CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

An Examination of Current Practices in Identifying Occupant Interactions in Renovation Projects

By

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CIFE Working Paper #WP121
December 2009

STANFORD UNIVERSITY

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CHAPTER 2

AN EXAMINATION OF CURRENT PRACTICES IN IDENTIFYING OCCUPANT INTERACTIONS IN RENOVATION PROJECTS

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Abstract

Renovations of occupied buildings are characterized by tenants moving and crews working in different locations within the building. Therefore, it is crucial for project planners to identify occupant interactions – instances where tenants and/or crews share spaces – in order to create a renovation schedule that has no disruptive interactions. Failure to identify these interactions during the planning stage can lead to unintended disruptions during renovation, causing loss in productivity and tenant dissatisfaction. Based on observations from seven renovation projects, this paper examines the state-of-the-art practices and performance of current renovation planning methods to identify occupant interactions. Identifying interactions using today's methods is difficult because the number of locations, tenants, crews, and renovation activities make the current manual identification process inaccurate and inefficient. This paper suggests that an automated method to identify interactions would enable project planners to integrate spatial, organizational, and temporal planning information and identifies the requirements for such a method. A review of existing concepts and methods shows that an automated method is feasible and highlights the extensions needed to enable an efficient representation of activities and accurate identification of shared spaces.

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1. Introduction

Building owners are renovating their existing buildings at an increasing rate, rather than constructing new ones (McKim et al. 2000). For example, the largest building owner in the United States, the United States General Services Administration, plans to spend $4.5 billion dollars from 2009 to 2012 to renovate a majority of its building stock into high performance green buildings (U.S. General Services Administration 2009b). The scope of renovation projects can vary from small maintenance projects to complete building systems upgrades and can be accomplished in buildings with various occupancy rates (Douglas 2006; Mansfield 2002). While complete renovations of vacant buildings are estimated to take up to 18 months, there is a time-cost trade-off between finishing a renovation quickly and obtaining rental income from a partially occupied building (Douglas 2006). Renovations of occupied buildings provide a balance between these factors and are a substantial and important portion of renovation projects today. The researchers analyzed summary data from 78 renovation projects and found that approximately 70% of these projects had a renovation scope which contained multiple systems upgrades and 50% had a duration of over 3 years; a good indication that these buildings will be occupied during renovation (U.S. General Services Administration 2009a).

Renovations of occupied buildings are different from new construction and require different project management methods. The presence of tenants creates the need to ensure that tenants are able to continue business operations while construction crews have consistent access to existing spaces to renovate the building. Space is limited and pre-defined by the locations of tenants. The movement of tenants and crews creates many unique arrangements of occupants in the building (i.e., building configurations) throughout the renovation. Therefore, renovations of occupied buildings require specialized attention to the relationships among building spaces, building occupants (i.e., tenants and crews), and renovation activities. Failure to understand these spatial, organizational, and temporal aspects of a renovation schedule can lead to disruptive interactions and potential loss in productivity of tenants and crews. With these considerations in mind, project planners must create a renovation schedule consisting of tenant move and construction activities that has no disruptive and few tolerable interactions.

While project planners attempt to sequence the renovation so that only one tenant or crew occupies a location at a time, there are instances where the tenants and crews must be in the same location. In these situations, the project planner not only needs to identify that two occupants are in the same location, but also needs to understand additional organizational information - which shift each occupant works (i.e., day, night, and weekend) and whether or not they can share spaces with others - to determine if the interaction is tolerable. Therefore, to identify occupant interactions accurately, project planners must be thorough, in analyzing each building configuration, and detailed, in analyzing each workshift. At the scale of real renovation projects, however, this is a difficult task.

The researchers participated in the planning phases of seven renovation projects which used traditional planning methods along with 4D models to manage renovation schedules. These seven projects are characteristic of many renovation projects. An analysis of summary data from 78 renovation projects found that the average size of a renovation project was approximately 560,000 sf with an average renovation duration of 3.5 years (U.S. General Services Administration 2009a). In the seven projects to which the research team had access to detailed project information, the average size was 680,000 sf with an average renovation duration of 4 years. The researchers created 4D models for six projects and analyzed three of these projects in depth to determine the accuracy of identifying interactions. Another project team member created the 4D model for one project.

Table 1 provides an overview of the characteristics of each renovation project at three levels: the project, the renovation schedule, and the renovation scheduling method. We collected data on various spatial (e.g., detail of spatial information, number of unique building configurations), organizational (e.g., number of tenants and crews, documentation and detail of organization information), and temporal (e.g., number of tenant move and construction activities, detail of renovation activities) aspects of each renovation project.

Based on an analysis of these seven renovation projects taking place from 2004 to 2015, this first part of this paper provides insights on the use of state-of-the art planning methods to identify occupant interactions and the challenges associated with these methods. Sections 2, 3, and 4 discuss these observations at the project, schedule, and scheduling method levels of detail, respectively. At the project level, the data show that renovation projects are complex in the number of occupant organizations and types of occupants found on renovation projects. On each of the seven renovation projects, there were between 13 and 114 occupant organizations (i.e, tenants and crews) for project planners to keep track of. At the schedule level, the number of and sequencing of tenant move and construction activities creates more unique building configurations than just the sum of the activities and also creates different types of possible occupant interactions. The number of tenant moves and construction activities created between 3 and 628 unique building configurations to analyze for the project planners of those projects.

