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Framework for Work-Space Planning Using Four-Dimensional BIM in Construction Projects

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Abstract

Each participant in a building construction project requires a dedicated work space in which to execute their activities. In this environment, inappropriate work-space planning in a construction site causes work-space problems, which results in a loss of productivity, safety hazards, and issues of poor quality. Therefore, the work space should be considered one of the most important resources and constraints to manage at a construction site. However, current construction planning techniques have proven to be insufficient for work-space planning because they do not account for the spatial feature of each activity. To establish a formalized work-space planning process, therefore, this paper categorizes work space by its function and movability and suggests a framework for a work-space planning process that contains five phases, including 4D building information model (BIM) generation, work-space requirement identification, work-space occupation representation, work-space problem identification, and work-space problem resolution. The proposed framework in this paper can improve the accuracy of work-space status representation and work-space problem identification by introducing the work-space occupation concept and the integrated work-space planning process that considers characteristics of activity, work space, and construction plan. In addition, this paper aims to ameliorate the work-space planning process through path analysis and a formalized work-space problem resolution process. To validate the proposed approach, a case project was tested. The result shows the efficiency and effectiveness of the proposed framework on improving the work-space planning process. Based on the result of this study, a project manager will be able to prevent possible work-space problems and their negative effects on project performance by devising a pertinent work-space plan during the preconstruction phase.

Introduction

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 work space for their resources—such as laborers, equipment, and materials—to execute their activities (Hammad et al. 2007; Riley and Sanvido 1997; Sadeghpour et al. 2006). Inappropriate work-space planning leads to work-space problems, 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). As a result, a project manager should consider the work space 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 and Zouein 1993).

Work space for activity execution is differentiated from other resources. First, the location and size of a work space occupied by a specific activity at a certain time is influenced by the nature of that activity and its construction plan (Riley and Sanvido 1995). Second, work-space utilization by each activity shows dynamic changes in three dimensions in accordance with time flow in a construction project (Akinci et al. 2002b; Tommelein and Zouein 1993; Winch and North

2006). Therefore, an integrated approach embracing the dynamic and complex features of a work space is required for a desirable work-space 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). Although the more sophisticated technique of line of balance (LOB) considers the spatial feature of the activity, it is still insufficient for work-space planning because it assumes that only one crew is able to occupy each work zone at a time (Akinci et al. 2002a). Owing to the lack of a formalized process for work-space planning, current work-space planning at the construction site relies on the planner's intuitive 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 work space; thus, mangers have experienced difficulties in proactively preventing work-space problems and their negative effects (Guo 2002; Kelsey et al. 2001; 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 finework space plan (Hammad et al. 2007; Said and El-Rayes 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 the 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. This study proposes a formalized work-space planning process in the 4D BIM environment to proactively handle incidences of work-space problems and to eliminate waste elements in a construction project.

There are two branches in a space planning–related area: (1) the space scheduling problem that is focused on work space for activity execution; and (2) the site layout problem that deals with the location and size of temporary facilities at a construction site (Winch and North 2006). Among these two areas, the space scheduling issue is more suitable for handling the dynamic and complex features of a work space in a construction process because the site layout is predetermined before the construction starts. Therefore, this study is focused on the space scheduling problem that deals with activity execution spaces from a dynamic perspective. In addition, this study assumes that the site layout of the construction project is established before the work-space planning process starts.

To achieve the purpose, this paper starts with critical reviews of previous related studies that investigate work-space representation and planning. Then, work space is classified by its function and movability. Based on the critical reviews of the preliminary studies and work space classification, this study proposes a work-space planning process that contains 4D BIM generation, work-space requirement identification, work-space occupation representation, work-space problem identification, and work-space problem resolution. Then, a case study applied with the suggested framework is presented. Finally, conclusions and recommendations for future research are offered.

Related Research

The purpose of work-space planning in a building construction project is to prevent work-space problems and unnecessary waste by predicting the work-space utilization status of each participant. Therefore, work-space planning includes a representation of workspace occupation status, work-space problems identification, and resolution. For an effective work-space planning process, diverse approaches have been suggested with regard to representing the state of work-space utilization and managing work-space problems. Table 1 summarizes the major features of previous studies that investigate the work-space planning process as well as the improvements made by this study. Thabet and Beliveau (1994) suggested a scheduling method integrating space demand and availability by comparing required space and available space for each activity in a specific work block. In a follow-up study, Thabet and Beliveau (1994) developed a space-constrained and resource-constrained scheduling system. Riley and Sanvido (1995) defined 13 construction work-space types and their behavior patterns in multistory building construction projects using site visits, interviews, and document reviews for 10 case project studies. Riley and Sanvido (1997) developed a methodology for work-space planning in a construction project through empirical studies on the space planning process. Guo (2002) attempted to identify work-space conflict in a construction project by manually overlapping work-space demands for each activity on a project's CAD drawings, and also proposed criteria for wor- space conflict resolution and a concept for path-space verification. Akinci et al. (2002a, b) developed a 4D workplanner space generator that automatically generates the work space for each object through the spatial relationship between objects and the work space defined by the construction method. Then Akinci et al. (2002c) suggested a method for categorizing and prioritizing identified work-space conflicts. Dawood and Mallasi (2006) developed a PECASO 4D simulator introducing three work-rate distribution types and 12 work execution patterns to identify work-space conflicts in a construction site. Chavada et al. (2012) suggested a more pragmatic model than that of previous studies in terms of workspace generation, allocation, and management for each activity in a 4D/5D BIM environment.

Table 1. Review on Related Studies and Improvement in this Study

Reference	Work-space problem identification	Operating environment	Activity execution progress representation	Integration of construction plan and work space	Work-space problem resolution
Thabet and Beliveau (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 work-space conflict resolution
Akinci et al. (2002b, c)	Yes	4D CAD		Determination of work space by construction methods	Prioritization of work-space conflict
Dawood and Mallasi (2006)	Yes	4D CAD	12 types of execution pattern and three 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 work space occupies whole work space during activity duration		Enumeration of possible solutions for work-space conflict
This paper	Yes	4D BIM	Differentiated work-space requirement and work-space occupation	Integration of activity execution plan and material management plan	Formalized procedure for work-space conflict resolution

Despite the number of previous studies that have considerably ameliorated the work-space planning process, these studies have several important limitations regarding work space–utilization status representation, work space problem identification, and resolution. A majority of previous studies assume that resources for activity execution occupy their required work space for the entire duration of the activity. However, some activities in a schedule plan could be broken down into several subactivities, and those activities are completed by executing their subactivities. Instead of the activity occupying the whole required space during the entire activity duration, subactivities pass through part of the required space several times as they complete their own task (Riley and Sanvido 1995). In this respect, previous studies’ assumptions fail to achieve an accurate representation of work-space utilization status. Moreover, previous studies only consider a schedule plan in the workspace planning process, and they overlook detailed plans to achieve the schedule plan such as an activity execution plan or a material management plan. Therefore, the location and size of the work space represented in the previous studies are difficult to update with modifications to these detailed plans. Third, previous studies are not able to reflect the different nature of workspace types because all types of work spaces are generated by the identical method regardless of the characteristics of each work-space type. For example, most previous studies identify work spaces for workers and materials through the identical method although space generation principles for those work spaces are different from one another. This study has attempted to further improve the findings of previous studies by: (1) differentiating the work-space requirement and work-space occupation for each activity; (2) integrating characteristics of the work space, activity, and construction plan to represent work-space occupation; and (3) presenting a formalized procedure for work-space problem resolution.

