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A NARRATIVE REVIEW OF WORKSPACE PLANNING IN CONSTRUCTION: CHALLENGES AND INSIGHTS

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ABSTRACT

Space on construction sites is not abundant as may be thought. In fact, workspace planning could become increasingly challenging at times. Moreover, improper workspace planning may lead to congestion and, hence, potential safety and productivity issues. Workspace planning aligns with Lean thinking through reducing wastes in workers' productivity, waiting time, double handling, and different types of flow. Meanwhile, there is generally a scarcity of research studies in this area especially in industrial projects. As such, this paper presents a narrative literature review of research conducted on workspace planning in construction. Specifically, the review aims to answer the following questions: What is a workspace? What are some methods used for workspace planning? What are the challenges faced in workspace planning? What decisions are essential for workspace planning? The last question tackles fundamental concepts in workspace planning such as flow types, area patterns, workspace classification structure, and spatial-temporal conflict identification and resolution. The study concludes with considerations to be scrutinized and adopted during the process of developing a well-thought-off workspace planning system.

KEYWORDS

Workspace, planning, spatial-temporal conflict, flow, area.

INTRODUCTION

Generally, evaluating space requirements and positioning construction operations to predetermined locations on site are often left until the project starts. It may be believed that space is abundant in a way that eliminates the need for prior planning; however, this is a fallacy. Proper workspace planning is necessary to avoid needless material handling, prevent spatial-temporal conflicts, and reduce travel times (Tommelein & Zouein, 1993). A workspace is a shared resource among all participants on a project, and every person on a construction project needs a separate workspace to carry out their tasks. Accordingly, improper workspace planning might lead to interferences between different crews, creating congestion that results in safety and productivity issues (Hammad & Zhang, 2011; Mallasi, 2006). Workspace management aims to ensure that workspace demand and availability match, thereby avoiding spatial conflict (Igwe et al., 2020).

However, the available scheduling methods have proved to be less sufficient for workspace planning because they neglect the spatial feature of each task. For instance, the Line-of-Balance

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(LOB) method considers that only a single crew can occupy each work zone at once, and it treats the space as a scalar one-dimensional variable, which omits substantial complexity faced when managing 3D space (Choi et al., 2014). This complexity could explain why researchers have replaced 2D sketches and 2D computer-aided design models used for workspace analysis (e.g., Zouein & Tommelein, 2001, Guo, 2002) with 4D and 5D BIM models that better represent the actual complexity of the real workspace (e.g., Chavada et al., 2012; Moon et al., 2014; Rohani et al., 2018). However, most of the existing 4D (3D + time) simulations are static where objects are generated in the simulation at discrete points in time, such as at task start point. Still, in reality, construction is dynamic, and the products appear progressively as they are built (Heesom et al., 2003). Moreover, a construction activity might require more than one workspace of varying geometry throughout different stages (Su & Cai, 2014). Thus, the construction workspace constantly changes, but such change is poorly assessed in current literature, especially for industrial projects (Bannier et al., 2016). For a workspace modelling approach to be effective, it needs to convey the actual workspace usage accurately and flexibly. Although a variety of 4D simulation models allowing full navigation through the model across time is available in the market, none of them adequately supports the scheduler during schedule preparation. These models primarily focus on visualizing the already completed schedules (Tulke et al., 2008). Additionally, spatial-temporal conflicts can be prevented through employing rules to control the movement of workers, equipment, and material. However, developing the rules that govern how the cells behave is difficult, particularly when there are many rules (Hammad & Zhang, 2011).

In short, workspace planning is complex in nature and entails a variety of decisions that are contingent on the distinct requirements of each workspace. Specifically, evaluating the initial requirements of and the continuous spatial-temporal change in the location and dimension of each workspace (i.e., through time and across all three dimensions) could be a major challenge in workspace planning. Meanwhile, there is generally a scarcity of academic research, especially in industrial projects (Bannier et al., 2016), that provides detailed analyses of workspace requirements, dynamic behaviours of workspaces, and impacts of different tasks on a workspace. As such, this paper presents a narrative literature review of research conducted on workspace planning in construction. A narrative literature review intends to "assemble and synthesize extant literature and provide readers with a comprehensive report on the current state of knowledge in the area under investigation" (Templier & Paré, 2015). In this context, this study first presents the definition of workspaces in construction, a brief review of some existing workspace planning methods, a description of some of the challenges encountered in workspace planning, and then highlights a set of considerations that must be accounted for in construction workspace planning.

