**11-08-15 (월)**	**11-08-24 (수)**
63	**Cable Tray Work**	**5 일**	**11-08-25 (목)**	**11-08-29 (월)**
64	AL Window Installation	6 일	11-07-27 (수)	11-08-01 (월)
65	Glazing	6 일	11-08-16 (화)	11-08-21 (일)
66	Masonry Work	12 일	11-08-30 (화)	11-09-10 (토)
67	Door Frame Installation in Brick Walls	6 일	11-09-11 (일)	11-09-16 (금)
68	**Plastering Work**	**10 일**	**11-09-17 (토)**	**11-09-26 (월)**
69	**Cold Room Panel Installation**	**4 일**	**11-09-17 (토)**	**11-09-20 (화)**
70	Water Proof Work in Restroom	3 일	11-09-17 (토)	11-09-19 (월)
71	Tile Work in Restroom	5 일	11-09-25 (일)	11-09-29 (목)
72	Drywall Framework	7 일	11-09-11 (일)	11-09-17 (토)
73	Drywall Insulation Work	6 일	11-09-18 (일)	11-09-23 (금)
74	Door Frame Installation in Drywall	2 일	11-09-18 (일)	11-09-19 (월)
75	**Drywall Finish Work**	**7 일**	**11-09-20 (화)**	**11-09-26 (월)**
76	Handrail Installation	6 일	11-09-20 (화)	11-09-25 (일)
77	Basic Painting Work	5 일	11-09-27 (화)	11-10-01 (토)
78	**Ceiling Work**	14 일	11-10-09 (일)	11-10-22 (토)
79	Finish Painting Work	7 일	11-10-23 (일)	11-10-29 (토)
80	Floor Finish Work	3 일	11-10-30 (일)	11-11-01 (화)
81	**Curtainwall Work**	**39 일**	**11-08-02 (화)**	**11-09-09 (금)**
82	Atrium Curtain Wall Work	10 일	11-08-02 (화)	11-08-11 (목)
83	Front Curtain Wall Work	10 일	11-08-12 (금)	11-08-21 (일)
84	Atrium Glazing	5 일	11-08-26 (금)	11-08-30 (화)
85	Front Glazing	5 일	11-09-05 (월)	11-09-09 (금)



Appendix C-2 Schedule Plan for Case Project after Workspace Planning Process

	작업 이름	기간	시작 날짜	완료 날짜
57	**4F**	**173 일**	**11-05-15 (일)**	**11-11-03 (목)**
58	Reinforced Concrete Work	28 일	11-05-15 (일)	11-06-11 (토)
59	Concrete Form Disassembly	10 일	11-06-26 (일)	11-07-05 (화)
60	Exposed Concrete Work	5 일	11-07-06 (수)	11-07-10 (일)
61	Vertical Piping Work	5 일	11-07-26 (화)	11-07-30 (토)
62	Vertical Duct Work	3 일	11-08-02 (화)	11-08-04 (목)
63	Horizontal Piping Work	15 일	11-07-31 (일)	11-08-14 (일)
64	**Horizontal Duct Work (1st)**	**7 일**	**11-08-15 (월)**	**11-08-21 (일)**
65	AL Window Installation	6 일	11-07-27 (수)	11-08-01 (월)
66	Glazing	6 일	11-08-16 (화)	11-08-21 (일)
67	Masonry Work	12 일	11-08-22 (월)	11-09-02 (금)
68	Door Frame Installation in Brick Walls	6 일	11-09-03 (토)	11-09-08 (목)
69	**Plastering Work**	**10 일**	**11-09-09 (금)**	**11-09-18 (일)**
70	**Cold Room Panel Installation**	**4 일**	**11-09-19 (월)**	**11-09-22 (목)**
71	Water Proof Work in Restroom	3 일	11-09-09 (금)	11-09-11 (일)
72	Tile Work in Restroom	5 일	11-09-17 (토)	11-09-21 (수)
73	Drywall Framework	7 일	11-09-03 (토)	11-09-09 (금)
74	Drywall Insulation Work	6 일	11-09-10 (토)	11-09-15 (목)
75	Door Frame Installation in Drywall	2 일	11-09-10 (토)	11-09-11 (일)
76	**Drywall Finish Work**	**7 일**	**11-09-12 (월)**	**11-09-18 (일)**
77	**Horizontal Duct Work (2nd)**	**4 일**	**11-09-19 (월)**	**11-09-22 (목)**
78	**Cable Tray Work**	**6 일**	**11-09-23 (금)**	**11-09-28 (수)**
79	Handrail Installation	6 일	11-09-12 (월)	11-09-17 (토)
80	Basic Painting Work	5 일	11-09-29 (목)	11-10-03 (월)
81	Ceiling Work	14 일	11-10-11 (화)	11-10-24 (월)
82	Finish Painting Work	7 일	11-10-25 (화)	11-10-31 (월)
83	Floor Finish Work	3 일	11-11-01 (화)	11-11-03 (목)
84	**Curtainwall Work**	**39 일**	**11-08-02 (화)**	**11-09-09 (금)**
85	Atrium Curtain Wall Work	10 일	11-08-02 (화)	11-08-11 (목)
86	Front Curtain Wall Work	10 일	11-08-12 (금)	11-08-21 (일)
87	Atrium Glazing	5 일	11-08-26 (금)	11-08-30 (화)
88	Front Glazing	5 일	11-09-05 (월)	11-09-09 (금)



Reference

Akinci, B., Fischer, M., and Kunz, J. (2002a). “Automated Generation of Work Spaces Required by Construction Activities.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 306~315

Akinci, B., Fischer, M. Kunz, J. and Levitt, R. (2002b). “Representing work spaces generically in construction method models.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 296~305

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002c). “Formalization and automation of time-space conflict analysis.” Journal of Computing in Civil Engineering, ASCE, 16(2), pp. 124~134

Bansal, V. (2011). "Use of GIS and Topology in the Identification and Resolution of Space Conflicts." Journal of Computing in Civil Engineering, ASCE, 25(2). pp. 159~171.

Chau, K. W., Anson, M., and Zhang, J. P. (2004). “Four-Dimensional Visualization of Construction Scheduling and Site Utilization.” Journal of Construction Engineering and Management, ASCE, 130(4), pp. 598~606

Chavada, R., Dawood, N. and Kassem, M. (2012). “Construction workspace management: the development and application of a novel nD planning approach and tool.” Journal of Information Technology in Construction, 17, pp. 213~236

Chua, D., Yeoh, K., and Song, Y. (2010). “Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design.” Journal of Construction Engineering and Management, ASCE, 136(6), pp. 641~649

Dawood, N. and Z. Mallasi (2006). “Construction workspace planning: Assignment and analysis utilizing 4D visualization technologies.” Computer- Aided Civil and Infrastructure Engineering, 21(7), pp. 498~513

DeLoura, M. A., Ahamd, A., Bilas, S., Boer, J., Dietrich, S. and Dybsand, E., et al. (2000). Game programming germs, Charles River Media Inc., USA, pp. 502~516

Eastman, C. Teicholz, P., Sacks, R., and Liston, K. (2008). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Whiley & Sons Inc., USA, pp. 25~64

Guo, S. J. (2002). “Identification and resolution of work space conflicts in building construction.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 287~295

Hammad, A., Zhang, C., Al-Hussein, M. and Cardinal, G. (2007). “Equipment workspace analysis in infrastructure projects.” Canadian Journal of Civil Engineering, 34(10), pp.1247~1256.

Kaming, P. F., Holt, G.D., Kometa, S. T. and Olomolaiye, P.O. (1998). “Severity diagnosis of productivity problems – a reality analysis.” International Journal of Project Management, 16(2), pp. 107~113.

Kelsey, J., Winch, G., and Penn, A. (2001). “Understanding the Project Planning Process: Requirements Capture for the Virtual Construction Site.” University College London, UK, Bartlett Research

Keneley, R. and Seppanen, O. (2010). Location-Based Management for Construction: Planning, Scheduling and Control, Son Press, USA, pp. 49 ~ 92

Madhavan, R., E. W. Tunstel and E. R. Messina (2009). Performance Evaluation and Benchmarking of Intelligent Systems, Springer, USA, pp. 139 ~ 168

Mallasi, Z. (2006). “Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation.” Automation in Construction, 15(5), pp. 640~655

Moller, T. and Haines, E. (2002). Real time Rendering, 2nd ed., A K Peters, Ltd., USA, pp. 631~668

National BIM Standard-United States Version 2, National BIM Standard-United States Project Committee, <http://www.nationalbimstandard.org/about.php> (2013.06.10)

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). Productivity Improvement in Construction, McGraw-Hill Inc, USA

Riley, D. R., and Sanvido, V. E. (1995). “Patterns of Construction-Space Use in Multistory Buildings.” Journal of Construction Engineering and Management, ASCE, 121(4), pp. 464~473

Riley, D. R., and Sanvido, V. E. (1997). “Space planning method for multistory building construction.” Journal of Construction Engineering and Management, ASCE, 123(2), pp. 171~180

Said, H. and K. El-Rayes (2013). "Optimal utilization of interior building spaces for material procurement and storage in congested construction sites." Automation in Construction 31(0), pp. 292~306.

Sadeghpour, F., Moselhi, O. and Alkass, S.T. (2006). "Computer-Aided Site Layout Planning." Journal of Construction Engineering and Management, 132(2), pp. 143~151.

Sedgewick, R. (2001). Algorithms in C++ Part 5: Graph Algorithms, Pearson Education Inc., USA, chapter 18.

Thabet, W. Y., and Beliveau, Y. J. (1994). "Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings." Journal of Construction Engineering and Management, ASCE, 120(1), pp. 96~116

Tommelein, I. D., and Zouein, P. P. (1993). "Interactive Dynamic Layout Planning." Journal of Construction Engineering and Management, ASCE, 119(2), pp. 266~287

Talmaki, S. and V. R. Kamat (2012). "Real-Time Hybrid Virtuality for Prevention of Excavation Related Utility Strikes." Journal of Computing in Civil Engineering, ASCE (On-line Published)

Wang, H. J., Zhang, J. P., Chau, K. W. and Anson, M. (2004). "4D dynamic management for construction planning and resource utilization." Automation in Construction 13(5), pp. 575~589.

Winch, G. M., and North, S. (2006). "Critical space analysis." Journal of Construction Engineering and Management, ASCE, 132(5), pp. 473~481

Zhang, C., Hammad, A., Zayed, T. M., Wainer, G, and Pang, H. (2007). "Cell-based representation and analysis of spatial resources in construction

국 문 초 록

건설프로젝트에서는 다양한 참여자들이 제한된 공간에서 각자의 작업공간을 차지하며 작업을 수행한다. 작업공간에 대한 부적절한 계획은 건설프로젝트의 생산성 감소, 작업 위험 증가 및 품질 저하 등의 문제로 이어지기 때문에 작업공간은 건설프로젝트에서 고려하여야 할 중요한 요소 중 하나이다. 그러나 간트 차트, Critical Path Method, 네트워크 다이어그램 등의 기존의 프로젝트 공사 계획 수립을 위한 방법들은 건설프로젝트에서의 작업공간을 고려하지 못하는 한계가 있었다.

본 연구에서는 체계적이지 못한 작업공간 계획으로 인하여 발생하는 작업공간 문제를 예방하기 위하여 작업공간을 그 기능과 이동가능성에 따라서 분류하고 4D BIM(Building Information Model) 생성, 필요작업공간 식별, 점유작업공간 표현, 작업공간문제 식별, 작업공간문제 해결 단계를 포함하는 4D BIM 기반의 작업공간 계획 프로세스를 제안한다.

제안된 프로세스는 점유 작업공간 개념의 도입하고 작업공간 및 액티비티의 특성 그리고 공사수행계획을 통합적을 고려함으로써 작업공간의 사용 상태 표현 및 작업공간 문제 식별의 정확도를 향상하였다. 또한 이동통로분석과 작업공간 문제 해결 프로세스를 포함함으로써 작업공간계획을 전체적인 관점에서 완성하였다.

제안된 작업공간 계획 프로세스의 적용 가능성 및 타당성을 검토하기 위하여 연구 시설물 1 개 층 마감공사를 대상으로 하여 사례 분석을 실시하였다. 사례 분석의 결과, 제안된 프로세스는 기존의 방법보다 개선된 작업공간 사용 상태 표현 및 작업공간 문제 식별을 달성하였으며, 작업공간 문제를 반영한 공정 계획 수립에 도움을 주었다.

본 연구의 결과를 바탕으로, 프로젝트 관리자는 본 공사 수행 이전에 공사에 필요한 작업공간을 미리 계획함으로써 서로 다른 액티비티 작업공간 사이의 간섭을 예방하고 이로 인하여 발생할 수 있는 건설프로젝트에서의 불필요한 손실을 예방할 수 있을 것으로 기대된다.

주요어: 작업공간, 작업공간 계획, 4D Building Information Model (BIM)

학 번: 2012-20566

Master of Science in Engineering

4D BIM-Based Workspace Planning Process for Building Construction

by

Byungjoo Choi

Department of Architecture & Architectural Engineering

The Graduate School

Seoul National University

February 2014

4D BIM-Based Workspace Planning Process for Building Construction

by

Byungjoo Choi

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Seoul National University

2014

Abstract

4D BIM-Based Workspace Planning Process for Building Construction

Byungjoo Choi

Department of Architecture and Architectural Engineering

The Graduate School

Seoul National University

Each participant in a building construction project requires their own workspace to execute their activities. In this environment, inappropriate workspace planning in a construction site causes workspace interferences, which results in a loss of productivity, safety hazards, and issues of poor quality. Therefore, the workspace should be considered one of the most important resources and constraints to manage at a construction site. However, the current construction planning techniques—such as Gantt Chart, Network Diagram, and Critical Path Method (CPM)—have proven to be insufficient for workspace planning because they do not account for the spatial feature of each activity. In order to establish a formalized workspace planning process, therefore, this paper categorizes workspace by its function and relocatability, and suggests a workspace planning process that contains five phases, including 4D Building Information Model (BIM) Generation, Workspace Requirement Identification, Workspace Occupation Representation, Workspace Interference Identification, and Workspace Interference Resolution. The proposed planning process in this paper can improve the accuracy of workspace status representation and workspace interference identification by introducing the workspace occupation concept and the integrated workspace planning process that considers characteristics of activity, workspace, and construction plan. In addition, this paper aims to ameliorate the workspace planning process through path analysis and a formalized workspace interference resolution process. In order to scrutinize the applicability of the proposed approach, a case project was tested. The result shows the applicability and effectiveness of the proposed method on improving the workspace planning process. Based on the result of this study, a project manager will be able to prevent possible workspace interferences and their negative effects on project performance by devising a pertinent workspace plan during the preconstruction phase.