In this study, the work-space requirement is defined as an entire space that is required for all resources of an activity during the entire duration of the activity. The work-space occupation is a partial space of the work-space requirement that is used by workers, materials, or equipment during a unit time period. To execute activity, work-space occupation successively passes through the work-space requirement during activity duration. As described in Fig. 1, the suggested framework in this study is able to distinguish between unrealistic and realistic work-space problems in the construction process. If Activity A and Activity B in Fig. 1 concurrently start, their work-space requirement overlaps, and the previous studies perceive this overlap as a work-space conflict. However, the work-space conflict does not actually occur because Activities A and B occupy the overlapped space on different days. In this study, this phenomenon is defined as an unrealistic work-space problem.

Work-Space Types

Before suggesting a framework for the work-space planning process, characteristics of a work space should be comprehended. To integrate the characteristics of a work space with the work-space planning process, this study classified work space by its function and movability. Classification by its function helps represent the whole work-space requirement without exception, and classification by movability is useful in identifying the cause of work-space problems and providing a pertinent resolution strategy for each issue.

Classification by Function

The function of work space explains why a specific work space is required for the activity execution. Among several efforts to categorize work-space types, Riley and Sanvido (1995) classified work spaces into 13 work-space types by observing the construction process. Based on Riley and Sanvido's (1995) classification, this study defines six functional work-space types by merging the work-space types that perform the same functions, as described in Fig. 2.

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

Indirect work space 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 work space is determined by site layout or predefined spatial relationships with the direct work space. Indirect work space includes: (1) setup space, which is the area for operating the overall construction