For the scheduling method, detailed spatial information (e.g., 2D CAD drawings) was available on all seven projects. However, organizational information (e.g., occupant work schedules and their space sharing abilities) was not documented at all on five projects. Since no information was known about occupants at the workshift level, the detail of the renovation activities was typically only by floor and activity (e.g., "Install spandrels on Floor 3"). Furthermore, the documentation of this information was not detailed or integrated, making manual identification time-consuming and inefficient. This prevented project planners from identifying potential space sharing opportunities. 4D models were helpful to integrate spatial and temporal information and to visualize changes in occupant locations, but they were unable to represent changing building configurations over time and the process to identify interactions remained manual.

Collectively, these challenges indicate the difficulties for project planners using traditional and 4D-based scheduling methods to relate the required spatial, organizational, and temporal renovation planning information in an integrated way to identify occupant interactions accurately. In the three projects analyzed in depth, the project planners identified, on average, only 53% of all the interactions found in the schedule. The necessity for thoroughness (i.e., analysis of every building configuration) and detail (i.e., analysis at the workshift level) creates an abundance of location, organization, and activity information that is practically impossible to analyze manually.

This second part of this paper suggests that a method to identify occupant interactions automatically would enable a more thorough and detailed analysis, with the potential for more accurate identification of interactions. By abstracting and classifying renovation planning information and types of occupant interactions, an automated method can be developed to allow a software tool to synthesize many instances of tenants, crews, and space sharing abilities instead of relying on the project planner to analyze each instance individually. In the absence of such abstractions and classifications, planners have to think about each instance of all the interactions individually in their mind and consider whether an interaction is tolerable or disruptive. As shown in our review of the seven projects in the first part of this paper, this becomes quickly intractable on typical renovation projects with several crews, many tenants and a duration of a few years and as multiple renovation schedules need to be analyzed due to new tenant and crew requirements or when the schedule is adjusted to address disruptive interactions. This paper identifies the representation and reasoning method requirements for an automated approach and discusses prior approaches from research in renovation planning methods, product modeling, occupant modeling, activity modeling, and space sharing identification methods.

Table 1. Characteristics of renovation projects, schedules, and scheduling methods

Project number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Extent of review	Created 4D model and detailed analysis of interactions	Created 4D model and detailed analysis of interactions	Created 4D model and detailed analysis of interactions	Reviewed 4D model created by project team member	Created 4D model	Created 4D model	Created 4D model
Project Characteristics							
Project size (in thousand sf)	335	1,300	419	1,200	516	862	1,300
Characteristics of occupants							
Number of occupant organizations							
Number of tenants	114	8	10	15	19	25	13
Number of crews	0	6	3	2	1	4	3
Types of tenants							
Regular	X	X	X	X	X	X	X
Sensitive		X					
Ongoing	X		X	X			
Types of construction crews							
non-sharable	N/A	X	X	X	X	X	X
semi-sharable	N/A	X	X				
sharable	N/A	X					
Multiple schedule alternatives to analyze	No	Yes	Yes	No	Yes	Yes	No
Characteristics of schedule							
Renovation activity characteristics							
Number of tenant move activities	97	16	23	27	21	11	16
Number of construction activities	0	292	23	28	27	23	36
Number of unique building configurations	3	628	92	22	21	34	14
Tenant move activities							
One-one	X	X	X	X	X	X	X
Many-many	X		X	X	X		X
Construction activities							
Support s		X			X	X	
Potential occupant interactions (√ indicates interaction confirmed by project planner)							
Tenant-tenant interaction	**X - √**	X	**X - √**	X	X	X	X
Major tenant-crew interaction		**X - √**	**X - √**	X	X	X	X
Minor tenant-crew interaction		**X - √**	X				
Crew-crew interaction		**X - √**			X	X	
Characteristics of scheduling methods							
Analysis of renovation activities							
Determine locations of occupants over time	X	X	X	X	X	X	X
Identify Occupant Interactions	X	X	X	X	X	X	X
Analyze swing space square footage information			X	X		X	
Traditional method							
Detail of spatial information	Space	Space	Space	Space	Space	Space	Space
Documentation and detail of organization information							
Location	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Work schedule	No	Tenant - No Crew - Yes	No	No	Tenant - Yes Crew - No	No	No
Space sharing ability	No	No	No	No	No	No	No
Documentation and detail of tenant move activity							
Specific tenant	Yes	No	No	No	No	No	Yes
Specific start and end locations	Space	Floor	Floor	Floor	Floor	Floor	Floor
Detail of construction activity	N/A	Workshift	Activity	Activity	Activity	Activity	Activity
Number of building configurations analyzed by project planner	2	0	54	9	21	7	0
Number of interactions found	0	77	0	N/A	N/A	N/A	N/A
4D Model							
Purpose of 4D model **	1	2	1,2,3	1	1	1,2,3	1,2
Detail of 4D model							
Number of spaces	1098	59	102	104	122	67	7788
Number of activities	97	308	46	68	48	34	52
Number of dummy activities	97	16	23	55	26	6	13
Documentation and detail of tenant move activity							
Specific tenant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Specific start and end locations	Space	Space	Space	Space	Space	Space	Space
Detail of construction activity	N/A	Workshift	Activity	Activity	Activity	Activity	Activity
Documentation and detail of organization information							
Location	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Work schedule	No	No	No	No	No	No	No
Space sharing	No	No	No	No	No	No	No
In-Depth Analysis							
Number of total interactions identified through in-depth analysis and confirmed by project planner	11	119	17				