Keywords: Workspace, 4D Building Information Model (BIM), Space Scheduling, Project Management

Student Number: 2012-20566

Contents

List of Tables

List of Figures

Chapter 1 Introduction

This chapter deals with the importance of the workspace and current practice of the workspace planning process in a construction project. To solve the problems, research objectives are established. Then, research process to attain the objectives is addressed.

1.1 Research Background and Objectives

One of the distinctive features in a building construction project is limited site space (Bansal 2011; Chua et al. 2010; Said and El-Rayes 2013). Regarding this constraint, each participant requires specific workspace for their resources—such as laborers, equipment, and materials—in order to execute their activities (Hammad et al. 2007; Riley and Sanvido 1997; Sadeghpour et al. 2006). Inappropriate workspace planning leads to workspace interferences, resulting in a loss of productivity, safety hazards, and issues of poor quality (Kaming et al. 1998, Oglesby et al. 1989; Zhang et al. 2007). For example, Riley and Sanvido (1997) detected 71 workspace conflicts between four participations during a two-month study period. Also empirical studies of factors affecting site productivity indicate that workspace interference cause decreasing of the productivity by 30% in a construction project (Kaming et al. 1998). As a result, a project manager should consider the workspace as one of the consequential resources and constraints to be managed at a construction site, alongside time, cost, laborer equipment, and material (Akinci et al. 2002a; Chavada et al 2012; Dawood and Mallasi 2006;

Tommelein et al. 1993).

Workspace for activity execution is differentiated from other resources. First the location and size of a workspace occupied by a specific activity at certain time is influenced by nature of the activity and its construction plan (Riley and Sanvido 1995). Second, workspace utilization by each activity shows dynamic changes in three dimensions in accordance with time flow in a construction project (Akinci et al. 2002b; Tommelein et al. 1993; Winch and North 2006). Therefore, an integrated approach embracing the dynamic and complex features of a workspace is required for a desirable workspace plan.

However, current construction planning techniques—such as Gantt Chart, Network Diagram, and Critical Path Method (CPM)—have limitations in that they cannot account for the spatial feature of each activity, and consider only construction schedules (Chau et al. 2004; Mallasi 2006; Wang et al. 2004). Due to the lack of a formalized process for workspace planning, current workspace planning at the construction site relies on planners' intuition and empirical knowledge (Akinci et al. 2002c; Sadeghpour et al. 2006). In this circumstance, even for experienced project managers, it is challenging to completely comprehend the complex and dynamic features of a workspace, thus mangers have experienced difficulties in proactively preventing workspace interferences and their negative effects (Guo 2002; Winch and North 2006). Moreover, recently increased requirements for a short duration schedule at large and complex projects in an urban area make it more difficult to design a fine workspace plan (Hammad et al. 2007; Said et al. 2013; Wang et al. 2004).

In recent years, there have been numerous efforts attempting to manage the dynamic and complicated feature of the building construction process. Among these efforts, a recent achievement in 4D Building Information Model (BIM), which links objects in 3D BIM and their corresponding activities in a project schedule, has demonstrated advances in efficiently handling dynamic and complicated changes during the construction process. Based on these achievements, this study proposes a 4D BIM-based workspace planning process, which integrates the characteristics of workspace, activity and construction plan, in order to proactively handle incidences of workspace interferences and to eliminate waste elements in a construction project.

1.2 Research Scope and Process

There are two branches in a space planning related research area, which are the space scheduling problem and the site layout problem. The space scheduling problem focuses on a workspace for the activity execution in a dynamic perspective and the site layout problems deals with a location of the temporary facilities in a static perspective (Winch and North 2006). Among these two branches, the scope of this study limited in a scheduling problem which treats planning the workspace for activity execution.

The suggested framework in this study is developed in the following process. First, this paper discusses critical reviews of previous related studies that investigate workspace planning process and workspace classification. Then, workspace is classified by its function and relocatability. Based on critical reviews on previous studies and workspace classification, this study proposes a workspace planning process using 4D BIM which contains 4D BIM Generation, Workspace Requirement Identification, Workspace Occupation Representation, Workspace Interference Identification, and Workspace Interference Resolution. Then, a case study applied with the suggested workspace planning process is presented. Finally, conclusions and recommendations for future research are offered. The entire research process of this paper is summarized in Figure 1-1.

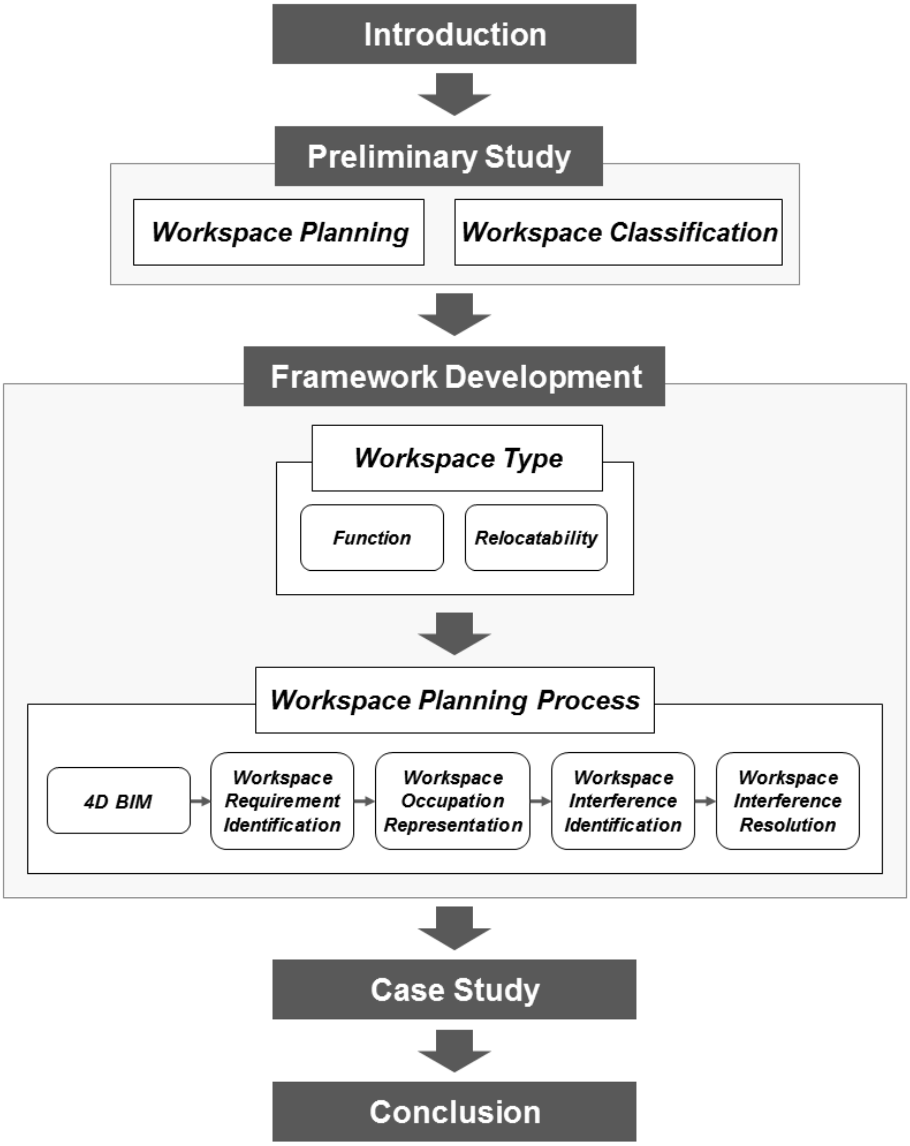


Figure 1-1. Research Process

Chapter 2 Preliminary Study

Prior to developing a framework for the workspace planning process in a construction project, this chapter reviews previous studies which deal with workspace planning process and workspace classification. This chapter also addresses this study's strategies to overcome previous studies' limitations.

2.1 Literature Review on Workspace Planning Process

The purpose of the workspace planning in a building construction project is to prevent workspace interferences and unnecessary wastes by predicting the workspace utilization status of each participant. Therefore, workspace planning includes a representation of workspace occupation status, workspace interference identification, and resolution. For an effective workspace planning process, diverse approaches have been suggested with regard to representing the state of workspace utilization and managing workspace interferences. Table 2-1 summarizes the major features of previous studies that investigate the workspace planning process as well as the improvements made by this study.

Thabet and Beliveau (1994) proposed a scheduling method that integrates space demand and space availability. To evaluate space availability, they first manually identified physical available space within the AutoCAD environment. They broke the available workspace into a number of work blocks and allocated activities to each work block. To describe productivity decrease due to the limited available workspace, they introduced a space capacity factor that is computed by the ratio of space demand to available workspace for the activity. In a follow-up study, Thabet and Beliveau (1997) developed a Space-Constrained and Resource-Constrained Scheduling system. However, their approach could not identify workspace conflict exactly because they were focus on congestion in the work block rather than interference between workspace for activities.

Guo (2002) attempted to identify workspace conflict in a construction project by manually overlapping workspace demands for each activity on a project's CAD drawings. He also introduced the concept of a path demand analysis which examines whether the plan provides sufficient path area for laborer and material movement. Their approach presents some important limitations in terms of manual execution of workspace conflict identification and path analysis and ambiguous method for representation of workspace demand for each activity.

Akinci et al. (2002 a, b) developed a 4D WorkPlanner Space Generator that automatically generates the microlevel workspace requirement via incorporating the construction method for installment each product breakdown structure (PBS) and its' spatial requirement information in 4D CAD model. Then in Akinci et al. (2002 c) suggested a method for categorizing and prioritizing identified workspace conflicts. Their approach considered conflicting workspace's type and the properties which are defined by the ratio of conflicting volume to total volume of workspace requirement. In spite of substantial advancement than previous studies, they limited their analysis scope to microlevel space that excluded macrolevel workspace such as material storage area and path area for crew and material movement. Also their approach with direct relationship between workspace and building components rather than activity separated from general planning practice at construction site.

Dawood and Mallasi (2006) developed a PECASO 4D simulator introducing three work rate distribution types and twelve work execution patterns in order to identify workspace conflicts in a construction site. They also proposed the multi-criteria quantification function to assess criticality of workspace competition among the activities.

Chavada et al. (2012) presented methodology that integrates Critical Path Method and Building Information Modeling data for workspace management. They proposed workspace management process that includes workspace generation process, conflict detection process, congestion detection process and resolution process in 4D/5D environment. Moreover their approach to identify workspace conflicts has important limitation because they only identify workspace conflicts among the activities which have schedule conflicts.

Despite the number of previous studies that have considerably ameliorated the workspace planning process, these studies have several important limitations regarding workspace utilization status representation, workspace interference identification, and resolution. A majority of previous studies assume that resources for activity execution occupy their required workspace for the entire duration of the activity. However, this assumption fails to achieve an accurate representation of the workspace occupation since the activity is executed by utilizing a part of the entire workspace requirements repetitively and successively in the actual construction project. Moreover, the location and size of the workspace represented in the previous studies cannot be updated with modifications to the construction plan, such as an activity execution plan or a material management plan. Finally, relatively little attention has been paid to the formalized process for workspace interference resolution and path analysis in the previous studies. This study has attempted to further improve the previous studies' findings by: (1) differentiating the workspace requirement and workspace occupation for each activity in order to reflect the way of workspace utilization in an actual construction project; (2) integrating characteristics of the workspace, activity, and construction plan for representing workspace occupation; (3) including path analysis process which is overlooked in most of previous studies; and (4) presenting a formalized procedure for workspace interference resolution.

Table 2-1. Review on Related Studies and Improvement by this Study

Author (Year)	Workspace Interference Identification	Operating Environment	Activity execution Progress Representation	Integration of Construction Plan and Workspace	Workspace Interference Resolution
Thabet and Belilveau (1994)	Limited (Congestion)	CAD	Workspace occupies allocated areas for entire duration of activity	Not Mentioned	Not Mentioned
Guo (2002)	Yes	CAD		Manually reflect when construction plan changes	Criteria for workspace conflict resolution
Akinci et al. (2002)	Yes	4D CAD		Determination of workspace by construction methods	Prioritization of workspace conflict
Dawood and Mallasi (2006)	Yes	4D CAD	12 types of execution pattern and 3 types of work rate	Manually reflect when construction plan changes	Mentioned conflict resolution process in the case study
Chavada et al. (2012)	Yes	4D BIM	Required workspace occupies whole workspace during activity duration		Enumeration of possible solutions for workspace conflict
Choi et al. (2013)	Yes	4D BIM	Differentiated workspace requirement and workspace occupation	Integration of activity execution plan and material management plan	Formalized procedure for workspace conflict resolution

2.2 Literature Review on Workspace Classification

Before developing a workspace planning process, it is important to explain different types of workspace in related studies. Workspace classification helps to comprehend characteristics of workspace and to extend the comprehension to the workspace planning process.

Riley and Sanvido (1995) proposed a Construction Space Model that defines twelve construction workspace types and their behavior patterns in multi-story building using site visits, interviews, and document reviews for ten case project studies. Guo (2002) categorized workspace into four types of workspaces based on the user of each workspace—such as labor, equipment, material, and temporary facility—in order to represent status of workspace utilization. Mallasi (2006) introduced the concept of product and process for workspace classification and defined eight workspace types. Wu and Chiu (2010) regarded construction workspace as a combination of building component space, site layout space, human workspace, equipment space, and material space. Chavada et al. (2012) tried to classify workspace by adopting a terminology which distinguishes between value added and non-value added activities. Table 2 summarizes the previous studies' workspace classifications.

In spite of numerous efforts of the previous studies classifying workspace, these approaches have some limitations in the workspace planning process. Most of previous studies fail to integrate the characteristics of each workspace type and workspace planning process, since they only regard workspace classification as means of the workspace conflict categorization.

Furthermore, previous studies are not able to reflect the different nature of workspaces types since all types of workspaces are generated by the identical method regardless of the characteristics of each workspace type.

Table 2-2. Reviews on Previous Workspace Classification

Author (Year)	**Riely and Sandivo (1995)**	**Guo (2002)**	**Mallasi (2006)**	**Wu and Chiu (2010)**	**Chavada et al. (2012)**
Classifi-cation	Layout Area Unloading Area Material Path Staging Area Personnel Path Storage Area Prefabrication Area Work Area Tool/Equipment Area Debris Area Hazard Area Protected Area	Working Space Storage Space Waste Space Set-up Space Path Space	Product Space Workspace Equipment Space Equipment Path Storage Space Path Space Protected Space Support Space	Building Component Workspace Site layout Workspace Labor Workspace Equipment Workspace Material Workspace	Main Workspace Support Workspace Object Workspace Safety Workspace

2.3 Summary

The previous chapter reviewed limitations of the previous studies which investigate workspace planning process and workspace classification. In spite of considerable improvements by these studies, they are not able to represent the actual workspace utilization status in a construction project due to the insufficient assumptions. Moreover, they fail to integrate information related in workspace planning process.