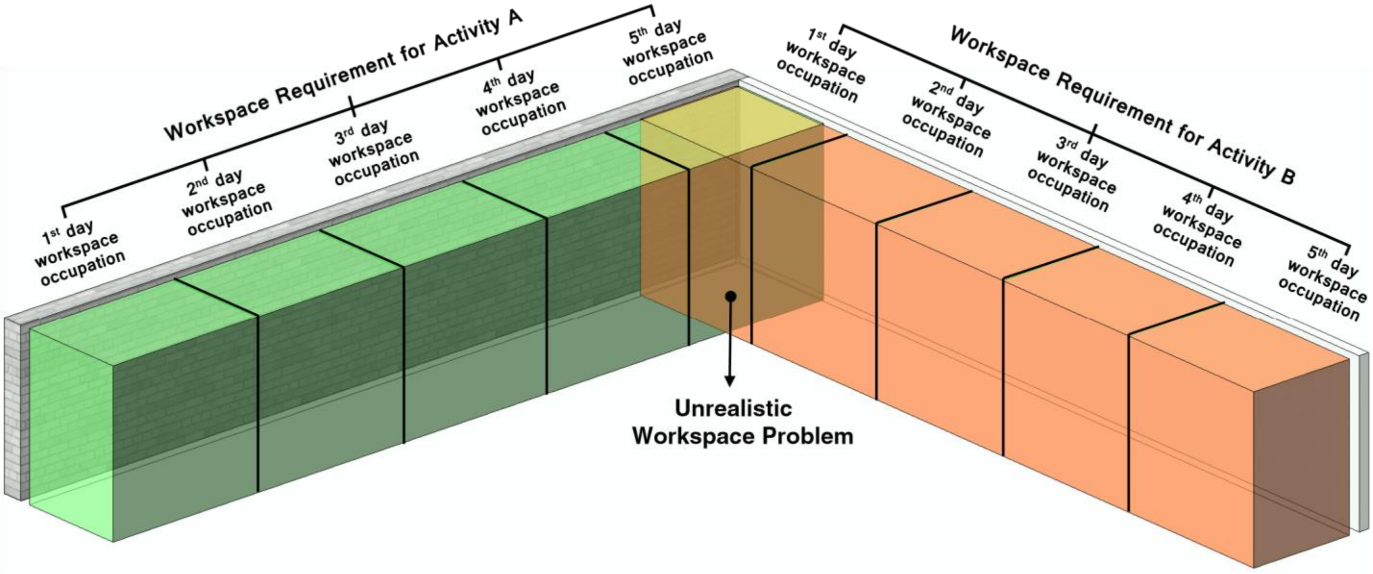


Fig. 1. Concept of work-space requirement and work-space occupation

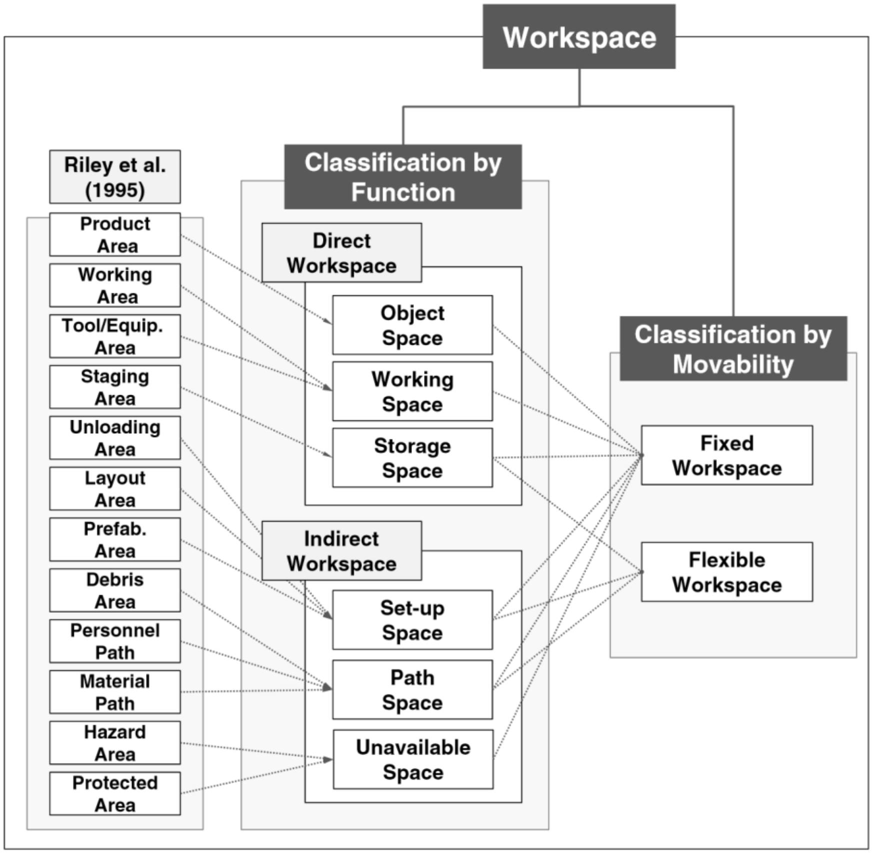


Fig. 2. Work-space classification structure

project, such as a tower crane and lift car; (2) path space, which is the area required for the movement of resources, such as a laborer or equipment material; and (3) unavailable space or the unusable area resulting from the protection of established building components or safety issues caused by certain activity executions. Table 2 summarizes the definition and important attributes of each workspace type.

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

Classification by Movability

Work-space classification by its attributes contributes to the effective enhancement of the comprehension and utilization of the work-space characteristics information. Among several work-space attributes, movability is one of the most paramount properties because it assists in identifying the causes of workspace problems and detects apposite resolution strategies for each issue. Therefore, this study classifies work space into fixed work space and flexible work space by movability, as indicated in Fig. 2.

Fixed work space is a space that is not able to arbitrarily change its location. For instance, the location of working space is determined by a spatial relationship 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 work space. On the other hand, the location of flexible work space 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 allocation 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 work space. However, not all storage spaces are categorized as flexible work space because the movability 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 work space because those materials are stored at a specific assigned block at a site by the material allocation plan. On the other hand, owing 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 fixed work space.

In direct work space, object space and working space are classified as fixed work space. In the case of storage space, work-space type based on movability is determined by the characteristics of the materials as previously described. Unavailable space is a type of fixed work space because working space and object space, which determine the location of the unavailable space, belong to fixed work space. Finally work-space types by movability for setup space and path space are determined by the flexibility of the construction plan that defines the location of the work space.

Table 2. Functional Work-Space Classification

Type of work space	Definition	Location and size of work space	Generation and expiration of work space
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 and equipment required to execute each activity on the site	Spatial relationship with corresponding object defined by construction method determines the location and size of the space	Working space is generated at the starting point of the activity and expires at the 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 the starting point of the activity and expires at the ending point of the activity
Indirect work space			
Setup space	Areas required to operate overall construction project (e.g., tower crane, scaffolding, and lift car)	Temporary facility layout determines the location and size of the space	Setup space is generated at the starting point of the independent activity or related activity and expires at the 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
Unavai-lable space	Areas that are prohibited to use owing to a 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

Work-Space Planning Process

Based on the previous work-space classification, this section discusses the work-space planning process that deals with the dynamic and complicated features of work space in a construction project. Fig. 3 presents a schematic diagram for the overall work-space planning process.

The work-space 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 and storage-space requirements for activities are identified in light of information about construction methods and materials for activity execution; (3) the status of work-space occupation for all types of work space is represented by reflecting the construction plan, such as the activity execution plan or material management plan; (4) work-space problems are identified through the spatial clash-detection algorithm and path analysis process; and (5) a pertinent solution for the identified work-space problem is presented by considering characteristics of the activity, work space, and construction plan. The details of each phase are discussed in the subsequent sections.

The work-space planning process suggested in this study automatically generates work space and identifies work-space problems when required information and detailed construction plans are offered. For automated work-space requirement identification, this study builds required databases for typical types of activities at a construction site (e.g., piping work, ductwork, cable tray work, masonry work, plastering work, drywall work, waterproofing work, and ceiling work). Meanwhile, a formalized tool for devising a detailed construction plan, which is necessary for work-space occupation representation, is not sufficient in the construction project.

In this regard, the work-space generation function in the developed framework can be applied to a visualization tool in the decision making process for those construction plans. Before representing work-space occupation, project managers are able to devise detailed construction plans based on the identified work-space requirements in their construction project.