****1** Visualize tenant moves **2** Validate schedule **3** Identify vacant square footage

2. Characteristics of renovation projects

A successful renovation project occurs when tenants and crews are satisfied with the renovation process (Greenberg 2000; Holm 2000), while still meeting schedule and budget constraints. Identifying occupant interactions is a crucial aspect to delivering successful renovation projects because occupant satisfaction typically means that occupants are not unnecessarily disrupted during the renovation process. Tenants are able to continue their business operations. Construction crews are able to complete construction activities without unforeseen work stoppages. Therefore, early identification of occupant interactions during the planning process enables project planners to ensure that there are no disruptive interactions during renovation. But, as summarized above, this can be challenging since typical renovation projects have many occupants with different work schedules and abilities to share space.

The connection between ensuring occupant satisfaction through the identification of occupant interactions highlights the relationship between project performance metrics and goals (i.e., zero disruptive occupant interactions in the renovation schedule) to support occupant business objectives (i.e., continual business operations). Since tenants are directly affected in renovations of occupied buildings, this relationship is much more salient than in new construction (where ongoing tenant business operations are typically not affected by the construction process). Consequently, there is an increased emphasis on the organizational behavior of occupants as it relates to project performance (i.e., when and how they can share spaces). This organizational behavior is discussed in the next section.

In addition to ensuring occupant satisfaction, project planners must also measure traditional project performance metrics such as budget and schedule constraints. As a result, project planners often develop multiple alternative renovation schedules and evaluate trade-offs between budget, schedule, and occupant satisfaction. Since each of these potential renovation alternatives must still ensure that occupants are not disrupted, the identification of occupant interactions is a necessary and important component of analyzing renovation schedules.

2.1. Multiple occupants

To identify occupant interactions, project planners must understand each occupant's organizational behavior (i.e., when they work and if they can share spaces), which changes during different workshifts. This is challenging because of the number and types of occupant organizations found on renovation projects. In the seven projects, there were a minimum of eight and a maximum of 114 tenant organizations to manage. While the number of crews was considerably lower (minimum of zero, maximum of six), four of the seven projects had three or more crews to manage. Not only were there multiple occupants, but each occupant had different work schedules and space sharing abilities. Since construction work often occurs during nights and weekends, project planners must understand if tenants can share spaces during different workshifts (i.e., day, night, and weekend). Conversely, project planners must also understand if the type of construction activity allows crews to share space.

Three types of tenants and three types of crews were found on the seven renovation projects. Table 2 summarizes these types of occupants based on their work schedule and ability to share space. Abstracting the organizational behavior of occupants allows project planners to identify opportunities for better project performance (e.g., more efficient utilization of building spaces), while still ensuring that occupants do not encounter any disruptive interactions. This abstraction also supports the development of an automated method to identify occupant interactions (described later in this paper). The result is a more efficient analysis of time-cost trade-offs among different renovation scenarios. Without these abstractions, project planners must analyze each tenant organization individually, which is time-consuming and inefficient due to the number of tenants in a building. The following sections describe each type of occupant.

Table 2. Characteristics of occupants based on work schedule and ability to share space

		Types of tenants			**Types of crews**		
		Typical	**Sensitive**	**Continuous Operations**	**Non-sharable**	**Semi-Sharable**	**Sharable**
Work Schedule	Day	Working	Working	Working	Working	Off	Working
	Night	Off	Off	Working	Off	Working	Off
	Weekend	Off	Off	Working	Off	Working	Off
Space Sharing Ability	Can crews share space during off-hours?	Yes	No	No	No	Yes	Yes, and during working hours

2.1.1. Types of Tenants

We observed three types of tenants in the seven renovation projects.

***Typical* -** The most typical type of tenant found on all seven projects was one that worked only during the workweek with a typical daily 8:00AM-5:00PM work schedule. These tenants allowed construction crews to work in their space at night, but not during the day.

***Sensitive* -** Some tenants were sensitive to construction crews in their space. Due to their business operations, some tenants had sensitive documents or valuables. In these situations, project planners had to move the tenant into swing space (i.e., vacant space within the building that a tenant temporarily moves into) if the tenant did not want to share the space at all or had to hire security guards to watch over construction crews as they worked during off-hours. This type of tenant was found on one project.

***Continuous Operations* -** A third type of tenant was one that had 24/7 operations. In these cases, construction crews could not work in their space at any time. To maintain 24/7 operations, swing space had to be completely built and functional to provide a smooth transition to new space with minimum disruption to operations. The construction crews could only work in the original space after it was vacated. This type of tenant was found on three projects.

2.1.2. Types of Crews

We observed three types of crews in the seven renovation projects.

***Non-sharable* –** The most typical type of crew could not share space with other occupants because of safety hazards or an inability to clean up the workspace for another occupant. For example, in Project 3, asbestos abatement required tenants to move off the entire floor. Even partial tenant occupancy was considered unsafe. In Project 7, tenants were not allowed to share spaces with crews as they built out new tenant space. This type of crew was found on all seven projects.