METHODOLOGY

This study followed a review procedure similar to the six-step procedure proposed by Templier & Paré (2015) for conducting literature reviews, which includes (1) formulating the problem, (2) searching the literature, (3) screening for inclusion, (4) assessing quality, (5) extracting data, and (6) analysing and synthesizing data. It should be noted that the quality assessment of the studies was limited to their relevance to the defined problem, their clarity, and their contribution to the body of literature found on the topic. As such, the research design and methods used in the studies were not evaluated. Moreover, given the limited size of research conducted on workspace planning in construction, the initially formulated problem in Step 1 was aimed to identify studies generally conducted on workspace planning in construction. The next step consisted of conducting an initial search for relevant studies published in reputable journals (e.g., *Automation in Construction*, *Journal of Construction Engineering and Management,* etc.) in order to determine significant research areas on the topic. Upon completing this initial search and screening the full texts of the identified studies, Step 1 was revisited to formulate more specific research questions in order to better direct the search process. As such, the following questions were formulated: *What is a workspace? What are some methods used for workspace planning? What are the challenges faced in workspace planning? What decisions or considerations are essential for workspace planning?* Next, for each question, the literature was searched for relevant studies (Step 2), and the studies were screened for data pertinent to the question of interest (Steps 3, 4, and 5). Finally, the data extracted for each question was synthesized to provide a summary that helps the reader understand the current state of knowledge on the topic (Step 6).

DEFINITION OF WORKSPACE

Construction crews need space to execute work and to move, fabricate, and store materials. They typically occupy space for predefined time intervals and move through the site in various patterns based on the type of their work and the material involved. Workspace is the 3D physical space needed to cater for a resource, characterized by its shape and volume, and governed by material quantities, dimensions, shape, and stacking ability (Riely & Sanvido, 1995; Riley & Sanvido, 1997). The common practice is to represent a workspace by a 3D bounding volume which can take different forms such as a bounding box, a bounding sphere, an oriented bounding box, an axis aligned bounding box (Choi et al., 2014), a rectangular box (Dashti et al., 2021), or a cylinder (Rohani et al., 2018). Another practice is the cell representation where the site layout is represented by a grid of numerous interconnected cells; this representation is mainly used for moveability analysis (Wang et al., 2019). A work envelope is defined as a 3D space volume enclosing a building component, and allowing a construction worker to be there and perform a construction task on this component, along with corresponding equipment and material (Bannier et al., 2016). Rohani et al. (2018) consider a transparent cylinder with a base area of 3.14 m^2 and a volume of 5.5 m^3 for representing the workspace needed by a static man-hour. Moreover, research has constantly revealed that productivity decreases when the threshold of one worker occupying 28 m^2 is crossed (Riley & Sanvido, 1997) . Su and Cai (2014) distinguish between two aspects to consider in workspace planning, namely workspace structure and the method of geometric modelling. The workspace structure determines the way the workspaces are arranged to correctly represent a construction task and the way they are managed for project participants to access the required information. As for the method of geometric modelling, it indicates how to generate workspace geometries.

OVERVIEW OF WORKSPACE PLANNING METHODS

Tommelein and Zouein (1993) presented MovePlan as a 2D interactive dynamic layout planning model. It is a construction schedule augmented with data required to establish layouts, such as resources and their dimensions, and which positions temporary facilities and movement of material and equipment on site. The model output can be additionally refined by integrating geometric detail and advanced graphical packages. Akinci et al. (2002) presented a mechanism for automating the process of generating workspaces and creating a space-loaded production system. Superintendents were asked to describe the workspaces needed generally based on the construction method they are intending to use. Such generic descriptions address the size and position of every workspace qualitatively as being oriented with reference to an object. Dawood et al. (2005) developed the virtual construction site (VIRCON) as a set of assisting tools for project planners to do informed and accurate planning decisions when allocating activities' execution spaces. However, several limitations were noted with the developed system, such as lack of visual representation of spatial overload simultaneously with the project plan, difficulty in allocating space, not being user friendly, and need for manual optimization. Spatial overload occurs when the aggregated space demand matches or exceeds available space.