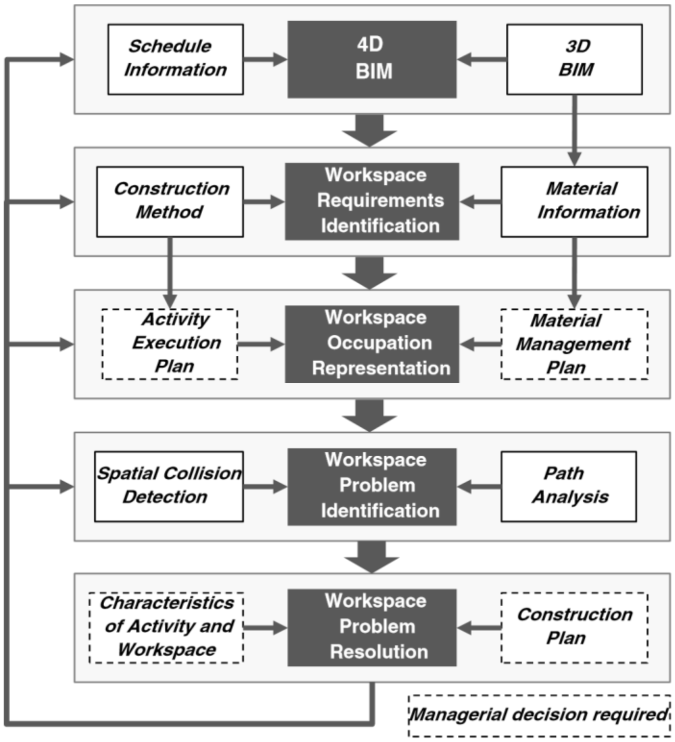


Fig. 3. Work-space planning process

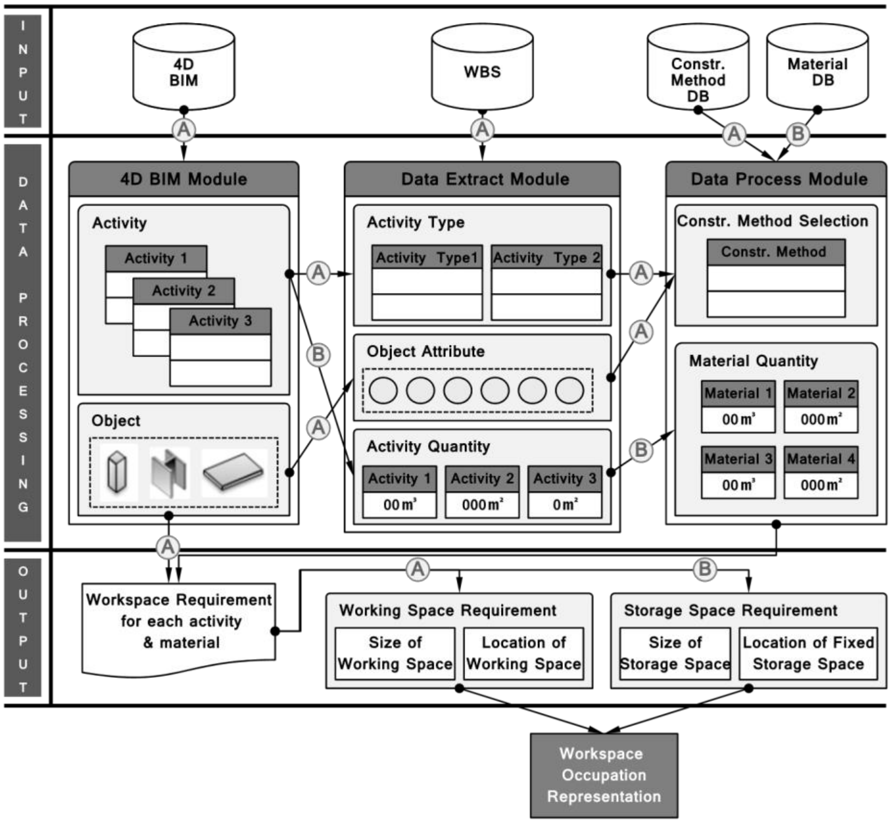


Fig. 4. Work-space requirement identification

4D BIM Generation

The first task for work-space planning is to generate a 4D BIM for a project. A 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. 2008; National Institute of Building Sciences (NIBS) 2013]. Each object in BIM is defined by parameters and relationships between parameters that determine geometric and additional properties of the object. As described in Fig. 3, 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 work-space changes in accordance with the construction process. To represent the status of work-space occupation and to identify work space–related problems, this study utilized information about activity schedule, object quantity, and the geometric properties of the project that were contained in 4D BIM.

Work-Space Requirement Identification

The work-space requirement identification phase is a process to identify the entire working and storage-space requirements for the execution of a specific activity. The detailed process for this phase is shown in Fig. 4.

The construction method and material information databases are necessary for work-space 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 database includes information about the physical features of each material, as well as the quantitative relationship between activities and materials. To widen the application of the suggested framework, this study builds a construction method database (DB) and material information DB for typical finish activities in the construction project. For example, this study defines typical construction methods for wall finish activities (i.e., standing work, work platform, rolling scaffolding, scissor lift, suspended platform, and aerial work platform). However, in the case of a project-specific construction method or material, a project manager should define the information about those elements according to the established database structure.

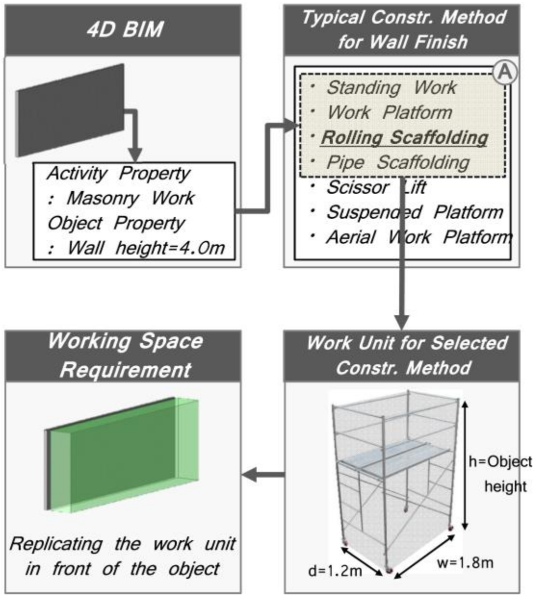


Fig. 5. Example of masonry activity working space identification

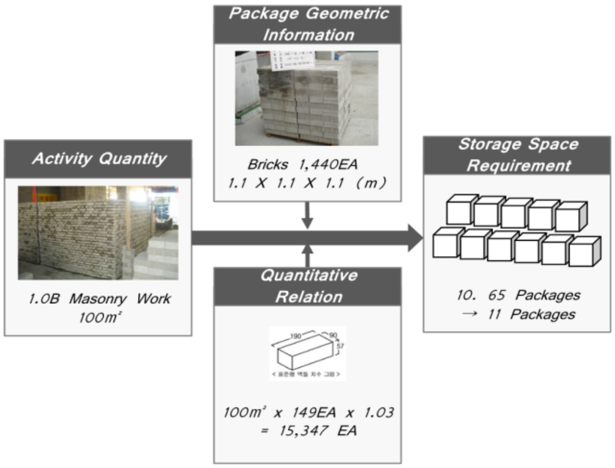


Fig. 6. Example of brick material storage space identification

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 candidate 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 Fig. 4). Akinci et al. (2002a) suggested a method to generate the work space for each object using the spatial relationship between an object and the work space, presented in the form of a transformation matrix. Based on this method, the whole requirement of working space for each activity could be identified. Fig. 5 describes the detailed process of work-space requirement identification for a masonry work activity example. An object in 4D BIM contains activity properties and physical properties of the object. The activity property (masonry work) identifies the construction method's candidates (A in Fig. 5), and physical property (wall height ¼ 4.0 m) determines the definitive construction method. The rolling scaffolding is selected among the construction method's candidates for the masonry work because the height of the wall object associated with the activity is more than 3.0 m but less than 5.0 m; thus, the working space requirement of the activity is identified by repeating the unit work space for the rolling scaffolding work to all of the wall objects. 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