***Semi-sharable* –** Another type of crew could not share space with other occupants while the crew was working, but they were willing to share the space if they were off-shift. In most cases, this meant that the crew would work in a tenant space at night. At the end of their shift, they cleaned up to enable tenants to work during the next day. This process, repeated for the duration of the activity, is an example of a tolerable interaction between tenants and crews. This type of crew was found on two of the seven projects.

***Sharable* –** Another type of crew was able to share space regardless of whether or not they were working. For example, in Project 2, the project planner determined that the fire alarm installation activity could occur in the same space where tenants were working because it would only be a minor disruption to the tenants. This type of crew was found on only one project.

2.2. Trade-offs between occupant satisfaction, budget, and schedule

Since project planners have to manage multiple conflicting goals, they have to compare different scheduling alternatives. In four of the seven projects, the planners had to evaluate different schedule alternatives. Figure 1 shows an example of the trade-off decisions that project planners must make. The planners had to evaluate which of the five different sequencing alternatives had the best performance for schedule, budget, and tenant satisfaction (i.e., measured by the number of tenants that must move twice).

Sequencing Option	Construction Time	Time Savings	Cost Savings
Concept Design Schedule	60 months		
Sequence One	55 months	5 months	$440,000 - $600,000
Sequence Two	56 months	4 months	$880,000 - $1,200,000
Sequence Three	52 months	8 months	$1,760,000 - $2,400,000
Sequence Four	45 months	15 months	$3,300,000 - $4,500,000
Sequence Five	36 months	24 months	$5,280,000 - $7,200,000

Sequencing Option	Number of tenants that must move twice
Sequence One	16
Sequence Two	21
Sequence Three	21
Sequence Four	24
Sequence Five	9

Figure 1.Comparison of five schedule alternatives for Project 5

Similar evaluation of alternative sequencing plans needed to be performed on three other projects as well. In Project 2, the planner needed to understand if adding variable air volume (VAV) boxes to the scope of work would increase the amount of time tenants would have to move into swing space. The additional scope to the project was approved only after it was determined that it would not have an impact on tenant moves. In Project 3, the planners had to evaluate the time savings from using one floor or three floors of swing space. The decision informed whether the owner would have to lease additional space outside the building. In Project 6, the planner had to evaluate the time-cost trade-offs of moving a major tenant to lease space during the renovation. In all cases, however, the project planner must determine whether each alternative sequence has no disruptive interactions and few tolerable interactions, further emphasizing the need to identify occupant interactions.

3. Analyses of renovation schedules

Each possible renovation schedule must first be evaluated to determine if the schedule is a viable solution. To determine if the schedule is viable, the project planners needed to:

- ***Identify occupant interactions*** **-** An occupant interaction occurs if there is more than one occupant in the same location. To ensure that tenants and crews can work without interruption, project planners need to track occupant locations over time to identify potential occupant interactions. This analysis occurred on all seven projects. If a tenant and crew are scheduled to be in the same location, the project planner must account for each occupant's work schedule and space sharing abilities to determine if the interaction will be disruptive or tolerable. Disruptive interactions must be eliminated by re-sequencing the renovation activities. Tolerable interactions must be communicated to tenants and crews early. Prior research also identified that spatial and temporal aspects of renovation projects need to be communicated to tenants, including schedule and location of tenant moves, target completion dates, time constraints, and changes in access routes (Fawcett and Palmer 2004; Hassanain and Al-Mudhei 2006; McKim et al. 2000).

- ***Identify square footage of swing space needed over time*** **-** This information is used to determine if the rental cost of moving additional tenants to lease space is worth the time savings in freeing up space for construction workers to use and to determine the efficiency of swing space use. By understanding the amount of used and unused swing space over time, the project planner can determine the ideal "space buffer" for the project (i.e., the trade-off between paying for unused space versus the risk of occupant interactions from a building with higher tenant occupancy). This analysis was required on two of the seven projects. The identification of swing space is a subset of identifying occupant interactions because swing space is the remaining un-occupied space in the building. Since project planners need to determine the locations of occupants to identify occupant interactions, they consequently have the information necessary to identify swing spaces. Therefore, the remainder of this paper focuses on identifying occupant interactions with the understanding that identifying the square footage of swing space is a subset of this analysis.

3.1. Challenges in analyzing renovation schedules

Two characteristics of renovation schedules make it difficult to identify occupant interactions:

- The ***number of renovation activities*** creates many unique building configurations to be analyzed. In five of the seven renovation projects examined (Projects 3-7)[3], the renovation schedule contained an average of 19 tenant move activities, 27 construction activities, and 36 different building configurations.

- The ***sequencing of the activities*** also creates the potential for four different types of tolerable or disruptive interactions, which must be distinguished, since each interaction type has a different management response (e.g., notify tenants, re-sequence activities). On the three projects examined in depth (Projects 1-3), two of the projects had multiple types of interactions. On all three projects, project planners had difficulties identifying and distinguishing interactions accurately.