In order to be an effective and applicable process, a workspace planning process should consider following requirements;

(1) Effective method for representing actual status of the workspace utilization
(2) Workspace classification for integrating with the workspace planning process
(3) Integration of characteristics of the workspace, activity, and construction plan in workspace planning process
(4) Formalized workspace interference resolution process

Chapter 3 Workspace Classification

Before suggesting a workspace planning process, characteristics of a workspace should be comprehended. In order to integrate the characteristics of a workspace with the workspace planning process, this study classified workspace by its function and relocatability. Classification by its function helps represent the whole workspace requirement without exception, and classification by relocatability is useful in identifying the cause of workspace interferences and providing a pertinent resolution strategy for each issue.

3.1 Workspace Classification by Function

The function of workspace explains why a specific workspace is required for the activity execution. Among several efforts to categorize workspace types, Riley and Sanvido (1995) classified workspaces into thirteen workspace types by observing the construction process. Based on Riley and Sanvido's (1995) classification, this study defines six functional workspace types by merging the workspace types that perform the same functions, as described in Figure 3-1.

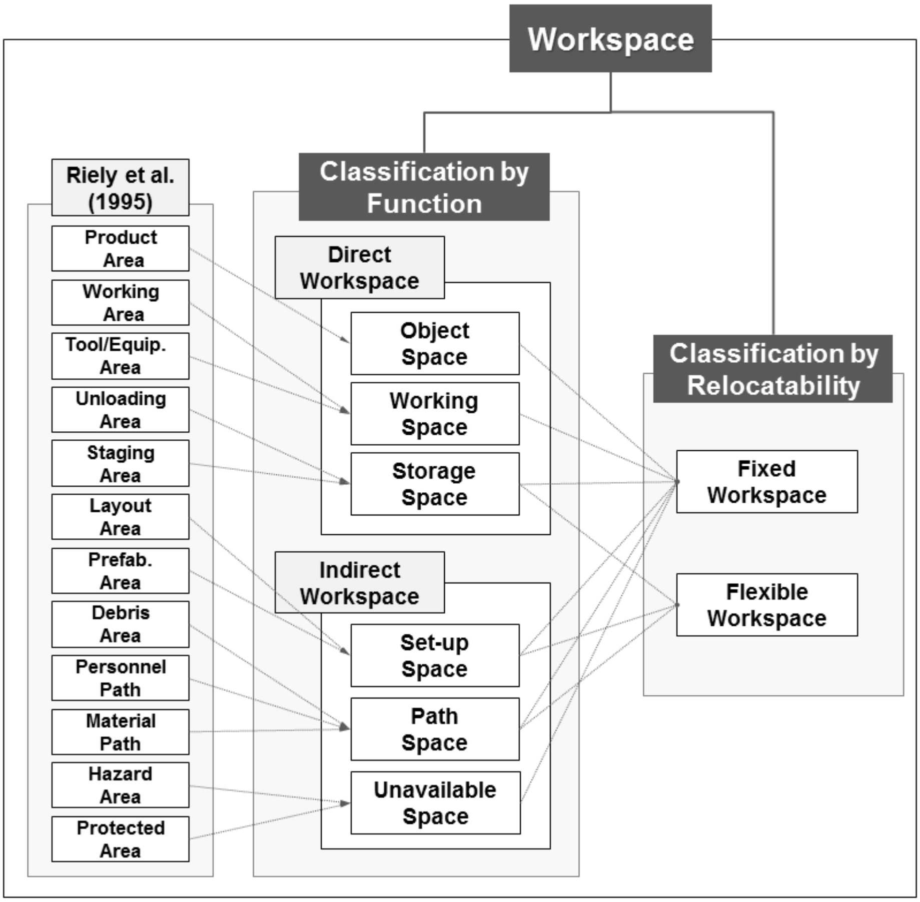


Figure 3-1. Workspace Classification Structure

Workspace in a construction project could be categorized as *direct workspace* or *indirect workspace* depending on its function. *Direct workspace* is associated with the execution of specific activity in a direct way, and the location and size of the workspace is determined by the geometric features of the related object or construction plan for the activity. *Direct workspace* includes: (1) *Object space* - the area occupied by a building component itself such as a wall, doors, or windows; (2) *Working space* - the area required for crews or equipment to execute a specific activity that contributes physical changes in a construction project; and (3) *Storage space* - the area for storing materials for each activity execution in a construction project.

Indirect workspace has either an indirect relationship with the execution of a specific activity or is associated with the execution of multiple activities. The location and size of an *indirect workspace* is determined by temporary facility layout plans or predefined spatial relations with the *direct workspace*. *Indirect workspace* includes: (4) *Set-up space* - the area for operating the overall construction project, such as a tower crane and lift car; (5) *Path space* - the area required for the movement of resources such as a laborer or equipment material; and (6) *Unavailable space* - unusable area due to the protection of established building components or safety issues caused by certain activity executions. Table 3-1 summarizes the definition and important attributes of each workspace type.

Table 3-1. Functional Workspace Classification

Workspace Type		Definition	Location and Size of Workspace	Generation and Expiration of Workspace
Direct Work-space	Object Space	Areas occupied by building components such as walls, doors, and windows.	Geometric features of building components determine the location and size of the space.	Object space is generated at starting point of linked activity and preserved until project completion.
	Working Space	Areas required for laborers, equipment, etc., required to execute each activity on the site.	Spatial relation with corresponding object defined by construction method determines the location and size of the space.	Working space is generated at starting point of the activity and expired at ending point of the activity.
	Storage Space	Areas required for materials storage before consuming them for executing each activity.	Geometric feature of material and quantity of corresponding activity determine size of the space. Material management plan determines location of the space.	Storage space is generated at starting point of the activity and expired at ending point of the activity.
Indirect Work-space	Set-up Space	Areas required to operate overall construction project (e.g., Tower crane, Scaffolding, Lift car, etc.).	Temporary facility layout determines the location and size of the space.	Set-up space is generated at starting point of independent activity or related activity and expired end point of the activity.
	Path Space	Areas required for movement of laborers, equipment, and materials in a construction project.	Construction method for the activity and geometric feature of materials determines the minimum path width and height.	Defined minimum path width and height is required during corresponding activity duration.
	Unavailable Space	Areas that are prohibited to use due to safety issue related to the execution of a specific activity and the protection of certain building components.	Hazardous condition defined by construction method and object protection condition determines the location and size of the space.	Unavailable space is preserved during corresponding activity duration or object protection duration determined by the object feature.

In this study, in order to represent the whole workspace without exception, requirements of the *direct workspace* are identified by integrating information about objects, construction methods, and materials. Then, the status of *direct workspace* occupation is represented by reflecting the activity execution plan and material management plan. Finally, the status of *indirect workspace* occupation is represented by referring to the occupied *direct workspace* and other construction plans. Through these processes, project managers are able to accurately predict the status of workspace utilization in a construction project and to identify all possible workspace interferences in advance.

3.2 Workspace Classification by Relocatability

Workspace classification by its attributes contributes to the effective enhancement of the comprehension and utilization of the workspace characteristics information. Among several workspace attributes, relocatability is one of the most paramount properties, since it assists in identifying the causes of workspace interferences and detects apposite resolution strategies for each issue. Therefore, this study classifies workspace into *fixed workspace* and *flexible workspace* by relocatability, as indicated in Figure 3-1.

Fixed workspace is a space that is not able to arbitrarily change its location. For instance, the location of *working space* is determined by a spatial relation with an object defined by a selected construction method. A project manager is not able to change the location of *working space* unless the construction method selection changes; thus, *working space* is categorized as *fixed workspace.* On the other hand, the location of *flexible workspace* varies by the modification of the construction plan. In general, a project manager plans how to distribute materials for a specific activity before the activity execution. The material distribution plan could be modified by a project manager's managerial decision, and thus the location of *storage space* for the materials would also change according to the revised plan. In this case, *storage space* is categorized as *flexible workspace*. However, not all *storage spaces* are categorized as *flexible workspace* because the relocatability of *storage space* is determined by the characteristics of the materials. For example, the *storage space* for plumbing and duct materials required by Mechanical Electrical Plumbing (MEP) work is *flexible workspace*, since those materials are stored at a specific assigned block at a site by the material distribution plan. On the other hand, due to the difficulty of movement, *storage space* for brick materials required for masonry work should be located adjacent to the *working space* for the activity. Therefore, *storage space* for a brick material is categorized as *flexible workspace.*

In *direct workspace*, *object space and working space* are classified as *fixed workspace.* In the case of *storage space*, workspace type based on relocatability is determined by the characteristics of the materials, as described above. *Unavailable space* is a type of *fixed workspace*, since *working space* and *object space*, which determine the location of the *unavailable space*, belong to *fixed workspace*. Finally workspace types by relocatability for *set-up space* and *path space* are determined by the flexibility of the construction plan that defines the location of the workspace.

3.3 Summary

Prior to developing a workspace planning process, a workspace classification structure is suggested in this chapter. Workspace is categorized as *direct workspace,* which contains *object space, working space,* and *storage space,* and *indirect workspace*, which includes *set-up space*, *path space,* and *unavailable space*, by its function. In addition, this study classifies workspace as *fixed workspace* and *flexible workspace* by whether or not the location of workspace can be changed arbitrarily.

Based on the functional classification of the workspace, the status of the workspace utilization in a construction project could be identified and represented without exception. Moreover, workspace classification by relocatability is used for identifying the cause of workspace interferences and finding pertinent resolution strategies for the identified workspace interferences in a suggested workspace planning process.

Chapter 4. Workspace Planning Process

Based on the previous workspace classification, this section discusses a workspace planning process that deals with the dynamic and complicated features of a workspace in a construction project. In general, a schedule plan in a construction project is established as follow: (1) creating baseline schedule using CPM algorithm; (2) identifying the restrictions and constraints on the baseline schedule and; (3) resolving the problems and modifying baseline schedule (Kenley and Seppanen 2010). This study follows this general planning process.

The workspace planning process proposed in this study consists of five phases: (1) 4D BIM, which is able to simulate changes in a construction project using linkages between objects in 3D BIM and corresponding activities in the project schedule plan, is generated; (2) the *working space* and *storage space* requirement for each activity is identified in light of information about construction methods and materials for the activity execution; (3) the status of workspace occupation for all types of workspace is represented by reflecting the construction plan, such as the activity execution plan or material management plan; (4) workspace interferences are identified thorough the spatial clash detection algorithm and wall follower algorithm; and (5) a pertinent solution for the identified workspace interference is presented by considering characteristics of the activity, workspace, and construction plan.

Figure 4-1 presents a schematic diagram for overall workspace planning process.

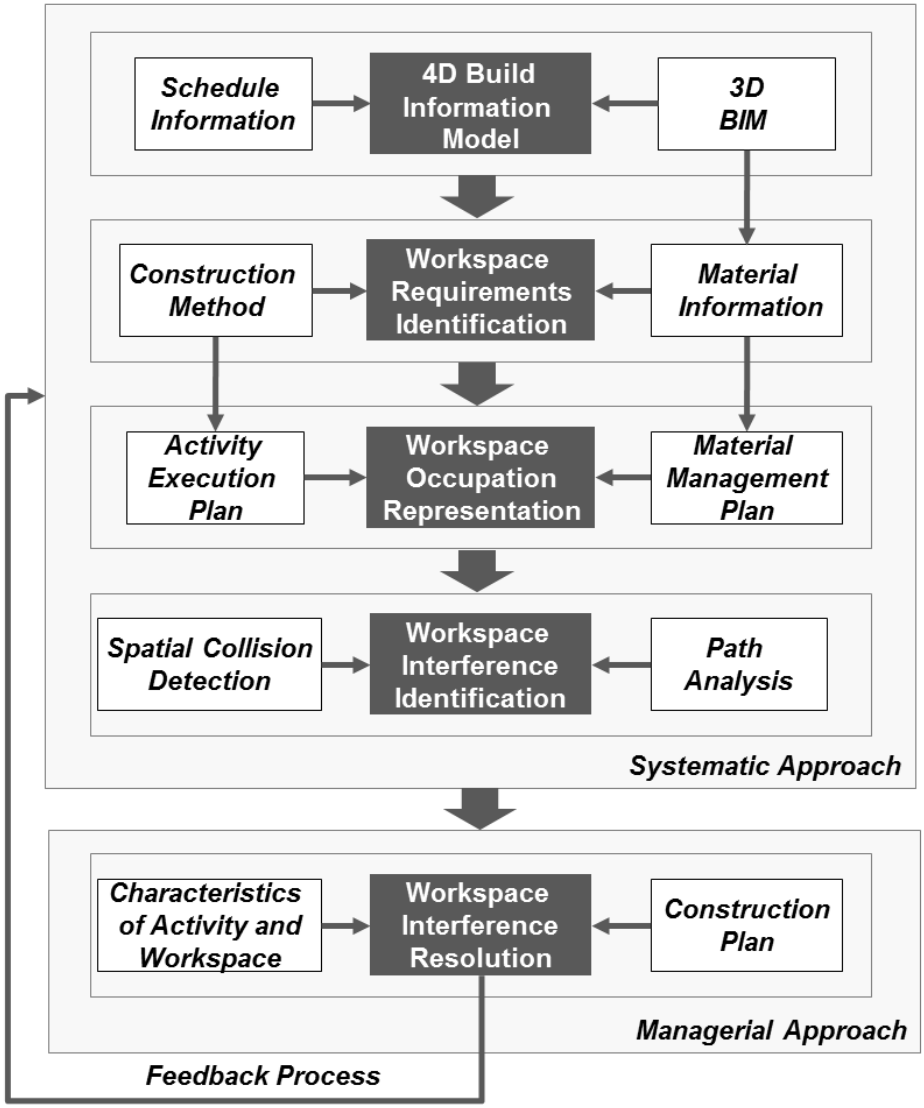


Figure 4-1 Workspace Planning Process

4.1 4D BIM Generation

The first task for workspace planning is to generate 4D BIM for a project. BIM is a digital representation of the physical and functional characteristics of a facility and the related project life cycle information; it uses the object-based parametric modeling method (Eastman et al. 2007; NBIS 2013). Each object in BIM is defined by parameters and relationships between parameters that determine geometric and additional properties of the object. 4D BIM is able to integrate information of building components and project schedule by linking between each object in 3D BIM and the corresponding activity in a schedule plan. 4D BIM can represent dynamic geometric changes in a building construction project, and is useful in identifying workspace changes in accordance with the construction process. In order to represent the status of workspace occupation and to identify workspace-related problems, this study utilized information about activity schedule, object quantity, and the geometric properties of the project that were contained in 4D BIM.