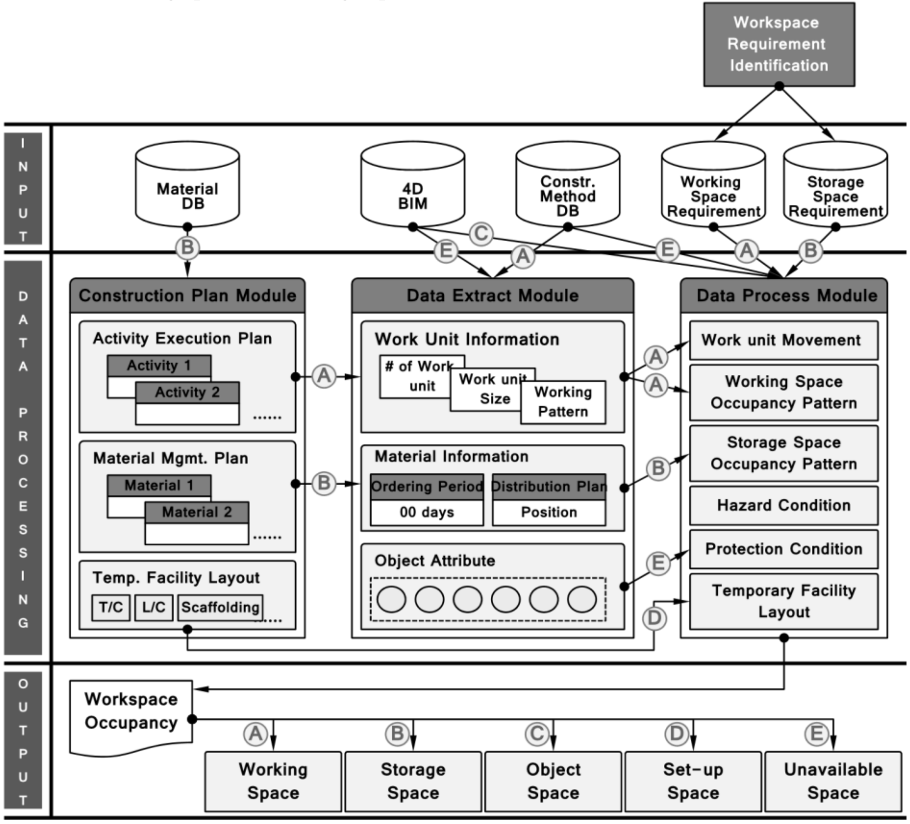


Fig. 7. Work-space occupation representation

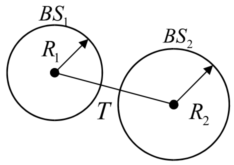
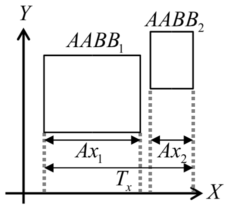
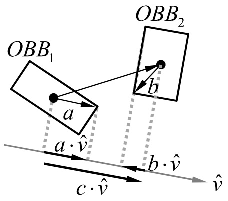
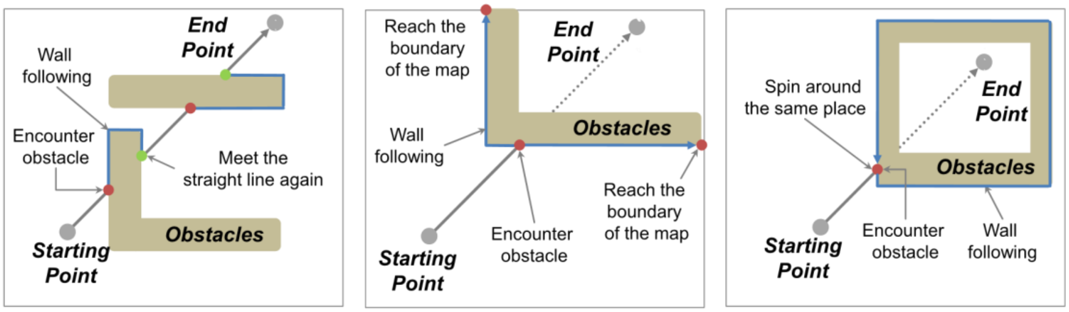
	Bounding Sphere	Axis-Aligned Bounding Box	Oriented Bounding Box
Diagram			
Collision Condition	$T < R_1 + R_2$	$T_x < Ax_1 + Ax_2$	$c \cdot \hat{v} < a \cdot \hat{v} + b \cdot \hat{v}$

Fig. 8. Spatial collision detection algorithm



Path Available **Path Not Available** **Path Not Available**

Fig. 9. Wall follower algorithm

Work-Space Occupation Representation

Work-space occupation representation is a phase that describes the state of the work-space utilization for all types of work space by reflecting the construction plan, such as activity execution plan and material management plan. The detailed process of this stage is delineated in Fig. 7.

An activity execution plan is a detailed plan for achieving each activity's schedule in an activity level. It determines the number of crews for each activity and each crew's execution pattern in a construction site. This study adopts Riley and Sanvido's (1995) workspace pattern analysis to define the activity execution pattern of each work unit. The material management plan is aimed at providing the necessary materials for workers when an activity should be performed, including purchasing work, supply planning, and how to handle materials at a construction site. To represent the workspace 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 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 Fig. 7).

The state of the storage space occupied by each material is determined by the order interval of each material and material allocation plan. A material allocation plan is a part of the material management plan that decides how many subunits it will divide the delivered materials into and how it will lay out those units. First, the total size of the storage space occupation for each material during one order interval is calculated by dividing the total size of the storage space requirement by the number orders for each material. The number orders for each material can be calculated by dividing the total duration of the corresponding activity by the order interval of each material. Then, the location and size of the storage space occupation for delivered materials are represented by referring to the manager's material allocation plan. In the case of fixed storage, location is determined using a predefined spatial relationship between storage space and working space (B in Fig. 7).

Table 3. Detail Criteria for Minimum Size of Path Space

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

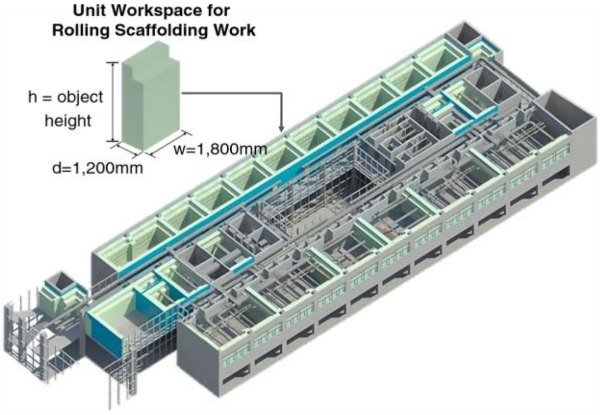


Fig. 10. Work-space requirement identification for drywall framework

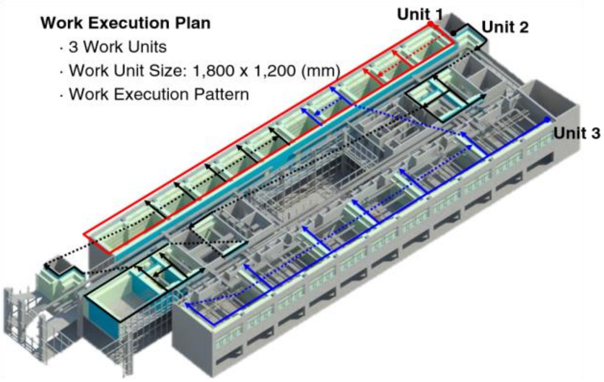


Fig. 11. Activity execution plan for drywall framework

Object space occupation would be perceived by the result of 4D BIM simulation (C in Fig. 7), and the location and size of the setup space are determined using the project manager’s site layout (D in Fig. 7). Finally, unavailable space is represented using a spatial relationship 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 Fig. 7).