3.1.1. Tenant Move and Construction Activities

Renovation activities describe the spatial, organizational, and temporal aspects of how the building configuration changes over time. Tenant move activities describe where (e.g., start and end spaces) and when tenants move. The types of tenant moves range from simple one-to-one moves to more complex tenant moves (e.g., a tenant moves from many spaces to many spaces). In Figure 2, the first tenant move depicts a many-to-one move and the second move depicts a one-to-one move. Construction activities describe where and when construction work occurs. Project planners need to consider not only the direct work spaces of the crews, but also any support spaces required. In Figure 2, the staging spaces are an example of support spaces.

[3]We did not factor Project 1 or 2 into this average because these projects had a heavy focus on tenant moves (Project 1) or construction activities (Project 2).

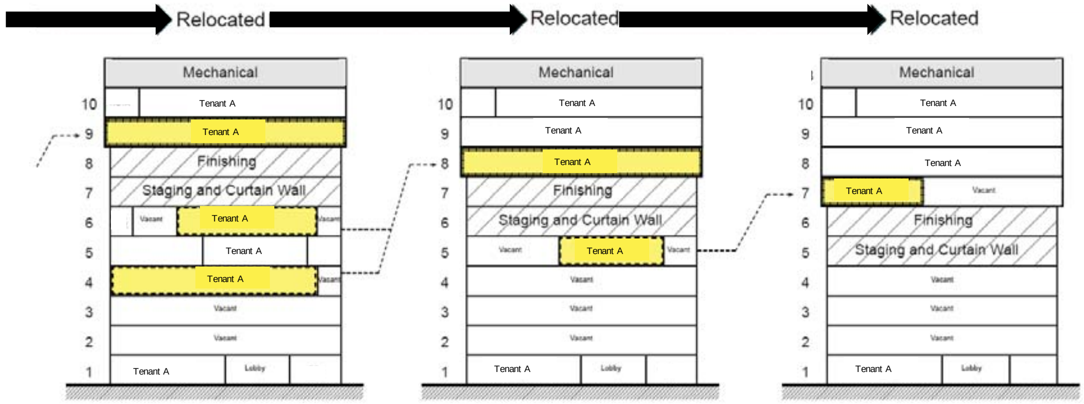


Figure 2. Renovation sequencing plan from Project 6 (modified to remove identifying information)

The detail of the tenant moves should be at the space (i.e., room) level because planners must determine if there is enough space available in the end location to accommodate the square footage the tenant had in the start location. For example, in Project 7, failure to account for occupant square footage forced the project team to add an additional construction activity to build out an additional floor to accommodate the tenants moving into the building. The square footage of spaces is typically found in 2D CAD drawings of the existing tenant locations. On all seven projects, 2D CAD drawings were part of the project documents.

The number of tenant moves and construction activities resulted in many building configurations that needed to be analyzed. Although there was an average of 36 unique building configurations on Projects 3-7, the planners analyzed – on average – only half of the configurations because state-of-the-art methods make it difficult to identify and analyze all unique building configurations. This lack of thoroughness of analysis in current practice is discussed in Section 4.

3.1.2. Complex sequencing creates potential interactions

The movement of tenants and crews to different locations creates potential interactions between tenants and crews (Table 3). The occupants' space sharing abilities need to be distinguished to identify tolerable and disruptive interactions and determine the appropriate management response (e.g., notify tenants, re-sequence activities). Since the occupants' space sharing abilities change over different workshifts, the analysis of occupant interactions must be performed at the workshift level. Table 1 indicates the potential types of interactions observed in the seven projects. The following four types of occupant interactions are possible:

***Tenant-Tenant Interactions* –** Tenant moves can lead to tenant-tenant interactions, where a tenant moves into a space that is already occupied by another tenant (i.e., a double-booked room). Since all of the projects involved tenant moves and multiple tenants, the potential for tenant-tenant interactions occurred on all seven projects. Management of tenant-tenant interactions involves moving tenants to a different location or changing tenant move dates to eliminate the interaction.

***Major Tenant-Crew Interactions* –** Major tenant-crew interactions occur when tenants and crews are working in the same space but at least one tenant and one construction crew each do not want to share the space. This potential situation, identified on six projects, occurs when there are both tenant move and construction activities. Sze et al. (2004) identified tenant complaints from crews working in the same spaces as the tenants and found that communication of tenant work schedules and prior identification that crews would be entering tenant spaces contributed to a reduction in the number of tenant complaints over the course of the renovation. These major tenant-crew interactions must be avoided to minimize disruptions and occupant dissatisfaction. Management of major tenant-crew interactions involves re-sequencing activities, deleting renovation scope, or changing construction methods to avoid this interaction.

***Minor Tenant-Crew Interactions* –** Minor tenant-crew interactions occur when a construction crew and a tenant are working in the same space, and they allow each other to share the space while the other works there as well. This potential situation, identified on two projects, occurs when there are weekend or nighttime construction activities. Pritcher (1998) describes this as "stealth construction…where a successful project means tenants did not know you were in their space." Other researchers also recommend this type of interaction to enable tenant business operations to continue (Fawcett and Palmer 2004). Management of minor tenant-crew interactions involves notifying the tenant ahead of the interaction that crews will be working in their space. Crews must also be notified that they will be working in a tenant-occupied space to ensure that the space is left in an acceptable condition after their workshift.

***Crew-Crew Interactions* –** When the scope of the construction calls for multiple crews with overlapping activities there is a chance for crew-crew interactions. Three of the seven projects had this type of situation. As space is valuable during renovations, project planners may plan to have multiple construction crews working in the same space. Management of crew-crew interactions is typically the responsibility of the general contractor.