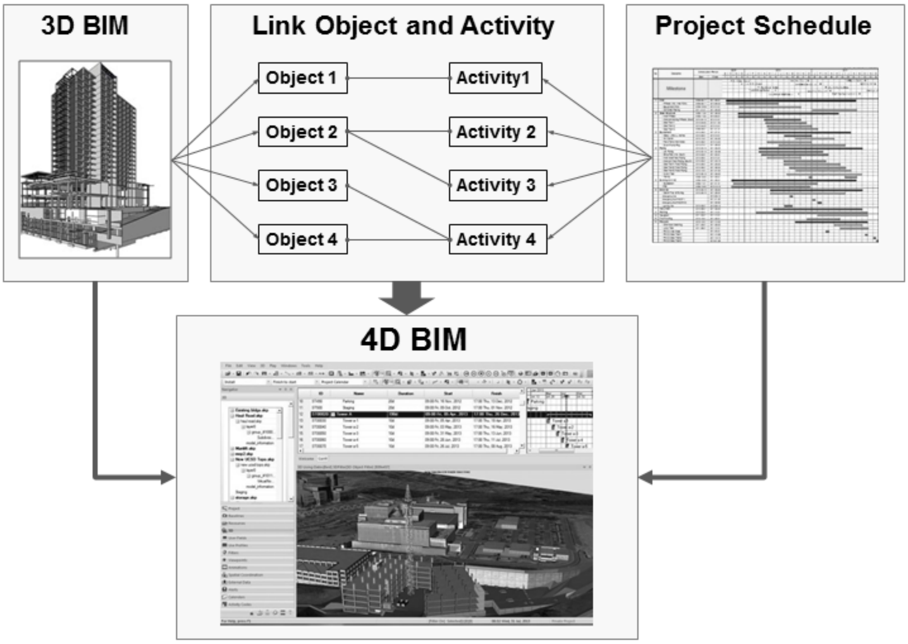


Figure 4-2. 4D BIM Generation

4.2 Workspace Requirement Identification

The *workspace requirement identification* phase is a process to identify the entire *working space* and *storage space* requirement for the execution of a specific activity. The detailed process for this phase is shown in Figure 4-3.

The construction method and material information databases are necessary for *workspace requirement identification*. The construction method database contains information about construction method selection criteria for each activity type and the spatial relationship between the object and *working space* that each construction method requires. The material information

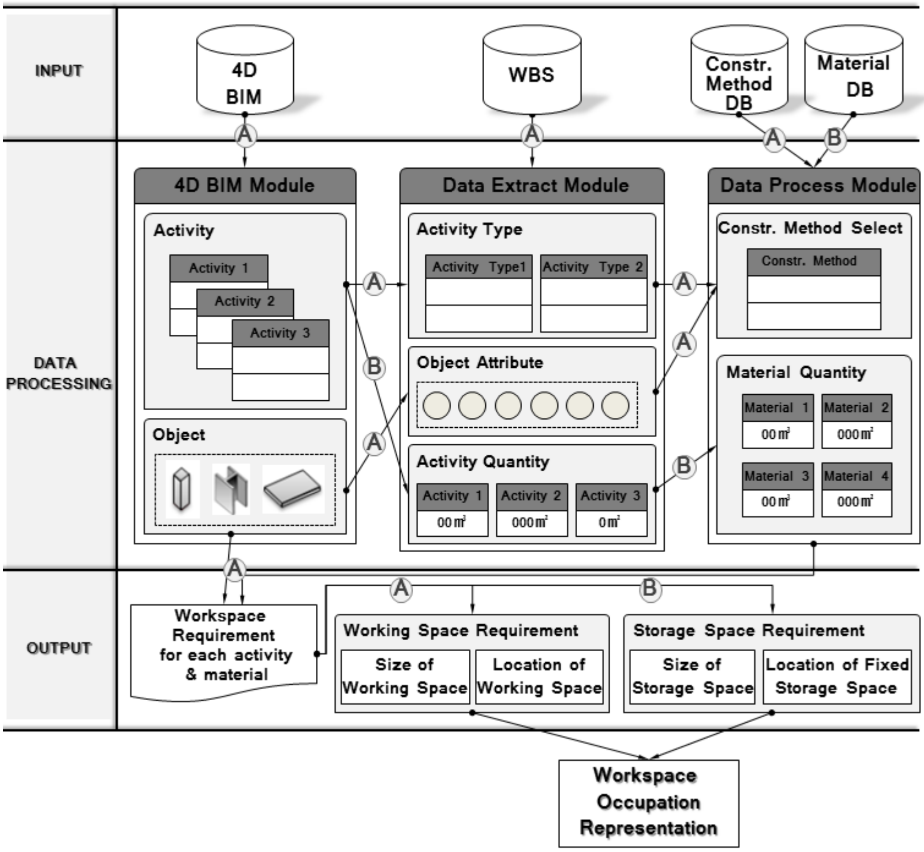


Figure 4-3. Workspace Requirement Identification

database includes information about the physical features of each material, as well as the quantitative relationship between activities and materials.

In order to identify the *working space* requirement, each activity extracted from 4D BIM is classified as an activity type through the work breakdown structure (WBS). A construction method for each activity is selected from possible construction methods for the activity type by considering the corresponding object's properties in 4D BIM. Afterward, the *working space* requirement for the activity execution is identified using the spatial relationship between *working space* and an object predefined in the construction method database (A in Figure 4). Akinci et al. (2002a) suggested a method to generate the workspace for each object using the spatial relationship between an object and the workspace, presented in the form of a transformation matrix. Based on this method, the whole requirement of *working space* for each activity could be identified.

To determine the *storage space* requirement, the quantities of each material needed to perform an activity are calculated by the quantity of the activity in 4D BIM and the quantitative relationship between the activity and the material in the material information database. The total size of the *storage space* for the material is established using geometric information of the materials found in the material information database. Then, the location of the fixed *storage space,* which should be adjacent to the *working space* owing to the nature of the material, is determined using the predefined spatial relationship between the *working space* and *storage space* (B in Figure 4-3).

Figure 4-4 depicts the detailed process of *storage space* requirement identification for a brick material example.

Most of the approaches for workspace planning developed in the previous studies identify workspace conflicts based on workspace requirements, which are assumed to occupy the whole required space for the entire activity duration (Akinci et al. 2002b; Chavada et al. 2012; Guo 2002; Winch and North 2006). However, in a real construction process, the activity is executed by successive and repetitive occupation as part of the workspace requirements (Riley and Sanvido 1995). Therefore, the pertinent methods for the representation of workspace occupation status are necessary to predict the actual workspace interferences.

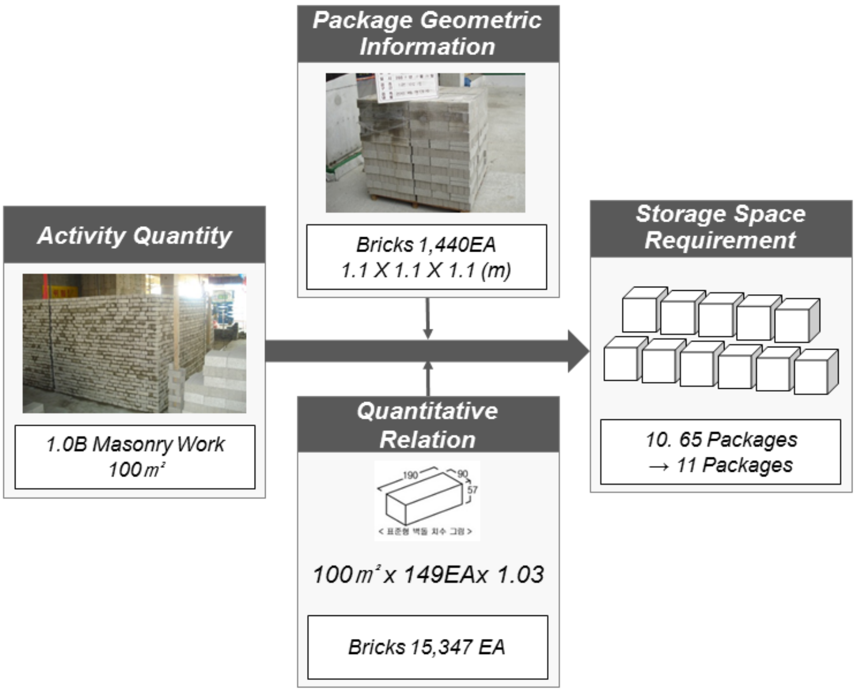


Figure 4-4. Example of Brick Material Storage Space Identification

4.3 Workspace Occupation Representation

Workspace occupation representation is a phase that describes the state of the workspace utilization for all types of workspace by reflecting the construction plan, such as activity execution plan and material management plan. The detailed process of this stage is delineated in Figure 4-5.

The activity execution plan explains the performance of an activity, and contains the number of work units for each activity and activity execution pattern of each work unit. This study adopts Riley and Sanvido's (1995) workspace pattern analysis in order to define the activity execution pattern of

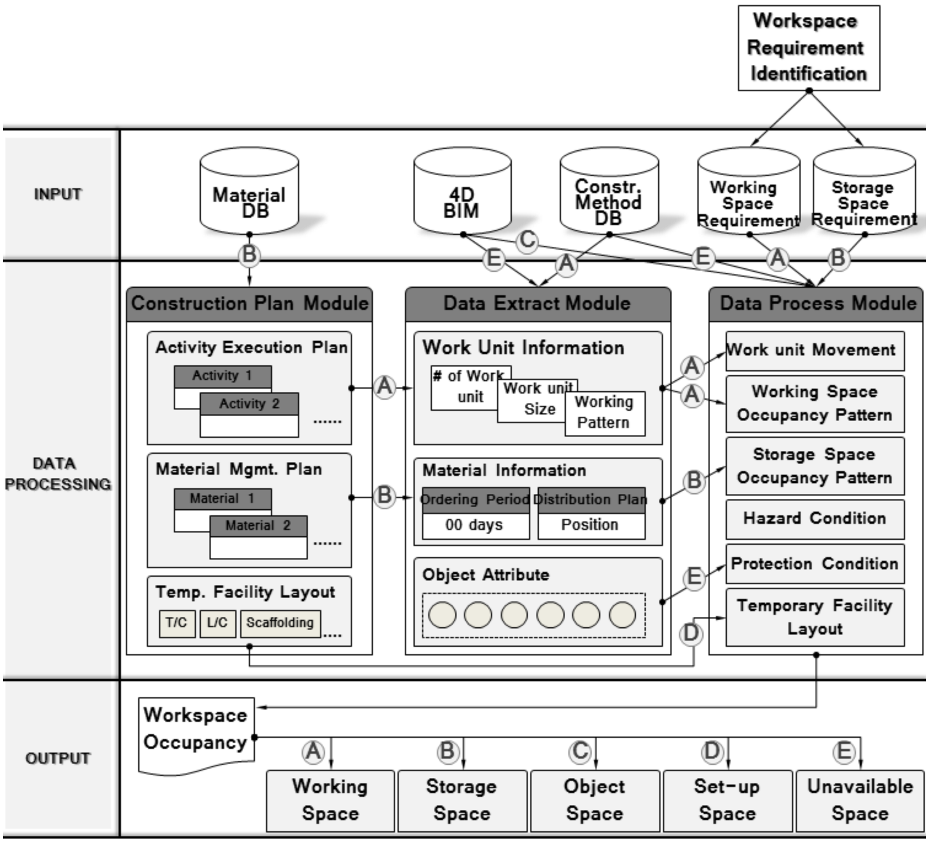


Figure 4-5. Workspace Occupation Representation

each work unit. The material management plan includes a material procurement plan that defines the quantity and period of material ordered and a material distribution plan that determines the layout for the materials imported to the construction site.

In order to represent the *working space* occupation, a *working space* occupation pattern is identified based on the size of each work unit defined in the construction method database, and the number of work units and the activity execution pattern are defined in the activity execution plan. Then, the velocity of each work unit passing along with the identified pattern is established by the activity quantity and duration derived from 4D BIM; the *working space* occupied by work units during a specific time period is represented based on the velocity (A in Figure 4-5).

The location and size of the *storage space* occupied by each material is determined by the material procurement plan and distribution plan. First, the total size of the *storage space* occupation at a specific time is calculated by dividing the size of the *storage space* requirement by the number of ordering times defined in the material procurement plan. Then, the location and size of the *storage space* occupation for imported material are represented by utilizing the material distribution plan. In the case of fixed *storage space*, location is determined using a predefined spatial relationship between *storage space* and *working space* (B in Figure 4-5).

Object space occupation would be perceived by the result of 4D BIM simulation (C in Figure 4-5), and the location and size of the *set-up space* are determined using the project manager's temporary facility layout plan (D in

Figure 4-5). Finally, *unavailable space* is represented using a spatial relation with the *object space,* which is defined by the protection condition in the object property, or using a spatial relationship with the *working space,* which is defined by the hazardous condition in the construction method database (E in Figure 4-5).

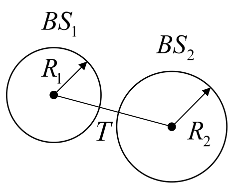
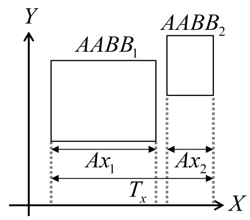
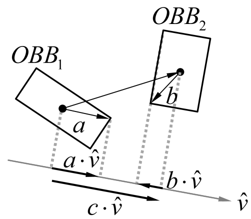
4.4 Workspace Interference Identification

In this study, the workspace interference is defined as a situation when the workspace for conducting an activity is not available. This situation can occur when different activities are required to occupy a specific space during the same time period, or when resources for activity execution cannot be accessed at their workspace due to obstructions created by other workspaces. Therefore, the *workspace interference identification* should include detecting not only workspace conflicts but also blocked paths.

Virtual spatial collisions in a 3D model are detected by the algorithm that generates minimized bounding volumes of the objects and identifies the conflict between each bounding volume. A 3D bounding volume is categorized by its shape into Bounding Spheres (BS), Axis-Aligned Bounding Boxes (AABB), or Oriented Bounding Boxes (OBB), as described in Table 4-1. BS identifies a spatial collision by comparing the sum of two bounding spheres' radii and the distance between the centers of two spheres. AABB detects a spatial collision by comparing the minimum and maximum values of the two bounding boxes that are parallel to their coordinate axes. OBB generates minimized bounding boxes around objects regardless of the objects' axis orientations, and determines a spatial collision between the two bounding boxes by identifying the existence of a separating axis (DeLoura et al. 2000; Moller and Haines 2002). When most objects at a job site are located parallel to a certain axis in a typical form, such as a box shape, AABB is the desirable method for identifying a spatial collision, but OBB is more pertinent to the emerging irregular-shaped building project, which contains numerous atypical objects.