Work-Space Problem Identification

In this study, the work-space problem is defined as a situation when the work space 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 work space because of obstructions created by other work spaces. Therefore, the workspace problem identification should include detecting not only work-space 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 interference 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 Fig. 8. BS identifies a spatial collision by comparing the sum of two bounding spheres’ radii and the distance between the centers of two spheres (Talmaki and Kamat 2012). AABB detects a spatial collision by comparing the minimum and maximum coordinate 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). AABB is much simpler spatial collision detecting method than OBB because AABB needs six times of comparison calculation, whereas OBB requires 15 times to detect spatial conflicts. However, OBB is able to detect conflicts more precisely than AABB if the object in the model is complicated or rotated (Tu and Yu 2009). 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 irregularshaped building project, which contains numerous atypical objects.

In this study, path analysis is defined as a process investigating whether or not available path space for all the resources at a construction site exists. 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 Fig. 9, 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).

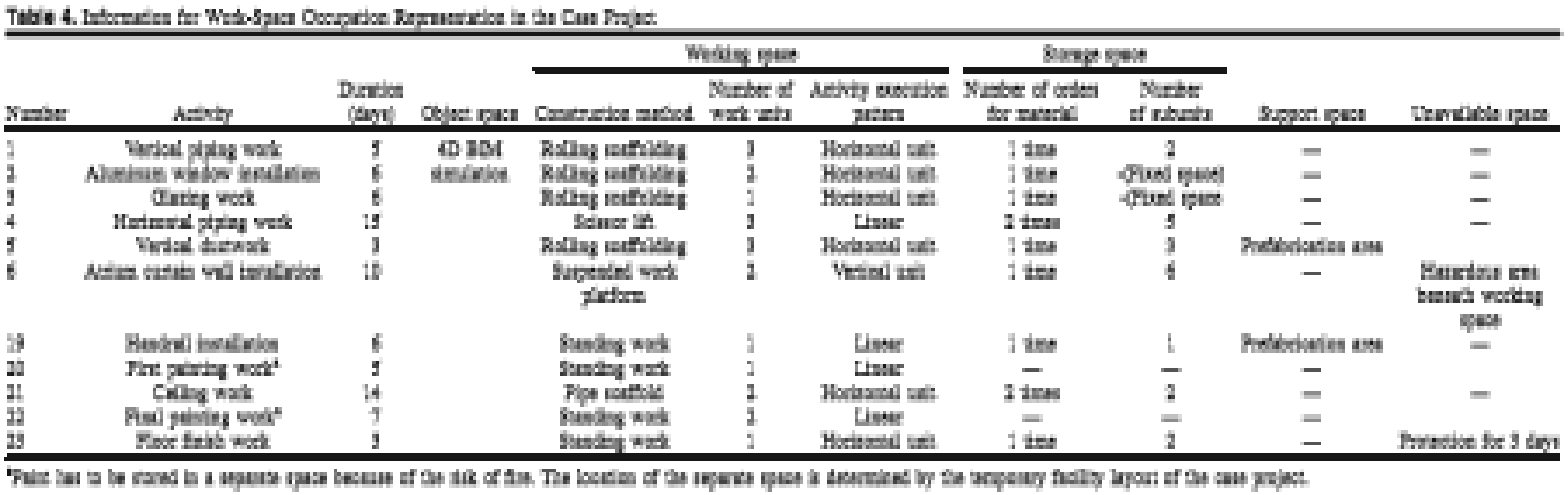


Table 4. Information for Work-Space Occupation Representation in the Case Project

				Working space			Storage space			
Number	Activity	Duration (days)	Object space	Construction method	Number of work units	Activity execution pattern	Number of orders for material	Number of subunits	Support space	Unavailable space
1	Vertical piping work	5	4D BIM simulation	Rolling scaffolding	3	Horizontal unit	1 time	2	—	—
2	Aluminum window installation	6		Rolling scaffolding	2	Horizontal unit	1 time	-(Fixed space)	—	—
3	Glazing work	6		Rolling scaffolding	1	Horizontal unit	1 time	-(Fixed space	—	—
4	Horizontal piping work	15		Scissor lift	3	Linear	2 times	5	—	—
5	Vertical ductwork	3		Rolling scaffolding	3	Horizontal unit	1 time	3	Prefabrication area	
6	Atrium curtain wall installation	10		Suspended work platform	2	Vertical unit	1 time	6	—	Hazardous area beneath working space
19	Handrail installation	6		Standing work	1	Linear	1 time	1	Prefabrication area	—
20	First painting work[a]	5		Standing work	1	Linear	—	—	—	
21	Ceiling work	14		Pipe scaffold	2	Horizontal unit	2 times	2	—	—
22	Final painting work[a]	7		Standing work	2	Linear	—	—	—	
23	Floor finish work	3		Standing work	1	Horizontal unit	1 time	2	—	Protection for 3 days

[a] Paint has to be stored in a separate space because of the risk of fire. The location of the separate space is determined by the temporary facility layout of the case project.

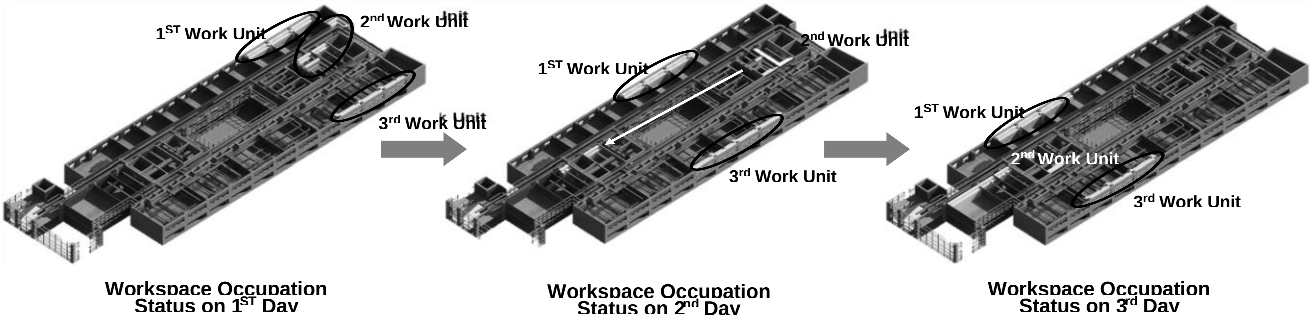


Fig. 12. Work-space occupation representation for drywall framework

Because 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 working space; (3) a material allocation 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 3.