Table 3. Table of occupant interactions and description of interactions

Occupant Interaction	**Disruptive or Tolerable?**	**Example**
Tenant-Tenant	Disruptive	Two tenants moved to the same space (e.g., double-booked room)  **Space X** **Tenant A** "Cannot Share" **Tenant B** "Cannot Share"
Major Tenant-Crew	Disruptive	A tenant and crew both working during the daytime  **Space X** **Tenant** "Cannot Share" **Crew** "Cannot Share"
Minor Tenant-Crew	Tolerable	A tenant working during the day, and a crew working at night  **Space X** **Tenant** "Can Share" **Crew** "Cannot Share"  **Space X** **Tenant** "Cannot Share" **Crew** "Can Share"
Crew-Crew	Tolerable	Two crews working in the same space  **Space X** **Crew A** "Can Share" **Crew B** "Can Share"

In the three projects analyzed in depth, project planners had a difficult time identifying occupant interactions accurately. We asked project planners initially to identify occupant interactions using their traditional planning methods (Table 1). We then analyzed each schedule in depth to identify occupant interactions. After we showed them the results, the project planners confirmed that Project 1 had tenant-tenant interactions, Project 2 had crew-crew, major tenant-crew, and minor tenant-crew interactions, and Project 3 had tenant-tenant and major tenant-crew interactions. On average on the three projects, project planners only identified only 53% of the occupant interactions. Sometimes, they completely missed or did not distinguish the correct type of interaction. Therefore, a better planning method is necessary to identify the number and type of occupant interactions accurately in a productive and timely manner to analyze renovation schedules. The following section describes the requirements for an improved renovation scheduling method to identify occupant interactions and highlights the challenges of traditional and 4D-based planning methods.

4. A good renovation scheduling method identifies occupant interactions

The renovation scheduling method needs to be:

- ***accurate*** in indentifying interactions,
- ***detailed*** enough to track occupants (and square footage of swing space) for each space at the workshift level,
- ***thorough*** enough to analyze all unique building configurations, and
- ***efficient*** so that it is not difficult for project planners to manage the information and perform the analysis.

To identify occupant interactions, project planners must understand the spatial, organizational, and temporal aspects of the renovation schedule. In other words, they must understand the relationships among building locations (i.e., spaces in the building), organizations (i.e., each occupant's work schedule and ability to share spaces), and renovation activities (i.e., tenant move and construction activities) (Figure 3). First, project planners must synthesize location and schedule information to track occupant locations. Once the locations of occupants are tracked over time, project planners can identify when and how tenants and crews are sharing spaces. If two or more occupants are sharing the same space, project planners need to understand organizational information to determine how occupants can share spaces. This space sharing ability can change during different workshifts. Once the locations and space sharing abilities of the occupants are known, project planners can identify and distinguish tolerable and disruptive occupant interactions from this information.

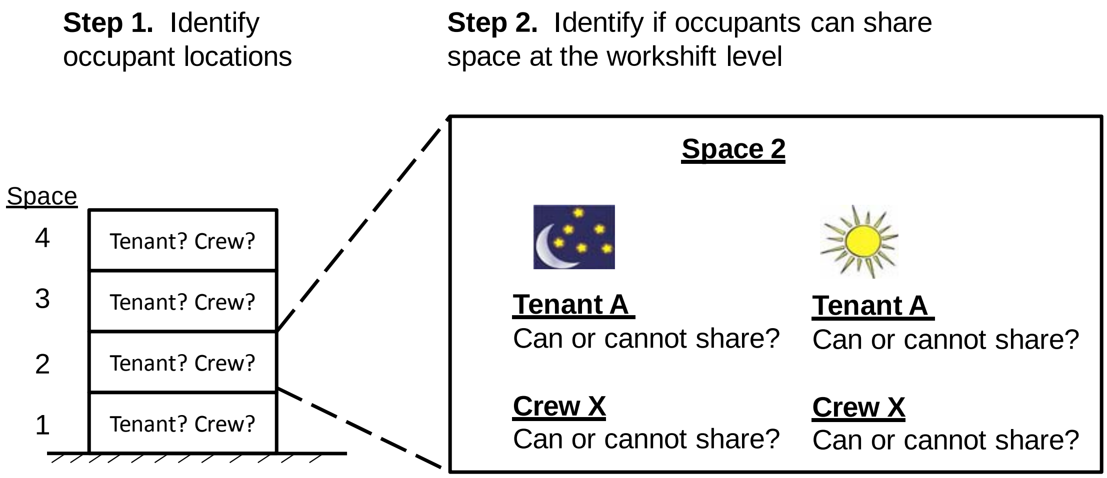


Figure 3.Identification of occupant interactions requires integration of spatial (e.g., Space 1, 2, 3, 4), organizational (e.g., Tenant A, Crew X), and temporal (e.g., nighttime and daytime workshifts) information**.**

Based on the seven projects, there were two challenges to using traditional methods. The following sections describe these challenges in detail with examples from two projects. First, the level of detail of the renovation planning information was not sufficient to identify the occupant interactions. Second, the information was also not integrated, resulting in multiple documents which contained the same information. This led to inconsistencies in the documentation. Since none of the information was in a single model, project planners had to synthesize information manually across multiple documents, which was difficult and not efficient. 4D models allowed project planners to represent additional detail and integrate spatial and temporal information, but these models were not efficient or thorough in identifying occupant interactions.