Su and Cai (2014) tackled workspace planning and modelling via a life-cycle approach. The study investigated workspace evolution patterns through an object-oriented data structure. Different life cycle stages of a task are identified along with corresponding needed workspaces which are then arranged into sequences. The developed model proved to be more accurate than models with single workspace representation. Moradi et al. (2015) developed a 4D-BIM system to dynamically detect spatial-temporal conflicts and quantify the corresponding impact on project performance. A workspace is generated and assigned by identifying four parameters which are orientation, width offset, length offset, and extension value. The proposed model allows more accurate detection of conflicts and determination of conflict severity. Kumar and Cheng (2015) presented a framework that makes use of BIM in creating dynamic layout models for construction sites. This is done through estimating the dimensions, size, and number of interim facilities needed at various stages of construction. Their results show through a demonstrative example that the developed model could achieve 13.5% reduction in travel distance as compared to traditional methods. Bannier et al. (2016) presented a framework for integrating information pertaining to work envelope needs among the steel and piping trades in order to support space planners during preconstruction phase. Superintendents on industrial projects were interviewed to define conventional work envelopes. Their results showed that the anthropomorphic characteristics of a population considerably affects work envelope requirements. Mirzaei et al. (2018) presented a 4D BIM model that dynamically detects and quantifies spatial temporal conflicts and their effect on project performance. The crew movement is taken into consideration by simulating four different execution patterns with four distinct starting points. Workspace planning is also looked at from a safety perspective. For instance, Choe and Leite (2017) developed a 4D planning process for construction safety that considers site-specific spatial and temporal information. Their findings revealed that risky zones, activities, and days could be prioritized when information relating to number of workers, occupation type, and zoning plan is included in project schedule.

All that being said, workspace planning studies mainly address building construction and are scarce for industrial construction.

CHALLENGES WITH WORKSPACE MODELLING

Dynamic workspace modelling is faced by two major challenges during construction planning, which are modelling the workspace's geometry and capturing its accurate dynamics. The term "workspace dynamics" simply refers to the dynamics occurring from change in geometry to position of workspaces across time. Since an activity can occur at different locations throughout different stages, one workspace falls short of representing such progressive series of workspaces. Moreover, each task impacts the workspace differently. For instance, a slab construction task increases the floor area as construction progresses, whereas a drywall construction task divides or partitions the existing space into reduced units (Riely & Sanvido, 1995). Commonly, actual workspace variations go unnoticed in planning and even in control (Wu & Guo, 2014). Figure 1 illustrates an example based on Riely and Sanvido (1995) of how a construction site constantly changes with time. Beginning at time t, no construction work takes place. After a while at time $t1 > t$, a slab construction task is in place. Further ahead at time $t2 > t1$, masonry works take place which encloses the space and reduces access. Finally, at time $t3 > t2$, drywall installation task occurs, altering the site layout. Failing to consider the dynamic progression of workspaces reflects negatively on planning as it may yield imprecise information to planners (Su & Cai, 2014). Another challenge is that generally, people who are given the task of space planning, such as field engineers or superintendents, might lack the skill and knowledge of assessing the precise geometric parameters of workspace needed by each task. Especially in industrial projects, academia efforts pertaining to identifying and representing the piping activities' workspaces are scarce (Bannier et al., 2016). In other words, research focusing on extracting and translating the semantic information relating to workspaces from superintendents is still behind.

Poor space planning will eventually lead to overlaps in workspaces among various trades and to workspace clashes, resulting in potential safety hazards and congestion that impacts productivity and creates waste (Hammad & Zhang, 2011; Mallasi, 2006). Research showed that congested workspaces suffer losses in productivity amounting to 65% and delay in project duration reaching 30% (Hosny et al., 2020). Moreover, people not abiding by the workspace allocated for them creates issues. For instance, at times, project participants such as individual subcontractors set up their temporary storage areas, causing obstructions to other subcontractors. Another example of bad practices is leaving shelves and other products in space and having to relocate them several times which adds to transport and waiting times (Binninger et al., 2018).