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

Work-Space Problem Resolution

In the work-space problem resolution phase, pertinent strategies are devised for the identified work-space problems by considering characteristics of an activity, work space, and construction plans. In other words, the project manager should consider the movability of the work space, the criticality of any activity, the activity execution plan, and the material management plan to resolve the workspace problems by the following:

1. Change the location of flexible work space: If there is a flexible work space among conflicted work spaces, the work-space problem could be resolved by changing the work-space location. When determining the location of the changed work space, the project manager should consider not only the location of the conflicted work space but also the location of other work spaces that are occupied by other activities at the same time. Moreover, the relocation of the path space resulting from the applied strategy has to be considered to prevent secondary work-space problems.
2. Change the schedule plan for noncritical activity: In the case inwhich every conflicted work space is a fixed work space, the work-space problems could be resolved by deferring a start date or changing the duration of the noncritical activity among the problematic activities. In order not to affect the total duration of the project, the schedule change for noncritical 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 executionplan and the material management plan are factors that determine the final status of work-space utilization in the workspace occupation representation phase. Therefore, the project manager can change the location of the working space and the related indirect work space through the modification of the activity execution pattern. Moreover, a work-space problem could be solved by revising the material management 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 work-spaceproblem that cannot be resolved by Steps 1–3 is resolved by changing a schedule plan for a critical activity. Changing the schedule plan for the critical activity may cause a project delay, it can prevent further damages caused by negative project

managementissues—such as unnecessary rework, safety hazard, and issues ofpoor quality—owing to theinterference of thework space. When changing the schedule plan for critical activities, the project manager should examine whether or not the critical path is changed because of the changed schedule plan.

5. Change the activity logic: Some work-space problems between object space and fixed work space may not be resolved by Steps 1–4. This type of work space problem occurs when the project manager fails to consider the work space for an activity when determining the activity sequence. Therefore, this type of work-space problem could be prevented by changing an activity-performing logic with the consideration of the work space for the activity.
6. Validation of selected resolution strategy: Finally, the validation of the selected work space–problem resolution strategy from the preceding process is examined by again inputting the strategy into the work-space planning process. In this process, the project manager can confirm the validity of the selected strategy through the identification of secondary workspace problems by the selected strategy.

Case Study

A research building construction project at Seoul National University in South Korea was examined to validate the proposed framework in this study. The case project was a one-floor finish work of the 1,850-m^2 floor building; this project was to take 90 days and be composed of 23 activities, including vertical piping and finishing. First, 4D BIM was generated with the combination of 3D BIM and an initial construction schedule.

A required work space 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 work-space requirement because most objects in the case project were located parallel to the project’s local axes in a box shape. Fig. 10 explains an example of the work-space identification for a drywall framework activity. The rolling scaffolding was determined as a construction method for framing drywall. The entire work-space requirement of the drywall framework activity was identified by replicating the unit work space for a rolling scaffolding work to all of the associated objects, as described in Fig. 10.

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 Fig. 11. The size of each work unit was the same as the one for the rolling scaffolding (1,800 × 1,200 mm). Based on this process, a daily occupation status of working space for the activity could be represented as Fig. 12.

Through the process from 4D BIM generation to work-space occupation representation as explained with the example of drywall framework activity, the work-space occupation status for all 23 activities could be represented. Table 4 shows the detailed information on work-space occupation representation for several activities of the case project.

After representing the work-space occupation for all activities, possible work-space problems could be identified using spatial collision detection and path analysis. For example, Fig. 13 displays the spatial conflict between the working spaces for drywall framework activity and object space for cable tray. This work-space problem 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 resulting from work-space interferences.

A total of 37 work space problems were identified by spatial collision detection (31 problems) and path analysis (six problems) from the case study, and Table 5 summarizes a part of the identified work-space problems. The correct location of a work-space problem was perceived by the values in the work-space problem location information boxes in Table 5, which indicates the maximum and minimum x-, y-, and z-coordinate values for the conflicted rectangular space identified by the AABB algorithm. This study improves the precision of work-space problem identification by including six more work-space problems by path analysis. Moreover, this study also improves the accuracy of work-space problem identification by removing 40 unrealistic work-space problems in the case project. For example, among plastering work and drywall finish work, which overlap for 6 days in a schedule plan, 17 workspace conflicts were detected based on the work-space requirement concept. However, 13 of those conflicts are eliminated by workspace occupation representation suggested in this study. This implies that the plastering work and the drywall finish work use the same 13 spaces on different dates although both activities are concurrently executed. In addition, this study completes work-space problem identification by adding one more work-space conflict identified by path analysis.

Work-space conflicts between object space and working space most frequently occur (22 times) among total 37 work-space problems. The working space for a construction activity is frequently interrupted by the object space for an MEP activity, implying that the lack of communication between managers in different areas leads to an inappropriate work-space plan. In addition, the characteristic of the case project —research facility requires more MEP systems than common buildings—also affects this result. However, work-space problems related to unavailable space and setup space do not occur in the case project. This is because one-floor finish work requires relatively little unavailable space and setup space.