4.1. Insufficient detail of location, organization, and schedule information

The following example illustrates the level of detail of traditional renovation planning information for Project 3, highlighting the insufficient detail of organizational and temporal information. The planning documents provided occupant locations and square footages at the start and end of the renovation (Figure 4) and 2D, annotated CAD drawings of existing occupant locations (not shown). The tenant move schedule was at a floor-by-floor level of detail (Figure 5). There was no explicit documentation of occupant work schedules or space sharing requirements. This information was only in the project planner's head.

First, the lack of organizational information created the potential for disruptive interactions. The installation of structural spandrels required nighttime work, but there was no documentation on whether the tenant would allow this work to occur in their space at night. Conversely, there was no documentation that the construction crew could share the space with tenants. Second, the lack of detail of the renovation schedule did not support tracking occupants at the space or workshift level. Tenant move activities did not have information on specific tenants and specific locations for tenant moves. As a result, the project planner could not determine where occupants were located or calculate the amount of un-used swing space in the building over time.

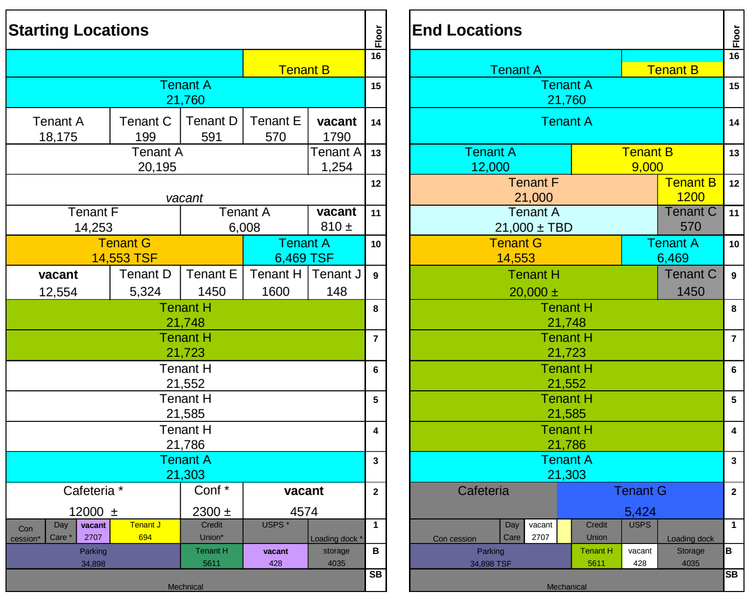


Figure 4. Start and end locations of tenants for Project 3

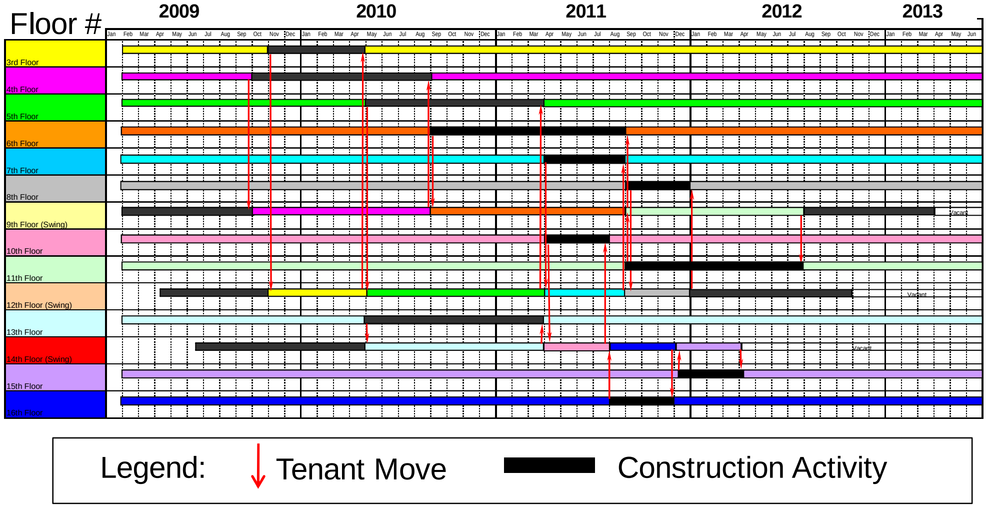


Figure 5. Excel spreadsheet of renovation activities by floor for Project 3

This example indicates that the following level of detail of spatial, organizational, and temporal information is necessary:

- The ***level of detail of the spatial information*** should be for each room (i.e., space) on each floor. All of the seven projects had access to this level of detail of spatial information, but the information was separate from other documents, making it difficult to track the locations and amount of square footage available for swing space as tenants move and construction crews work in different spaces.

- The ***level of detail of the organization*** information should document occupant work schedules and space sharing abilities at the workshift level. Only two projects had information on which workshifts occupants were working, but none had information on occupant space sharing abilities.