Path analysis is a process that investigates the existence of available *path space* for all of the necessary resources in a construction project. For path analysis, the wall follower algorithm—which is one of the best-known rules for a maze problem—was adopted in this study (Madhavan et al. 2009). The wall follower algorithm finds an available path using the following steps: (1) it creates a straight line from a starting point to a destination point; and (2) when the line encounters an obstacle, the line moves along the surface of the obstacle until it meets the predefined straight line again. As described in Figure 4-6, the algorithm determines that a path does not exist when a moving line spins around at the same place or when the line reaches the boundary of the map (Sedgewick 2001).

Table 4-1. Spatial Collision Detection Algorithm (DeLoura et al. 2000; Moller and Haines 2002)

	Bounding Sphere	**Axis-Aligned Bounding Box**	**Oriented Bounding Box**
Diagram			
Collision Condition	$T < R_1 + R_2$	$T_x < Ax_1 + Ax_2$	$\lvert c \cdot \hat{v} \rvert < \lvert a \cdot \hat{v} + b \cdot \hat{v} \rvert$

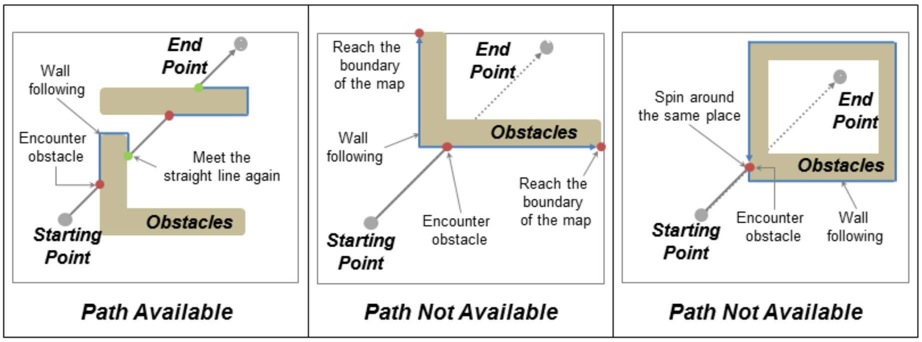


Figure 4-6. Wall Follower Algorithm (Sedgewick 2001)

Since diverse paths can be necessary at a construction site, path analysis should be conducted for every type of path required to execute an activity. Therefore, path analysis should include: (1) a laborer's path from an entrance to the *working space*, (2) a work unit's path from a *working space* to the next *working space*, (3) a material distribution path from an entrance to the *storage space,* and (4) a material transportation path from a *storage space* to the *working space*. The width of a straight line in the wall follower algorithm, which defines the minimum wideness of the necessary *path space*, is determined by the physical feature of the resource for the associated space. The detailed criteria of the minimum size of path space are described in Table 4-2.

Table 4-2. Detailed Criteria for Determining Minimum Size of Path Space

Path	**Reference for the straight line size**
Laborer's path	Size of Laborer
Work unit's path	Size of Laborer and Work unit in construction method DB
Material distribution path	Size of Laborer and material package in material information DB
Material transportation path	Size of Laborer and material unit in material information DB

The project manager can obtain the information of characteristics of activity and workspace at the location where workspace interferences possibly happen through a systematic approach from the *4D BIM generation* phase to the *workspace interference identification* phase. In addition to the systematic approach that helps to get objective information about the workspace interference, a managerial approach for the whole project perspective that considers a relationship with other activities is also required.

4.5 Workspace Interference Resolution

In the *workspace interference resolution* phase, pertinent strategies are devised for the identified workspace interferences by considering characteristics of an activity, workspace, and construction plans. In other words, the project manager should consider the relocatability of the workspace, the criticality of the activity, the activity execution plan, and the material management plan in order to resolve the workspace interferences as described in Figure 4-7.

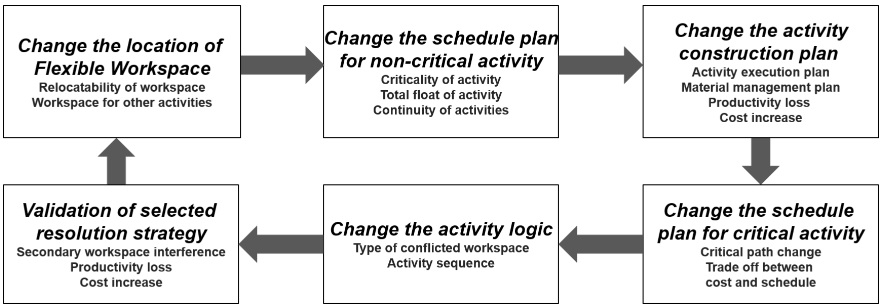


Figure 4-7. Workspace Interference Resolution Process

(1) Change the location of *flexible workspace*

If there is a *flexible workspace* among conflicted workspaces, the workspace interference could be resolved by changing the workspace location. When determining the location of the changed workspace, the project manager should consider not only the location of the conflicted workspace but also the location of other workspaces that are occupied by other activities at the same time.

(2) Change the schedule plan for non-critical activity

In the case where every conflicted workspace is a *fixed workspace*, the workspace interferences could be resolved by deferring a start date or changing the duration of the non-critical activity among the problematic activities. In order not to affect the total duration of the project, the schedule change for non-critical activity should be designed within the total float of the activity. The continuity of the activity should also be considered.

(3) Change the activity construction plan

The activity execution plan and the material management plan are factors that determine the final status of workspace utilization in the *workspace occupation representation* phase. Therefore, the project manager can change the location of the *working space* and the related *indirect workspace* through the modification of the activity execution pattern. Moreover, workspace interference could be solved by revising the material procurement plan and the distribution plan. When planning to change the construction plan, the project manager should consider the possible productivity loss and cost increase caused by the change.

(4) Change the schedule plan for critical activity

The workspace interference that cannot be resolved by methods 1–3 is resolved by changing a schedule plan for a critical activity. Although the schedule plan change for the critical activity can cause a project delay, it can prevent further damages caused by negative project management issues—such as unnecessary rework, safety hazard, and issues of poor quality—due to the interference of the workspace. When changing the schedule plan for critical activities, the project manager should examine whether or not the critical path is changed due to the schedule plan change.

(5) Change the activity logic

Some workspace interferences between *object space* and *fixed workspace* may not be resolved by methods 1–4. This type of workspace interference occurs when the project manager fails to consider the workspace for an activity when he/she determines the activity sequence. Therefore, this type of workspace interference could be prevented by changing an activity performing logic with the consideration of the workspace.

(6) Validation of selected resolution strategy

Finally, the validation of the selected workspace interference resolution strategy from the process described above is examined by again inputting the strategy into the workspace planning process. In this process, the project manager can confirm the validity of the selected strategy through the identification of secondary workspace interferences by the selected strategy

4.6 Summary

Based on the review on previous studies in chapter 2, and workspace classification in chapter 3, formalized workspace planning process is proposed in this chapter. The workspace planning process suggested in this study consists of five following phases.

(1) *4D BIM generation*, which is able to simulate changes in a construction project by linking between objects in 3D BIM and corresponding activities in the project schedule plan;

(2) *Workspace requirement identification* that identifies entire *working space* and *storage space* requirement for the execution of a specific activity by considering construction methods and materials for the activity execution;

(3) *Workspace occupation representation* which describes the state of the workspace utilization for all types of workspace by reflecting the construction plan, such as activity execution plan and material management plan;

(4) *Workspace interference identification* that detects potential workspace interferences in a construction project by the spatial clash detection algorithm and wall follower algorithm; and

(5) *Workspace interference resolution* which suggests pertinent solutions for identified workspace interferences by integrating consideration for characteristics of the activity and workspace and construction plan.

Chapter 5 Case Study

This chapter scrutinizes the applicability of the suggested workspace planning process in real world setting with an application example. The case project was a one floor finish work of the 1,850 m^2 floor research building construction project in Seoul National University.

5.1 Workspace Planning Process for Case Project

The case project was to take 90 days and be composed of 23 activities, including vertical piping and floor finishing work. Figure 5-1 displays *4D BIM generation* phase combined 3D BIM and an initial construction schedule.

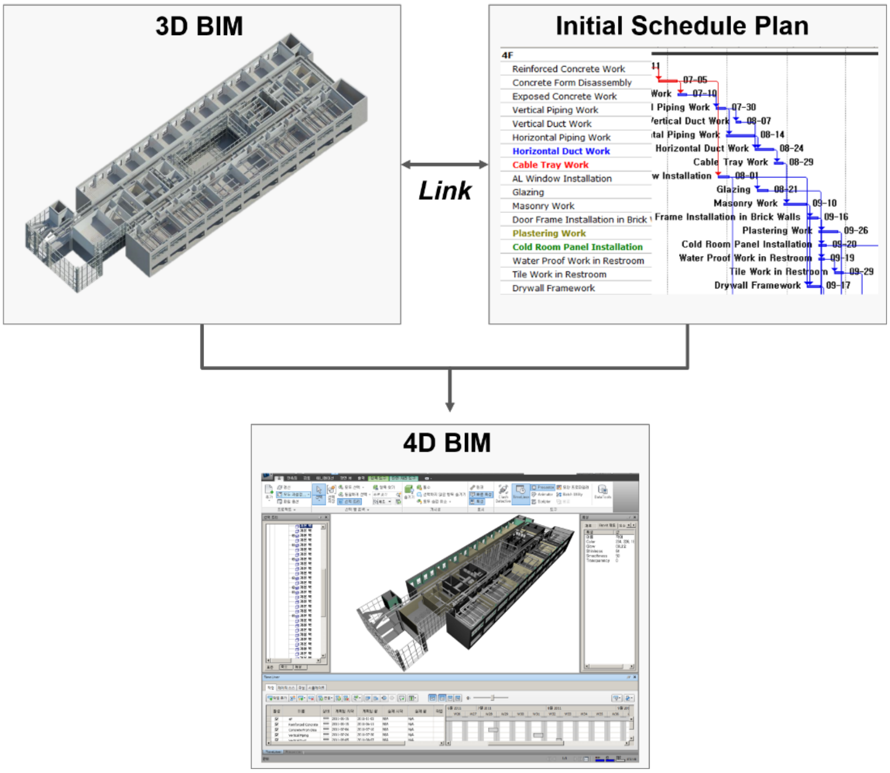


Figure 5-1. 4D BIM for the Case Project

A required workspace for each activity was identified based on the attributes of the object in 4D BIM, construction methods, and materials for activity execution. The AABB method was used to identify the workspace requirement as most objects in the case project were located parallel to the BIM's local axes in a box shape. Figure 8 explains an example of the workspace identification for a drywall framework activity. The rolling scaffolding was determined as a construction method for framing drywall because the height of the wall objects associated with the activity was consistently more than 3.0m but less than 5.0m; thus, the entire workspace requirement of the drywall framework activity was identified by replicating the unit workspace for a rolling scaffolding work to all of the associated objects, as described in Figure 5-2.

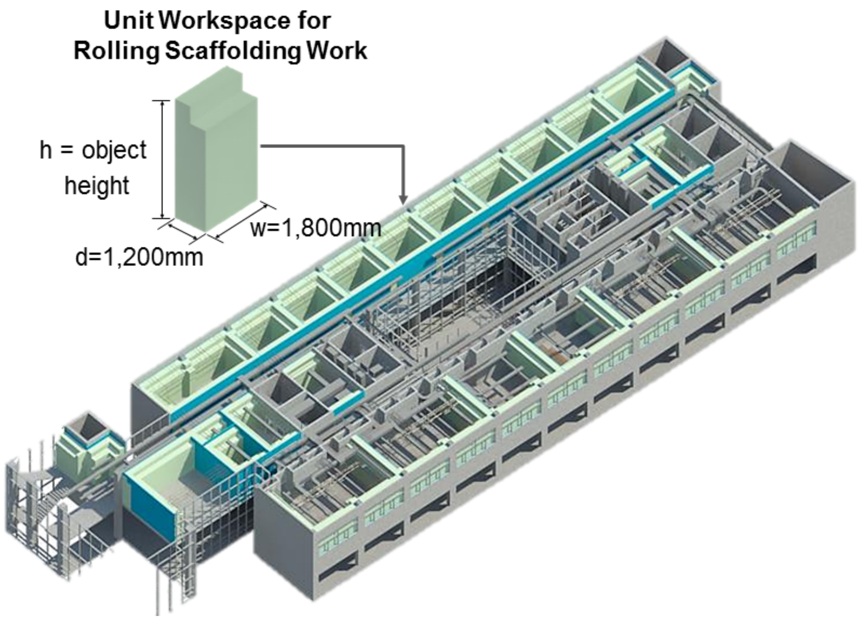


Figure 5-2. Workspace Requirement Identification for Drywall Framework

The project manager in the case project devised an activity execution plan, which divided the entire floor into three work zones—classroom zone (left), corridor zone (center), and laboratory zone (right)—that consider the schedule plans and quantity of the activity, as described in 5-3.

The size of each work unit was the same as the one for the rolling scaffolding (1,800mm x 1,200mm). Based on this process, a daily occupation status of *working space* for the activity could be represented as Figure 5-4. Through the process from *4D BIM generation* to *workspace occupation representation* as explained with the example of drywall framework activity, the workspace occupation status for all 23 activities could be represented. Table 5-1 shows the detailed information on *workspace occupation representation* for several activities of the case project.