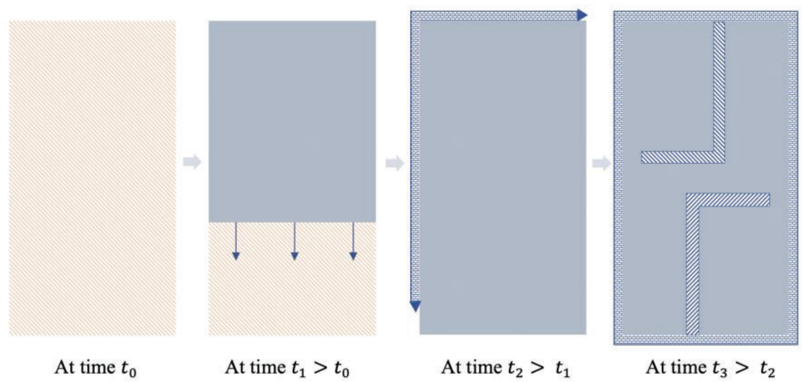

Figure 1: Evolution of workspace with time

FINDINGS: COMPONENTS OF WORKSPACE PLANNING

This section presents the main components required, but not exclusively, to formulate a workspace planning system as found in the literature. The first sub-section lists the different flow types in construction, followed by discussions on area patterns, workspace classification structure, conflict identification, and finally conflict resolution studies.

FLOW TYPES

When modelling workspaces on construction sites, it is integral to first identify all the entities that may occupy or "flow" within the workspace at any point in time. The verb "to flow" herein means "to move freely and continuously" as per the definition quoted by Kalsaas & Bolviken, (2010) and later adopted by Tommelein et al. (2022). Tommelein et al. (2022) distinguishes different types of flows in construction as depicted in Figure . Most studies focus on workflow, worker flow, and trade flow (Hosny et al., 2020; Kassem et al., 2015; Mallasi, 2006; Moon et al., 2014; Rohani et al., 2018; Su & Cai, 2014). A less number of studies considers additionally material, equipment, and tool flows (Choi et al., 2014; Dawood et al., 2005; Guo, 2002). As for the remaining flow types, they are mostly disregarded. Generally, each flow type gives rise to a specific pattern for workspaces, prefabrication areas, storage areas, and product space areas which are explained in the following sub-section. Also, each flow type might need specific workspaces. A workspace classification structure in presented in the sub-section following the area patterns.

AREA PATTERNS

Space behaviour patterns refer to the way a crew typically moves in a space across time to execute work elements. Such behaviour must be modelled to identify the links between tasks with distinct patterns and to forecast the workspace needed for task work elements. Riely and

Sanvido (1995) distinguished between four area patterns which are work area, prefabrication area, storage area, and product space patterns.

A work area pattern refers to the directions and locations where different work units are achieved for various tasks and materials. An example is following a linear pattern to perform ductwork and install conduit. A prefabrication area pattern describes positions of prefabrication areas on site that are needed for different tasks or types of material. An example of such an area pattern is having one prefabrication area per floor for conduit assemblies. A storage area pattern refers to locations where material is kept from the time it is delivered until the time it is used. An example is having bulk storage where material is stored in a single location per floor, then distributed to work areas as required. Finally, product space pattern describes the impact that completed work will have on the existing space for upcoming tasks. An example pattern is creating space for following activities such as slab construction. A direct impact is when work resulting from a task directly conflicts with space required by other tasks, generating thereby sequential dependencies between the tasks. If a task is completed without putting into place material that directly impacts the available space for upcoming activities, then the result is no impact (Riely & Sanvido, 1995).

Figure 2: Flow types in construction based on Tommelein et al. (2022)

WORKSPACE CLASSIFICATION STRUCTURE AND GENERATION PROCESS

Understanding the structure and function of a workspace is crucial for proper workspace modelling. Table 1 is compiled based on a study by Choi et al. (2014); it provides a workspace classification structure that can be used in formulating a workspace modelling system. A workspace can be classified as direct or indirect based on its function. For instance, a workspace is said to be direct when it is associated in a direct way with activity execution such as workspace for installing a window. Object space (product), working space (working, tool and equipment), and storage space (staging) are classified as direct workspaces. An indirect workspace is either indirectly related to the execution of an activity or is needed for execution of several activities such as a corridor for personnel path. Unavailable space (hazard, protected), set-up space (unloading, layout, prefabrication), and path space (debris, personnel, material) are all indirect spaces. Furthermore, a workspace is categorized based on its moveability which can be fixed like window installation workspace or flexible like storage areas. Various considerations play a role in determining the size and location of a workspace; such considerations include the components' geometric features, construction method, management plan, facility layout, etc. Finally, workspace generation and expiration follow certain rules as Table 1 shows. Generally, generating a workspace requires three steps. The first step is to determine a task necessary for constructing an element or product. The second step consists of identifying individual workspaces required in each stage of the task's life cycle. The third step calls for associating the identified workspaces with the product or element (Su & Cai, 2014). By assigning precedence relationships between the generated workspaces, a standardized sequence of workspaces can be attributed to each construction task.