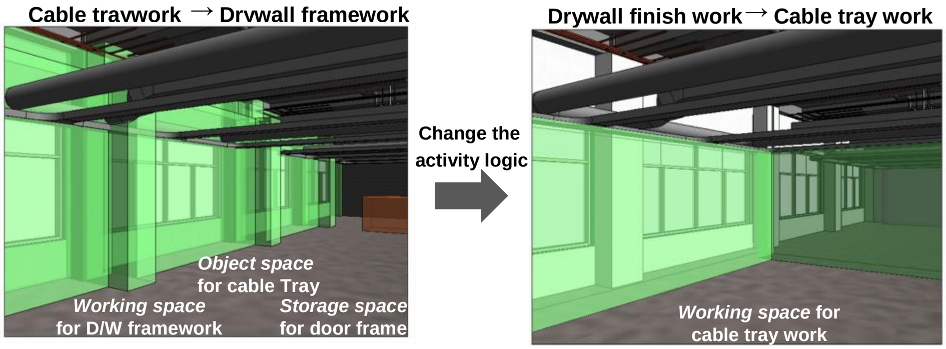


Fig. 13. Work-space problem identification and resolution example

Table 6. Result of Work-Space Problem Resolution in the Case Study

Work-space problem resolution strategy	Number	Rank
Change the location of flexible work space	3	3
Change the schedule plan for noncritical activity	2	4
Change the activity construction plan	15	2
Change the schedule plan for critical activity	—	5
Change the activity logic	17	1

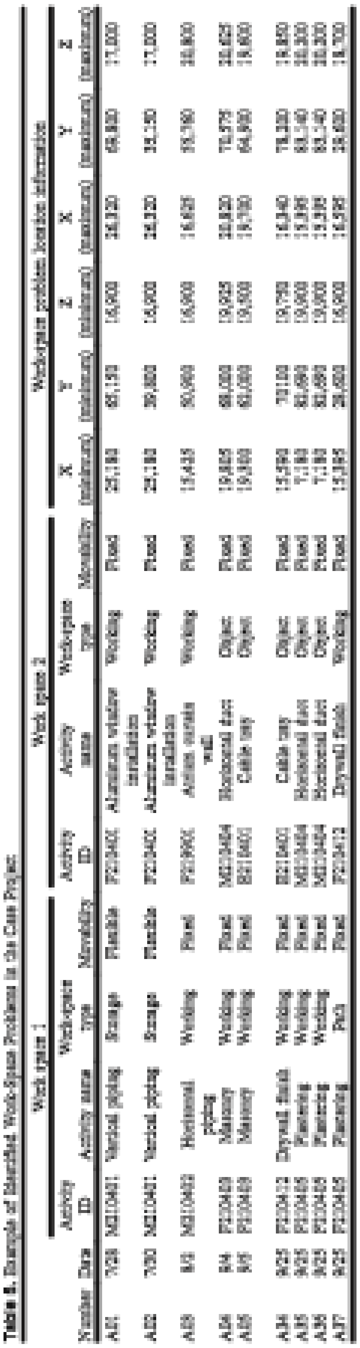


Table 5. Example of Identified Work-Space Problems in the Case Project

		Work space 1				Work space 2				Work-space problem location information					
Number	Date	Activity ID	Activity name	Work-space type	Movability	Activity ID	Activity name	Work-space type	Movability	X (minimum)	Y (minimum)	Z (minimum)	X (maximum)	Y (maximum)	Z (maximum)
A01	7/28	M210401	Vertical piping	Storage	Flexible	F210402	Aluminum window installation	Working	Fixed	25,180	65,150	16,900	26,320	69,800	17,000
A02	7/30	M210401	Vertical piping	Storage	Flexible	F210402	Aluminum window installation	Working	Fixed	25,180	39,800	16,900	26,320	35,150	17,000
A03	8/1	M210402	Horizontal piping	Working	Fixed	F219902	Atrium curtain wall	Working	Fixed	15,425	50,900	16,900	16,625	55,760	20,800
A04	8/4	F210409	Masonry	Working	Fixed	M210404	Horizontal duct	Object	Fixed	19,805	68,000	19,925	20,820	70,575	20,625
A05	8/5	F210409	Masonry	Working	Fixed	E210401	Cable tray	Object	Fixed	19,300	63,000	19,500	19,700	64,900	19,600
A34	9/25	F210412	Drywall finish	Working	Fixed	E210401	Cable tray	Object	Fixed	15,590	70100	19,750	16,340	78,200	19,850
A35	9/25	F210405	Plastering	Working	Fixed	M210404	Horizontal duct	Object	Fixed	7,180	81,690	19,900	15,395	83,140	20,200
A36	9/25	F210405	Plastering	Working	Fixed	M210404	Horizontal duct	Object	Fixed	7,180	81,690	19,900	15,395	83,140	20,200
A37	9/25	F210405	Plastering	Path	Fixed	F210412	Drywall finish	Working	Fixed	15,395	28,600	16,900	16,595	29,600	18,700

Identified work-space problems were resolved by changing the location of storage space for plastering work and vertical piping work (changing the location of flexible work space), delaying the start date of the cold-room panel installation (changing the schedule plan for noncritical 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). Table 6 presents how many times each strategy was applied to solve the identified work-space problems in the case project. Changing the activity logic strategy is the most frequently adopted solution for the work-space problems in the case project (17 times). This implies that work space has to be considered from the early stage of scheduling that determines the sequence of the activities. In addition, changing the activity construction plan is the second frequent work-space problem resolution strategy in the case project (15 times). This means that sharing work information with other activities before starting can be effective in preventing potential work-space problems in a construction project.

The revised schedule plan by the aforementioned work space– problem resolution strategies indicated a schedule delay because of a productivity decrease and other problems, implying that the project manager failed to properly consider work space for activity execution during the scheduling of the project. To complete the project without work-space problems, the project manager therefore this case project, the project manager planned to implement the crashing strategy, which is a technique adding additional resources to a critical path activity to catch up when there is a schedule delay, for one of the critical activities—ceiling work. Although this crashing plan was expected to decrease unit productivity resulting from additional resource input, it contributed to the improvement of the project performance by reducing the uncertainty of the project by preventing the work-space problems.

Conclusions

This study suggested a framework for work-space planning process in a 4D BIM environment that integrates the characteristics of activity, work space, and construction plan. From the case study, possible work-space problems were successfully identified and the appropriate resolution strategy for each work-space problem was suggested. The developed framework in this study improved the accuracy of work-space status prediction and work-space problem identification by introducing the work-space occupation concept.

The developed framework for the work-space planning process in this study can help the project manager prepare construction plans that are free of work-space problems. A construction plan that considers work space can help avoid severe problems—such as rework, a decrease in productivity, safety hazards, and issues of poor quality—all of which are caused by work-space problems. In addition, this study's 4D BIM–based approach for work-space 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.

The framework can also contribute to an effective work-space planning process by using a work-space occupation representation method that considers construction plan, characteristics of workspace types, and activity. Moreover, this study can be helpful in ameliorating the work-space planning process by including the path analysis process that has been overlooked in most of the previous studies. Finally, the study can contribute to completing the holistic perspective of work-space planning process by establishing a formalized work-space problem resolution process.

Despite these advantages, this study identified some limitations of the proposed approach. If there is no abundant data source— such as construction method DB and material information DB—enormous effort is required to prepare the input data. Also, generating the construction process reflecting BIM, which is crucial for the suggested framework, requires much effort. Future research will eventually address these limitations and help improve the construction planning process.

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