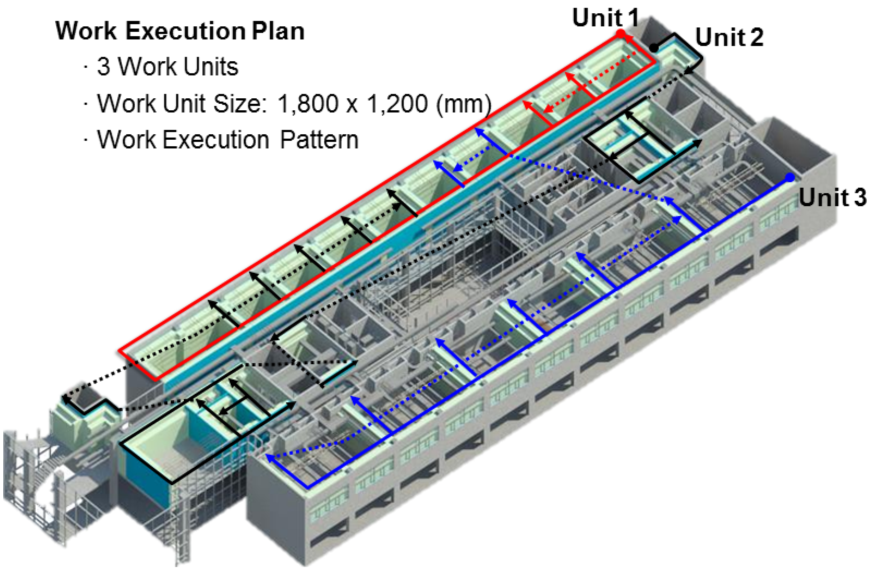


Figure 5-3. Activity Execution Plan for Drywall Framework

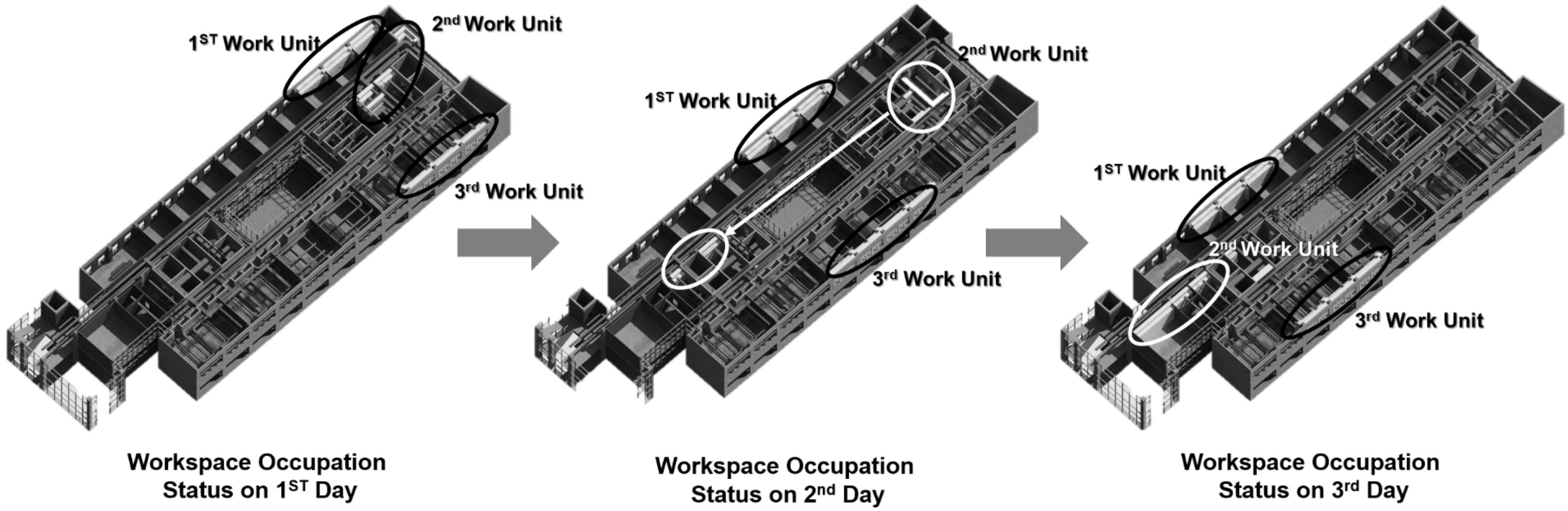


Figure 5-4. Workspace Occupation Representation for Drywall Framework>

Table 5-1. Information for Workspace Occupation Representation in the Case Project

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
1	Vertical Piping Work	5 days	4D BIM Simulation	Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 Places	-	-
2	AL Window Installation	6 days		Rolling Scaffolding	2 Units	Horizontal Unit	Ordering whole quantity at one time	Adjacent to Working Space	-	-
3	Glazing	6 days		Rolling Scaffolding	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Adjacent to Working Space	-	-
4	Horizontal Piping Work	15 days		Table Lift	3 Units	Linear	7 days	Distribute in 5 places	-	-
5	Vertical Duct Work	3 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 3 places	Prefabrication Area	
6	Atrium Curtain Wall installation	10 days		Car Gondola	2 Units	Vertical Unit	Ordering whole quantity at one time	Distribute in 6 places	-	Hazardous Area beneath Working Space
7	Atrium Glazing	5 days		Car Gondola	2 Units	Vertical Unit	Ordering whole quantity at one time	Distribute in 3 places	-	Hazardous Area beneath Working Space
8	Horizontal Duct Work	10 days		Table Lift	3 Units	Linear	5 days	Distribute in 4 places	Prefabrication Area	-

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
9	Cable Tray Work	5 days	4D BIM Simulation	Table Lift	2 Units	Linear	Ordering whole quantity at one time	Distribute in 3 places	-	-
10	Masonry Work	12 days		Rolling Scaffolding	3 Units	Linear	6 days	Adjacent to Working Space	-	-
11	Door Frame Installation in Brick Walls	6 days		Step Ladder	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 5 places	-	-
12	Plaster Work	10 days		Step Ladder	4 Units	Repeated Linear	5 days	Distribute in 5 places	-	-
13	Cold Room Panel Installation	4 days		Pipe scaffold	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 places	-	-
14	Water Proof Work in Restroom	3 days		Stand-up work	1 Unit	Horizontal Unit	-		-	Protection for 5 days
15	Tile Work in Restroom	5 days		Step Ladder	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 places	-	-
16	Drywall Frame Work	7 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 3 places		
17	Door Frame Installation in Drywalls	2 days		Step Ladder	1 Unit	Linear	Ordering whole quantity at one time	Distribute in 2 places		

No.	Activity	Duration	Object Space	Working Space			Storage Space		Support Space	Unavailable Space
				Construction Method	Work Unit	Occupancy Pattern	Order Period	Distribution Plan		
18	Drywall Finish Work	7 days		Rolling Scaffolding	3 Units	Horizontal Unit	Ordering whole quantity at one time	Distribute in 19 places		
19	Handrail Installation	6 days		Stand-up work	1 Unit	Linear	Ordering whole quantity at one time	Distribute in 1 place	Prefabrication Area	-
20	Base Painting Work	5 days		Stand-up work	1 Unit	Linear	-		-	-
21	Ceiling Work	14 days		Pipe Scaffold	2 Units	Horizontal Unit	7 days	Distribute in 2 place	-	-
22	Finish Painting Work	7days		Stand-up work	2 Units	Linear	-		-	-
23	Floor Finish Work	3 days		Stand-up work	1 Unit	Horizontal Unit	Ordering whole quantity at one time	Distribute in 2 place	-	Protection for 3 days
24	Temporarily Work		Temporarily Facility Layout	-	-	-	-	-	Lift Car T/C and etc.	-

After representing the workspace occupation for all activities, possible workspace interferences could be identified using spatial collision detection and path analysis. For example, Figure 5-5 displays the spatial conflict between the *working spaces* for drywall framework activity and *object space* for cable tray. This workspace interference could be resolved by changing the schedule of cable tray work execution, which was originally scheduled for execution before the drywall framework activity for the convenience of table lift movement. By putting the cable tray work execution after the drywall finish work activity, the productivity was somewhat lowered by the inconvenience of table lift movement during the cable tray work, but it actually prevented a delay of the project by avoiding more serious rework problems due to workspace interferences.

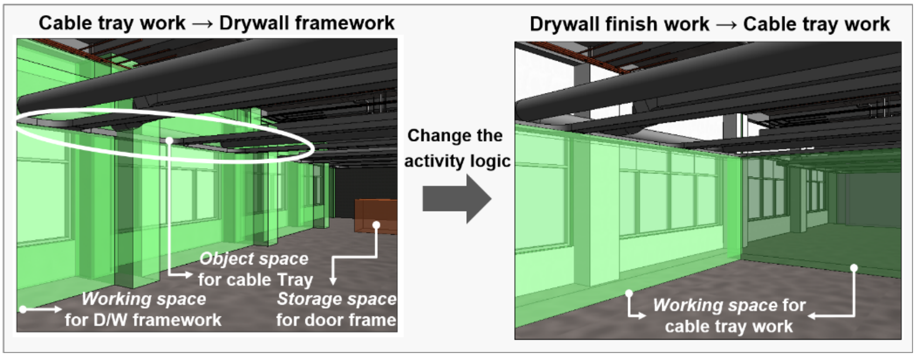


Figure 5-5. Workspace Interference Identification and Resolution Example

5.2 Results of Case Study

A total of 37 workspace interferences were identified by spatial collision detection (31 problems) and path analysis (6 problems) from the case study, and Table 6 summarizes a part of the identified workspace interferences. The correct location of the workspace interference was perceived by the values in the workspace interference location information boxes in Table 5-2, which indicates the maximum and minimum X, Y, and Z coordinate values for the conflicted rectangular space identified by the AABB algorithm. This study improved the accuracy of workspace status representation by introducing the workspace occupation concept. Moreover, it also improved the accuracy of workspace interference identification by removing 40 unrealistic workspace conflicts among 71 workspace conflicts that were identified using existing methods that could not distinguish workspace requirement from workspace occupation.

Table 5-2. Example of Identified Workspace Interferences in the Case Project

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A01	7/28	M210401	Vertical Piping Work	Storage Space	Flexible workspace	F210401	AL Window Installation	Working Space	Fixed workspace	25,180	65,150	16,900	26,320	69,800	17,000
A02	7/30	M210401	Vertical Piping Work	Storage Space	Flexible workspace	F210401	AL Window Installation	Working Space	Fixed workspace	25,180	39,800	16,900	26,320	35,150	17,000
A03	8/2	M210402	Horizontal Piping Work	Working Space	Fixed workspace	F219901	Atrium Curtain Wall Work	Working Space	Fixed workspace	15,425	50,900	16,900	16,625	55,760	20,800
A04	9/4	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	19,805	68,000	19,925	20,820	70,575	20,625
A05	9/5	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	19,300	62,000	19,500	19,700	64,900	19,600
A06	9/7	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	12,595	29,700	19,750	14,450	28,500	20,050
A07	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	15,490	32,500	20,300	15,890	37,725	20,600
A08	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,600	59,930	20,350	9,000	60,230	20,550
A09	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	6,695	25,950	19,950	7,095	27,900	20,250
A10	9/8	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	13,265	31,715	19,925	15,375	32,215	20,375

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A11	9/9	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	6,400	25,950	19,950	6,520	27,900	20,050
A12	9/10	F210403	Masonry Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	12,035	24,645	20,350	12,800	28,300	20,950
A13	9/10	F210403	Masonry Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	16,060	24,200	19,950	16,585	28,300	20,050
A14	9/11	F210409	Drywall Framework	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	24,870	71,785	19,500	25,120	80,715	19,600
A15	9/12	F210409	Drywall Framework	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	8,690	74,770	20,300	14,370	74,370	20,600
A16	9/11	F210409	Drywall Framework	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	25,625	70,670	20,925	25,650	82,050	20,950
A17	9/14	F210409	Drywall Framework	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	23,455	16,315	20,275	25,540	16,915	20,975
A18	9/16	F210409	Drywall Framework	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	19,135	57,270	19,455	24,645	58,020	19,855
A19	9/17	F210405	Plastering Work	Working Space	Fixed workspace	F210406	Cold Room Panel Installation	Storage Space	Fixed workspace	10,445	77,030	16,900	12,820	77,580	18,250
A20	9/17	F210406	Cold Room Panel Installation	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	10,250	77,030	16,900	11,250	78,230	18,700

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A21	9/17	F210407	Water Proof Work in Restroom	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	9,480	64,130	16,900	9,980	65,130	18,700
A22	9/18	F210407	Water Proof Work in Restroom	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	13,880	63,130	16,900	13,380	64,130	18,700
A23	9/20	F210405	Plastering Work	Storage Space	Flexible workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	5,580	78,290	16,900	6,395	80,490	18,000
A24	9/20	F210405	Plastering Work	Working Space	Fixed workspace	F210406	Cold Room Panel Installation	Storage Space	Fixed workspace	10,445	22,980	16,900	12,820	23,580	18,250
A25	9/20	F210406	Cold Room Panel Installation	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	10,250	22,980	16,900	11,250	24,180	18,700
A26	9/21	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	5,500	28,710	19,405	6,395	62,600	20,055
A27	9/22	F210412	Drywall Finish Work	Path Space	Fixed workspace	F210405	Plastering Work	Working Space	Fixed workspace	17,180	54,400	16,900	17,680	55,400	18,700
A28	9/23	F210412	Drywall Finish Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	25,000	29,670	18,955	25,270	38,825	19,055
A29	9/24	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	14,055	31,280	16,900	15,255	32,480	20,500
A30	9/24	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210402	Horizontal Piping Work	Object Space	Fixed workspace	25,145	28,675	20,255	25,540	39,975	20,355

No.	Date	Workspace 1				Workspace 2				Workspace Interference Location Information					
		Activity ID	Activity Name	Workspace type	Relocatability	Activity ID	Activity Name	Workspace type	Relocatability	X(min)	Y(min)	Z(min)	X(max)	Y(max)	Z(max)
A31	9/24	F210412	Drywall Finish Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	15,505	18,335	19,755	15,905	24,200	20,055
A32	9/24	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	18920	16,200	16,900	20,120	17,400	21,000
A33	9/25	F210405	Plastering Work	Working Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	14,055	28,570	16,900	15,255	29,770	20,500
A34	9/25	F210412	Drywall Finish Work	Working Space	Fixed workspace	E210401	Cable Tray Work	Object Space	Fixed workspace	15,590	70100	19,750	16,340	78,200	19,850
A35	9/25	F210405	Plastering Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,180	82,690	19,900	15,395	83,140	20,200
A36	9/25	F210405	Plastering Work	Working Space	Fixed workspace	M210404	Horizontal Duct Work	Object Space	Fixed workspace	7,180	82,690	19,900	15,395	83,140	20,200
A37	9/25	F210405	Plastering Work	Path Space	Fixed workspace	F210412	Drywall Finish Work	Working Space	Fixed workspace	15395	28600	16900	16595	29600	18700

Identified workspace interferences were resolved by changing the location of *storage space* for plastering work and vertical piping work (changing the location of *flexible workspace*), delaying the start date of the cold room panel installation (changing the schedule plan for non-critical activity), modifying the activity execution plan for horizontal piping work and plastering work (changing the activity construction plan), dividing horizontal duct work into two phases, and changing the sequence of the cable tray work (changing the activity logic).