Table 1: Workspace classification structure based on Choi et al. (2014)

Type	Function	Movability	Size & Location	Generation	Expiration
Direct space	*Object Space:* Product	Fixed	Determined by components' geometric features	At activity's starting point of activity	Until completion of project
	Working space: Working Tool, equipment	Fixed	Determined by construction method definition of spatial relationship with object	At activity's starting point	At activity's ending point
	Storage space: Staging	Fixed or flexible	Size determined by material's quantity and geometric features, Location determined by material management plan	At activity's starting point	At activity's ending point
Indirect space	*Unavailable space:* Hazard Protected	Fixed	Determined by protection condition of object and construction method's definition of hazardous condition	Preserved through activity duration or protection duration controlled by feature of object protected	
	Set-up space: Unloading Layout Prefabrication	Fixed or flexible	Determined by temporary layout of facility	At activity's starting point	At activity's ending point
	Path space: Debris path Personnel path Material path	Fixed or flexible	Min height and width of path determined by activity's construction method and material's geometric features	During duration of activity	

SPATIAL-TEMPORAL CONFLICT IDENTIFICATION AND EVALUATION

When a workspace overlaps with another or more during construction, a dynamic short-term clash called a spatial-temporal clash occurs. Site planning, project features, management concerns, logistic and resources, and external environment are all categories of potential reasons causing workspace conflicts (Hosny et al., 2018). A variety of tools are proposed in the literature to detect and evaluate spatial-temporal conflicts as summarized in Table 2. The early research used sketches to visualize conflicts. With the advancement in CAD systems and virtual reality modelling, conflict visualization became easier, and more aspects were added to the analysis such as cost. A conflict is mainly evaluated with respect to its severity which is calculated by assessing overlapping areas ratios, overlapping durations ratios, required and available spaces ratios, etc.

Table 2: Conflict visualization and evaluation

Study	Tools for visualization	Conflict Evaluation
(Zouein & Tommelein, 2001)	Sketch	-
(Guo, 2002)	2D CAD	$ISP^4 = \frac{interference\ space\ size}{original\ size} \times 100$ $IDP^5 = \frac{interference\ duration}{original\ duration} \times 100$
The VIRCON project (Dawood et al., 2005) (Winch & North, 2006)	2D CAD 4D-CAD (3D CAD models + time) 4D Virtual Reality Modelling Language (VRML) format	$Spatial\ loading = \frac{required\ space}{available\ space} \times 100$
(Mallasi, 2009)	4D-CAD and VRML	Geometrical adjacency algorithm
(Chavada et al., 2012)	5D (BIM + time + cost)	$CS^6 = \frac{conflicted\ duration}{current\ activity\ duration} \times 100$
(Moon et al., 2014)	4D-CAD (BIM)	$WCR^7 = \frac{adjacency\ distance}{expanded\ interval\ distance}$
(Kassem et al., 2015)	4D	$CS = \frac{conflicted\ duration}{current\ activity\ duration} \times 100$
(Rohani et al., 2018)	5D-CAD	-

SPATIAL-TEMPORAL CONFLICT RESOLUTION STRATEGIES

Whether planners develop schedules first and then resolve any identified spatial conflicts (i.e., follow a reactive approach) or attempt to directly generate conflict-free schedules (i.e., follow a more proactive approach), a set of commonly used conflict resolution strategies have been identified based on a review of relevant literature. Table 3 summarizes these strategies and highlights the ones considered or discussed in each of the reviewed studies. As suggested by Rohani et al. (2018), these strategies could be generally classified into two categories; The first category includes strategies that help resolve spatial conflicts without impacting the total project's duration and cost and, hence, can be considered less intrusive. Examples of such strategies include modifying the direction of work execution (e.g., north to south instead of south to north) or modifying activity start time within its float time. It is important to note, however, that even though certain strategies that are typically classified under this category may not have a direct impact on the project's duration or cost, they may have an indirect effect. For instance, modifying space size has been thought not to affect the schedule's critical path (Chavada et al., 2012) or the direct/indirect costs of the project (Rohani et al., 2018). However, reducing the size of a workspace may adversely affect the productivity of the corresponding activity (Guo, 2002), which, in turn, may lead to increased project's duration (if the activity is critical) and cost. Hence, when selecting strategies to resolve spatial conflicts, careful consideration of their potential consequences must be taken even if the strategies are deemed