The revised schedule plan by workspace interference resolution strategies mentioned above indicated a schedule delay due to productivity decrease and other problems. Such delay implies that the project manager failed to properly consider workspace for activity execution during the scheduling of the project. In order to complete the project without workspace interferences, the project manager therefore should have modified the schedule plan for critical activities based on the revised schedule plan. In this case project, the project manager planned to implement the crashing strategy for ceiling work, which was one of the critical activities, in order to catch up on the two-day delay caused by workspace interference resolution strategies. Although this crashing plan was expected to decrease unit productivity due to additional resource input, it contributed to the improvement of the project performance by reducing the uncertainty of the project by preventing the workspace interferences.

5.3 Summary

This chapter presents a process of the application for the suggested workspace planning process in an actual construction project. The finish work for one floor of a research building construction project in Seoul National University is served as a test bed. The purpose of the case study is to examine the effectiveness and applicability of the suggested process.

In the case study, 37 potential workspace interferences are identified and resolved in advance, throughout the suggested workspace planning process from *4D BIM generation* to *workspace interference resolution*. In addition, project manager in a case project can proactively prevent side effect of the workspace interferences resolution strategies by modifying the established schedule plan.

Chapter 6 Conclusion

This chapter summarizes the results obtained from the suggested process in this study and addresses the possible contributions that this study makes for the construction industry. In addition, the limitations of the study and areas for future related studies have been identified.

6.1 Result and Discussion

Workspace interferences would result in significant problems in a construction project such as a loss of productivity, safety hazards, and issues of poor quality. In order to prevent such negative impact of the workspace interference, this study presented a formalized workspace planning process using 4D BIM for building construction as follow;

(1) Studying on Previous Studies

There have been a number of efforts to address the status of workspace utilization and identify workspace related problems in a construction projects. Along with substantial achievements by previous studies, however, they still have some limitations in the representation of workspace occupation status, workspace interferences identification and resolution. Previous studies rely on the inaccurate assumptions about the workspace utilization and they also fail to integrate information about the characteristics of workspace and activity together with construction plan.

(2) Classifying Workspace by its Function and Relocatability

In order to integrate the characteristics of workspace and workspace planning process, this study classified workspace by its function and relocatability. Based on the functional classification of the workspace, the status of the workspace utilization would be represented without exception. Workspace classification by its relocatability is used for finding pertinent resolution strategies for the identified workspace interferences in a suggested workspace planning process.

(3) Suggesting a Workspace Planning Process

Based on the workspace classification, a formalized workspace planning process is proposed. Suggested process in this study improves the accuracy of workspace status prediction and workspace interference identification by introducing the workspace occupation concept. It also contributes to effective workspace planning process by integrating construction plan, characteristics of workspace types, and activity. Moreover, this study can help to ameliorate workspace planning process by including the path analysis process and workspace interference resolution phase that is overlooked in the most of previous studies.

(4) Practical Utilization

In order to examine the applicability of the proposed approach, a case project was tested. The result of the case study shows the applicability and effectiveness of the proposed process on enhancing the workspace planning process.

6.2 Contributions and Further Study

In spite of the significance of the workspace, current construction planning process fails to consider workspace for the activity properly in a building construction project due to its dynamic and complex nature. This study integrates the characteristics of workspace and workspace planning process. The contributions of this research are as follow;

(1) Improving Workspace Planning Process

The developed workspace planning process in this study can help the project manager prepare construction plans that are free of workspace interferences. A construction plan that properly considers workspace can help avoid severe problems in a construction project—such as rework, a decrease in productivity, safety hazards, and issues of poor quality—all of which are caused by workspace interferences. In addition, the suggested process in this study also contributes to cultivate the collaborative culture in a construction project since it prevents strife among the project participants due to workspace interruptions. All of this features of the suggested workspace planning process would be beneficial for planning of construction projects, in particular whey they are performed in cramped conditions.

(2) Expanding the Scope of BIM Application

This study's 4D BIM–based approach for workspace planning shows that the application scope of BIM can expand into diverse and contextual information that is generated during the construction process from the simple information that occurs as a consequence of the construction project.

Although the study work presented thus far hold a good promise by showing that the suggested workspace planning process can help enhance planning capabilities, the study needs to be further related studies in order to get more refined workspace planning process.

(1) Collecting Related Data

As mentioned, the suggested workspace planning process requires numerous types of database such as construction method database and material information database. When there is not abundant data source enormous efforts are required to prepare these data. Therefore, developing database for these types of data should be implemented before the suggested workspace planning process.

(2) Developing Construction Process Reflecting BIM

Construction process reflecting BIM is an indispensable component of the suggested process in this study. However, it is also true that numerous efforts are required for the generation of construction process reflecting BIM. Therefore, additional studies for effective BIM generation process are able to contribute to ameliorate effectiveness and applicability of the suggested workspace planning process.

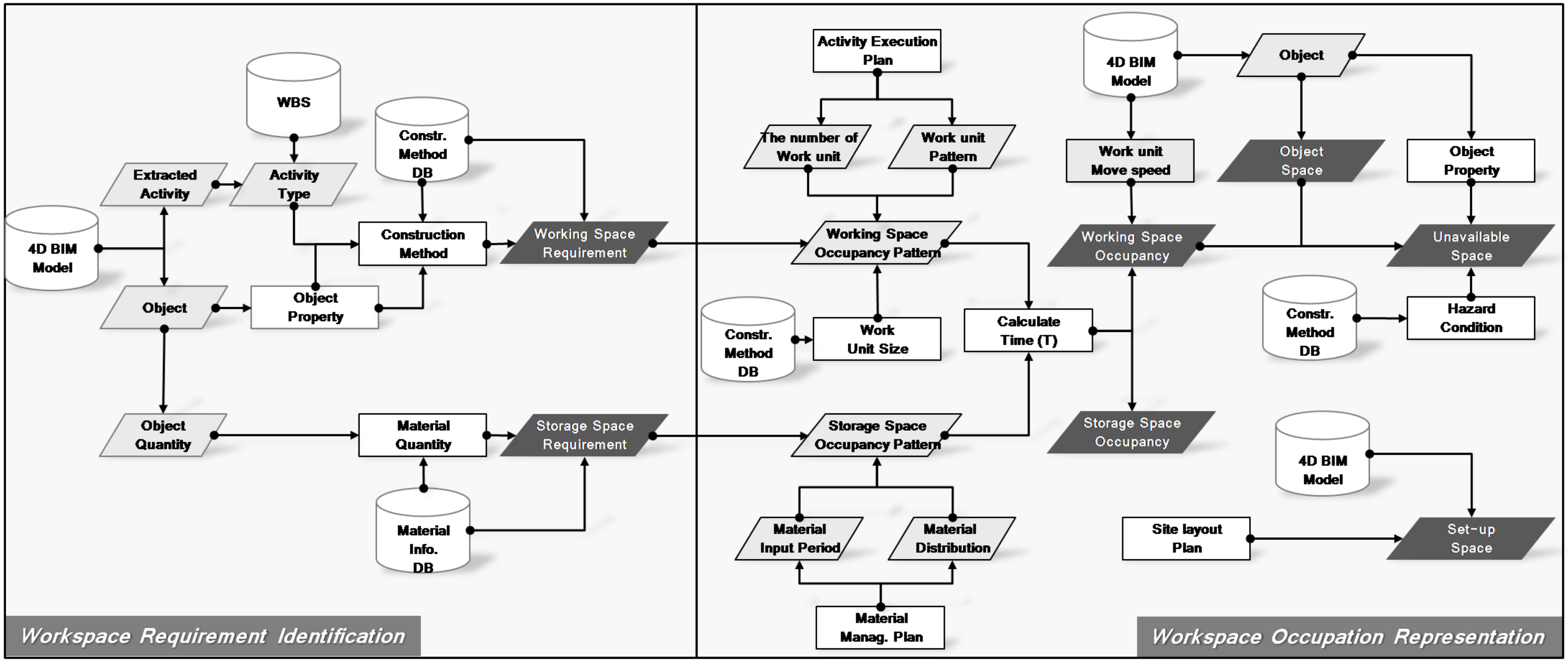
Appendices

Appendix A. Floor Chart for Workspace Requirement Identification and Workspace Occupation Representation

Appendix B. Selected Resolution Strategies for Identified Workspace Interferences in Case Project

Appendix C. Schedule plan for Case Project (Before & After Workspace Planning Process)

Appendix A. Flow Chart for Workspace Requirement Identification and Workspace Occupation Representation



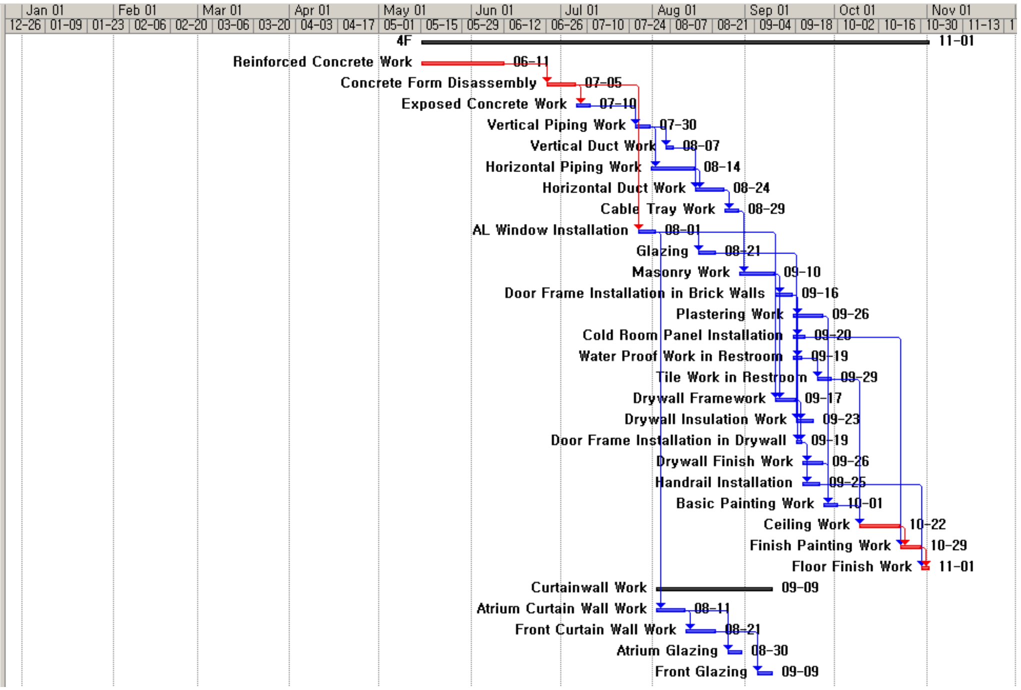
Appendix B. Selected Strategies for Identified Workspace Interferences in Case Project

No.	Date	Workspace 1		Workspace 2		Resolution Strategy
		Activity Name	Workspace type	Activity Name	Workspace type	
A01	7/28	Vertical Piping Work	Storage Space	AL Window Installation	Working Space	Change the location of Workspace 1
A02	7/30	Vertical Piping Work	Storage Space	AL Window Installation	Working Space	Change the location of Workspace 1
A03	8/2	Horizontal Piping Work	Working Space	Atrium Curtain Wall Work	Working Space	Change the activity execution plan for Workspace 1
A04	9/4	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A05	9/5	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A06	9/7	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A07	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A08	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A09	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A10	9/8	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A11	9/9	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A12	9/10	Masonry Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A13	9/10	Masonry Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A14	9/11	Drywall Framework	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A15	9/12	Drywall Framework	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A16	9/11	Drywall Framework	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A17	9/14	Drywall Framework	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A18	9/16	Drywall Framework	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2

No.	Date	Workspace 1		Workspace 2		Resolution Strategy
		Activity Name	Workspace type	Activity Name	Workspace type	
A19	9/17	Plastering Work	Working Space	Cold Room Panel Installation	Storage Space	Change the Schedule plan for Workspace 2
A20	9/17	Cold Room Panel Installation	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A21	9/17	Water Proof Work in Restroom	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A22	9/18	Water Proof Work in Restroom	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A23	9/20	Plastering Work	Storage Space	Drywall Finish Work	Working Space	Change the location of Workspace 1
A24	9/20	Plastering Work	Working Space	Cold Room Panel Installation	Storage Space	Change the Schedule plan for Workspace 2
A25	9/20	Cold Room Panel Installation	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A26	9/21	Drywall Finish Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A27	9/22	Drywall Finish Work	Path Space	Plastering Work	Working Space	Change the activity execution plan for Workspace 2
A28	9/23	Drywall Finish Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A29	9/24	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A30	9/24	Drywall Finish Work	Working Space	Horizontal Piping Work	Object Space	Change the activity logic for Workspace 2
A31	9/24	Drywall Finish Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A32	9/24	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A33	9/25	Plastering Work	Working Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1
A34	9/25	Drywall Finish Work	Working Space	Cable Tray Work	Object Space	Change the activity logic for Workspace 2
A35	9/25	Plastering Work	Working Space	Horizontal Duct Work	Object Space	Change the activity logic for Workspace 2
A36	9/25	Plastering Work	Working Space	Horizontal Duct Work	Object Space	Change the activity execution plan for Workspace 1
A37	9/25	Plastering Work	Path Space	Drywall Finish Work	Working Space	Change the activity execution plan for Workspace 1

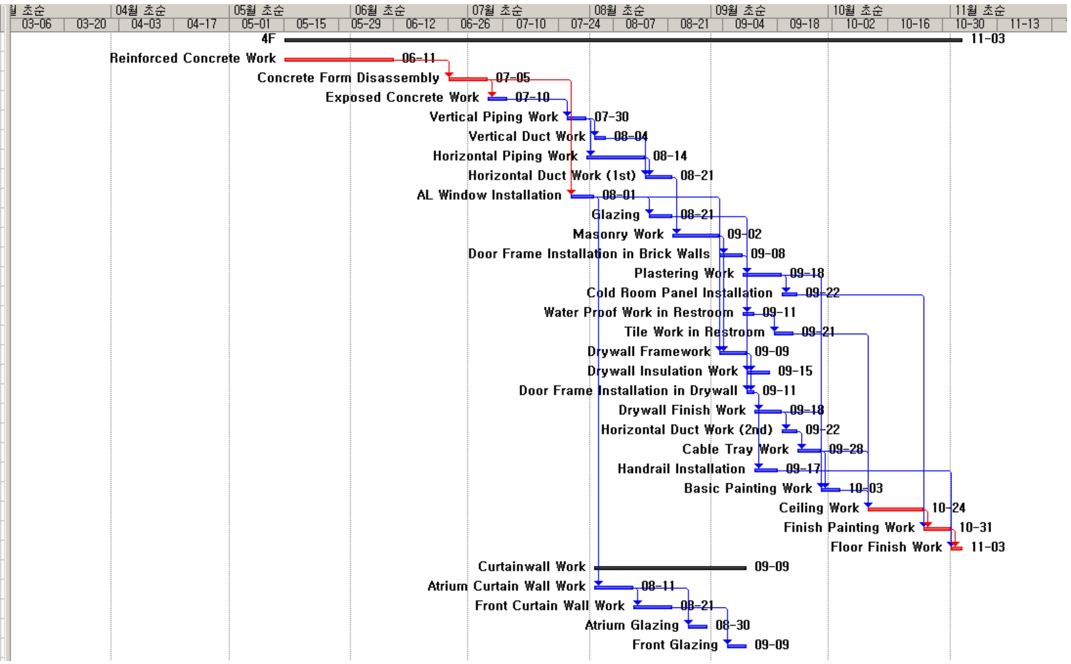
Appendix C-1 Schedule Plan for Case Project before Workspace Planning Process