[4] Interference Space Percentage
[5] Interference Duration Percentage
[6] Conflict Severity
[7] Workspace Conflict Ratio

non-intrusive. The second category includes strategies that are more intrusive and likely impact the project's duration and cost. Modifying the number of resources assigned to a critical activity in order to reduce the number of space users is one example of such strategies. Plainly, researchers recommend resorting to the second category only when certain spatial conflicts cannot be resolved using the first category strategies.

Table 3: Conflict resolution strategies

Strategies \ Studies		(Zouein & Tommelein, 2001)	(Guo, 2002)	The VIRCON project	(Dawood et al., 2005)	(Winch & North, 2006)	(Mallasi, 2009)	(Chavada et al., 2012)	(Moon et al., 2014)	(Kassem et al., 2015)	(Rohani et al., 2018)
1	Modify/delay activity start time	X	X	X	X	X		X	X	X	X
2	Modify resource allocation (i.e., number of space users)	X	X	X	X	X	X			X	X
3	Modify space location		X					X		X	X
4	Divide the original space into multiple smaller spaces		X								X
5	Modify activity duration		X	X	X	X		X			X
6	Split activity		X								X
7	Modify activity sequence		X							X	X
8	Modify space size		X					X		X	X
9	Store idle resources off site	X									
10	Modify execution direction						X			X	X
11	Modify the construction method		X					X			X

CONCLUSION AND ADDITIONAL CONSIDERATIONS FOR WORKSPACE PLANNING

The common practice in construction is to create schedules then resolve spatial-temporal conflicts. Workspace planning has not achieved diffusion in practice, especially in industrial projects that face lack of academia efforts in this regard. This paper presented a narrative literature review on workspace planning and summarized major findings from leading research studies. The study offers an overview of the existing workspace planning methods, challenges faced with workspace modelling, and general components that form the base for workspace planning such as flow types, area patterns, classification structure, and conflict identification and resolution. Moreover, this study offers below general considerations to examine when developing a space planning system. One thing to note is that a construction project goes through various phases from feasibility studies to construction, and operation and maintenance. Each phase is characterized with a distinct level of development (LOD) for the 3D models and project schedules. Such LODs strongly impact the 4D simulation's purpose and quality. Guidelines for defining and selecting LODs appropriate for project needs and progress are discussed further in a study by Guévremont and Hammad (2020). The considerations are:

What is the level of abstraction sought? What is the unit of analysis: project level, industry level, company level, team level, area level, etc.?

What LOD the system will tackle?

What level of complexity can the system handle?

What types of flow will the system consider?

Who will use the system (i.e. foremen, superintendents, planning engineers...)?

What will the system look like to help engineers better manage the space?

How to align the system with the Last Planner System (LPS)?

What kind of simulation is most suitable for the type of projects at hand?

How to perform solution evaluation of the developed system?

How to integrate BIM with the model?

What input should be included in the system?

How to define the parameters required for the system?

What templates are suitable for accommodating the modelling process?

Finally, some limitations are associated with this study. First, the paper is based on a narrative literature review, which means that the results are limited to the studies and sources that were included in the review. Therefore, the findings may not represent the complete picture of the field of workspace planning. Second, the paper provides general considerations for developing space planning systems, but it does not provide a detailed framework or methodology for implementing such systems. Third, the paper mentions the Last Planner System (LPS), which is a production planning and control system used in construction projects. However, it does not provide sufficient information on how to align space planning systems with LPS. In conclusion, if we can accurately assess the space requirements, patterns, and impacts of each task on the construction site, we can simulate different plans and generate optimized, conflict-free schedules. This research advocates taking a step back to look at planning from a different perspective, and then adopting the general considerations presented as a guide to develop space planning systems that meet the specific needs of each project.

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