	작업 이름	기간	시작 날짜	완료 날짜
55	**4F**	**171 일**	**11-05-15 (일)**	**11-11-01 (화)**
56	Reinforced Concrete Work	28 일	11-05-15 (일)	11-06-11 (토)
57	Concrete Form Disassembly	10 일	11-06-26 (일)	11-07-05 (화)
58	Exposed Concrete Work	5 일	11-07-06 (수)	11-07-10 (일)
59	Vertical Piping Work	5 일	11-07-26 (화)	11-07-30 (토)
60	Vertical Duct Work	3 일	11-08-05 (금)	11-08-07 (일)
61	Horizontal Piping Work	15 일	11-07-31 (일)	11-08-14 (일)
62	**Horizontal Duct Work**	**10 일**	**11-08-15 (월)**	**11-08-24 (수)**
63	**Cable Tray Work**	**5 일**	**11-08-25 (목)**	**11-08-29 (월)**
64	AL Window Installation	6 일	11-07-27 (수)	11-08-01 (월)
65	Glazing	6 일	11-08-16 (화)	11-08-21 (일)
66	Masonry Work	12 일	11-08-30 (화)	11-09-10 (토)
67	Door Frame Installation in Brick Walls	6 일	11-09-11 (일)	11-09-16 (금)
68	**Plastering Work**	**10 일**	**11-09-17 (토)**	**11-09-26 (월)**
69	**Cold Room Panel Installation**	**4 일**	**11-09-17 (토)**	**11-09-20 (화)**
70	Water Proof Work in Restroom	3 일	11-09-17 (토)	11-09-19 (월)
71	Tile Work in Restroom	5 일	11-09-25 (일)	11-09-29 (목)
72	Drywall Framework	7 일	11-09-11 (일)	11-09-17 (토)
73	Drywall Insulation Work	6 일	11-09-18 (일)	11-09-23 (금)
74	Door Frame Installation in Drywall	2 일	11-09-18 (일)	11-09-19 (월)
75	**Drywall Finish Work**	**7 일**	**11-09-20 (화)**	**11-09-26 (월)**
76	Handrail Installation	6 일	11-09-20 (화)	11-09-25 (일)
77	Basic Painting Work	5 일	11-09-27 (화)	11-10-01 (토)
78	**Ceiling Work**	14 일	11-10-09 (일)	11-10-22 (토)
79	Finish Painting Work	7 일	11-10-23 (일)	11-10-29 (토)
80	Floor Finish Work	3 일	11-10-30 (일)	11-11-01 (화)
81	**Curtainwall Work**	**39 일**	**11-08-02 (화)**	**11-09-09 (금)**
82	Atrium Curtain Wall Work	10 일	11-08-02 (화)	11-08-11 (목)
83	Front Curtain Wall Work	10 일	11-08-12 (금)	11-08-21 (일)
84	Atrium Glazing	5 일	11-08-26 (금)	11-08-30 (화)
85	Front Glazing	5 일	11-09-05 (월)	11-09-09 (금)



Appendix C-2 Schedule Plan for Case Project after Workspace Planning Process

	작업 이름	기간	시작 날짜	완료 날짜
57	⊟ **4F**	**173 일**	**11-05-15 (일)**	**11-11-03 (목)**
58	Reinforced Concrete Work	28 일	11-05-15 (일)	11-06-11 (토)
59	Concrete Form Disassembly	10 일	11-06-26 (일)	11-07-05 (화)
60	Exposed Concrete Work	5 일	11-07-06 (수)	11-07-10 (일)
61	Vertical Piping Work	5 일	11-07-26 (화)	11-07-30 (토)
62	Vertical Duct Work	3 일	11-08-02 (화)	11-08-04 (목)
63	Horizontal Piping Work	15 일	11-07-31 (일)	11-08-14 (일)
64	**Horizontal Duct Work (1st)**	**7 일**	**11-08-15 (월)**	**11-08-21 (일)**
65	AL Window Installation	6 일	11-07-27 (수)	11-08-01 (월)
66	Glazing	6 일	11-08-16 (화)	11-08-21 (일)
67	Masonry Work	12 일	11-08-22 (월)	11-09-02 (금)
68	Door Frame Installation in Brick Walls	6 일	11-09-03 (토)	11-09-08 (목)
69	**Plastering Work**	**10 일**	**11-09-09 (금)**	**11-09-18 (일)**
70	**Cold Room Panel Installation**	**4 일**	**11-09-19 (월)**	**11-09-22 (목)**
71	Water Proof Work in Restroom	3 일	11-09-09 (금)	11-09-11 (일)
72	Tile Work in Restroom	5 일	11-09-17 (토)	11-09-21 (수)
73	Drywall Framework	7 일	11-09-03 (토)	11-09-09 (금)
74	Drywall Insulation Work	6 일	11-09-10 (토)	11-09-15 (목)
75	Door Frame Installation in Drywall	2 일	11-09-10 (토)	11-09-11 (일)
76	**Drywall Finish Work**	**7 일**	**11-09-12 (월)**	**11-09-18 (일)**
77	**Horizontal Duct Work (2nd)**	**4 일**	**11-09-19 (월)**	**11-09-22 (목)**
78	**Cable Tray Work**	**6 일**	**11-09-23 (금)**	**11-09-28 (수)**
79	Handrail Installation	6 일	11-09-12 (월)	11-09-17 (토)
80	Basic Painting Work	5 일	11-09-29 (목)	11-10-03 (월)
81	Ceiling Work	14 일	11-10-11 (화)	11-10-24 (월)
82	Finish Painting Work	7 일	11-10-25 (화)	11-10-31 (월)
83	Floor Finish Work	3 일	11-11-01 (화)	11-11-03 (목)
84	⊟ **Curtainwall Work**	**39 일**	**11-08-02 (화)**	**11-09-09 (금)**
85	Atrium Curtain Wall Work	10 일	11-08-02 (화)	11-08-11 (목)
86	Front Curtain Wall Work	10 일	11-08-12 (금)	11-08-21 (일)
87	Atrium Glazing	5 일	11-08-26 (금)	11-08-30 (화)
88	Front Glazing	5 일	11-09-05 (월)	11-09-09 (금)



Reference

Akinci, B., Fischer, M., and Kunz, J. (2002a). “Automated Generation of Work Spaces Required by Construction Activities.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 306~315

Akinci, B., Fischer, M. Kunz, J. and Levitt, R. (2002b). “Representing work spaces generically in construction method models.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 296~305

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002c). “Formalization and automation of time-space conflict analysis.” Journal of Computing in Civil Engineering, ASCE, 16(2), pp. 124~134

Bansal, V. (2011). "Use of GIS and Topology in the Identification and Resolution of Space Conflicts." Journal of Computing in Civil Engineering, ASCE, 25(2). pp. 159~171.

Chau, K. W., Anson, M., and Zhang, J. P. (2004). “Four-Dimensional Visualization of Construction Scheduling and Site Utilization.” Journal of Construction Engineering and Management, ASCE, 130(4), pp. 598~606

Chavada, R., Dawood, N. and Kassem, M. (2012). “Construction workspace management: the development and application of a novel nD planning approach and tool.” Journal of Information Technology in Construction, 17, pp. 213~236

Chua, D., Yeoh, K., and Song, Y. (2010). “Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design.” Journal of Construction Engineering and Management, ASCE, 136(6), pp. 641~649

Dawood, N. and Z. Mallasi (2006). “Construction workspace planning: Assignment and analysis utilizing 4D visualization technologies.” Computer- Aided Civil and Infrastructure Engineering, 21(7), pp. 498~513

DeLoura, M. A., Ahamd, A., Bilas, S., Boer, J., Dietrich, S. and Dybsand, E., et al. (2000). Game programming germs, Charles River Media Inc., USA, pp. 502~516

Eastman, C. Teicholz, P., Sacks, R., and Liston, K. (2008). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Whiley & Sons Inc., USA, pp. 25~64

Guo, S. J. (2002). “Identification and resolution of work space conflicts in building construction.” Journal of Construction Engineering and Management, ASCE, 128(4), pp. 287~295

Hammad, A., Zhang, C., Al-Hussein, M. and Cardinal, G. (2007). “Equipment workspace analysis in infrastructure projects.” Canadian Journal of Civil Engineering, 34(10), pp.1247~1256.

Kaming, P. F., Holt, G.D., Kometa, S. T. and Olomolaiye, P.O. (1998). “Severity diagnosis of productivity problems – a reality analysis.” International Journal of Project Management, 16(2), pp. 107~113.

Kelsey, J., Winch, G., and Penn, A. (2001). “Understanding the Project Planning Process: Requirements Capture for the Virtual Construction Site.” University College London, UK, Bartlett Research

Keneley, R. and Seppanen, O. (2010). Location-Based Management for Construction: Planning, Scheduling and Control, Son Press, USA, pp. 49 ~ 92

Madhavan, R., E. W. Tunstel and E. R. Messina (2009). Performance Evaluation and Benchmarking of Intelligent Systems, Springer, USA, pp. 139 ~ 168

Mallasi, Z. (2006). “Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation.” Automation in Construction, 15(5), pp. 640~655

Moller, T. and Haines, E. (2002). Real time Rendering, 2nd ed., A K Peters, Ltd., USA, pp. 631~668

National BIM Standard-United States Version 2, National BIM Standard-United States Project Committee, <http://www.nationalbimstandard.org/about.php> (2013.06.10)

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). Productivity Improvement in Construction, McGraw-Hill Inc, USA

Riley, D. R., and Sanvido, V. E. (1995). “Patterns of Construction-Space Use in Multistory Buildings.” Journal of Construction Engineering and Management, ASCE, 121(4), pp. 464~473

Riley, D. R., and Sanvido, V. E. (1997). “Space planning method for multistory building construction.” Journal of Construction Engineering and Management, ASCE, 123(2), pp. 171~180

Said, H. and K. El-Rayes (2013). "Optimal utilization of interior building spaces for material procurement and storage in congested construction sites." Automation in Construction 31(0), pp. 292~306.

Sadeghpour, F., Moselhi, O. and Alkass, S.T. (2006). “Computer-Aided Site Layout Planning.” Journal of Construction Engineering and Management, 132(2), pp. 143~151.

Sedgewick, R. (2001). Algorithms in C++ Part 5: Graph Algorithms, Pearson Education Inc., USA, chapter 18.

Thabet, W. Y., and Beliveau, Y. J. (1994). “Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings.” Journal of Construction Engineering and Management, ASCE, 120(1), pp. 96~116

Tommelein, I. D., and Zouein, P. P. (1993). “Interactive Dynamic Layout Planning.” Journal of Construction Engineering and Management, ASCE, 119(2), pp. 266~287

Talmaki, S. and V. R. Kamat (2012). “Real-Time Hybrid Virtuality for Prevention of Excavation Related Utility Strikes.” Journal of Computing in Civil Engineering, ASCE (On-line Published)

Wang, H. J., Zhang, J. P., Chau, K. W. and Anson, M. (2004). "4D dynamic management for construction planning and resource utilization." Automation in Construction 13(5), pp. 575~589.

Winch, G. M., and North, S. (2006). “Critical space analysis.” Journal of Construction Engineering and Management, ASCE, 132(5), pp. 473~481

Zhang, C., Hammad, A., Zayed, T. M., Wainer, G, and Pang, H. (2007). "Cell-based representation and analysis of spatial resources in construction

국 문 초 록

건설프로젝트에서는 다양한 참여자들이 제한된 공간에서 각자의 작업공간을 차지하며 작업을 수행한다. 작업공간에 대한 부적절한 계획은 건설프로젝트의 생산성 감소, 작업 위험 증가 및 품질 저하 등의 문제로 이어지기 때문에 작업공간은 건설프로젝트에서 고려하여야 할 중요한 요소 중 하나이다. 그러나 간트 차트, Critical Path Method, 네트워크 다이어그램 등의 기존의 프로젝트 공사 계획 수립을 위한 방법들은 건설프로젝트에서의 작업공간을 고려하지 못하는 한계가 있었다.

본 연구에서는 체계적이지 못한 작업공간 계획으로 인하여 발생하는 작업공간 문제를 예방하기 위하여 작업공간을 그 기능과 이동가능성에 따라서 분류하고 4D BIM(Building Information Model) 생성, 필요작업공간 식별, 점유작업공간 표현, 작업공간문제 식별, 작업공간문제 해결 단계를 포함하는 4D BIM 기반의 작업공간 계획 프로세스를 제안한다.

제안된 프로세스는 점유 작업공간 개념의 도입하고 작업공간 및 액티비티의 특성 그리고 공사수행계획을 통합적을 고려함으로써 작업공간의 사용 상태 표현 및 작업공간 문제 식별의 정확도를 향상하였다. 또한 이동통로분석과 작업공간 문제 해결 프로세스를 포함함으로써 작업공간계획을 전체적인 관점에서 완성하였다.

제안된 작업공간 계획 프로세스의 적용 가능성 및 타당성을 검토하기 위하여 연구 시설물 1 개 층 마감공사를 대상으로 하여 사례 분석을 실시하였다. 사례 분석의 결과, 제안된 프로세스는 기존의 방법보다 개선된 작업공간 사용 상태 표현 및 작업공간 문제 식별을 달성하였으며, 작업공간 문제를 반영한 공정 계획 수립에 도움을 주었다.

본 연구의 결과를 바탕으로, 프로젝트 관리자는 본 공사 수행 이전에 공사에 필요한 작업공간을 미리 계획함으로써 서로 다른 액티비티 작업공간 사이의 간섭을 예방하고 이로 인하여 발생할 수 있는 건설프로젝트에서의 불필요한 손실을 예방할 수 있을 것으로 기대된다.

주요어: 작업공간, 작업공간 계획, 4D Building Information Model (BIM)

학 번: 2012-20566