- The ***level of detail of the activities*** in the schedule should support tracking occupants at the space and workshift detail. Tenant move activities should relate spatial, organizational, and temporal information to describe specific tenants and specific locations for tenant moves. Only two of the seven projects named specific tenants, and only one project linked specific tenants to specific start and end locations in the schedule. The detail of the moves was often found from other project documents. For construction activities, only one project distinguished the activities to the workshift level. Five of the six projects that had construction activities described the activities at the activity level, but it was unclear during which workshift the activities would occur.

4.2. Multiple sources of documentation

On all seven projects, there were multiple sources for the schedule and location information, which required the project planners to ensure that each source was up to date and coordinated. For example, in Project 2, the day-night-weekend construction activity matrix, which describes the workshift of the construction activities, was not integrated with other project documentation. As a result, the renovation schedule had construction activities scheduled during the daytime, where the matrix indicated nighttime work. In Project 1 (Figure 6), the project planner used three sets of 2D CAD drawings to coordinate the tenant moves. The tenant locations in the end location drawings, however, were not consistent with the start locations and the moves indicated in the move management drawings.

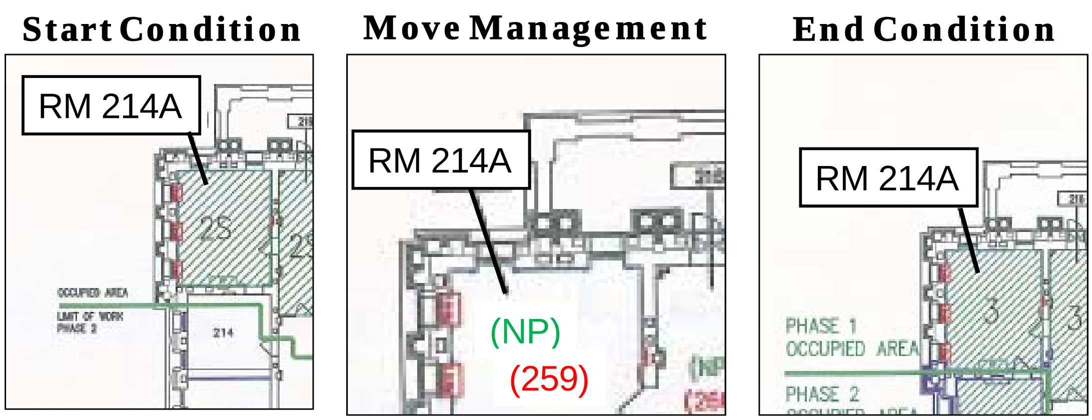


Figure 6. Three sets of 2D CAD documents for Project 1 were used to manage tenant move activities. The documents were inconsistent; the starting conditions and the move management information did not result in the same locations shown on the end condition drawings.

The following example shows the difficulty of synthesizing multiple sources of occupant location and schedule information to understand changing building configurations for an 18-story office building (Project 4). Project planners needed to track 15 tenants and 2 construction crews in 104 spaces for 27 tenant move activities and 28 construction activities. This translates to 22 unique building configurations. Figure 7 shows the renovation schedule in a spreadsheet format. The two bold vertical lines correspond to the two different building configurations shown in Figure 8. The information about the month and year of the tenant move is found in the schedule, but the level of detail of each tenant move activity is only at the floor level. There is no indication of which tenants are moving and the locations of these moves in the schedule. Figure 8, however, has specific information on the locations of each tenant at the space level, but there is no information on the dates of the move. In addition, the locations of construction crews are not depicted in the building configurations although there are construction activities depicted in the renovation schedule. Therefore, the two documents must be analyzed together to understand the sequencing and changing building configurations. With traditional methods, this is a manual process, which is not thorough or efficient. As a result, the project planners analyzed only 9 of the 22 building configurations.

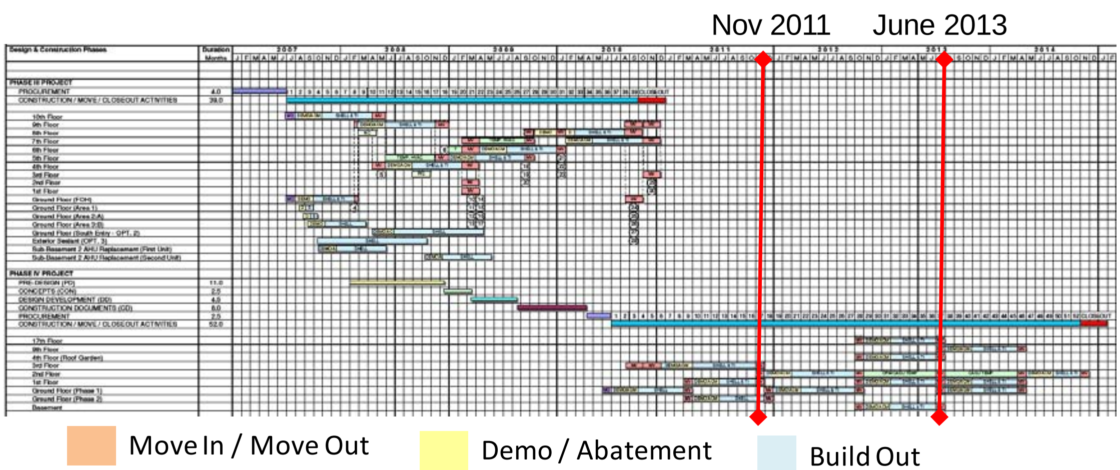
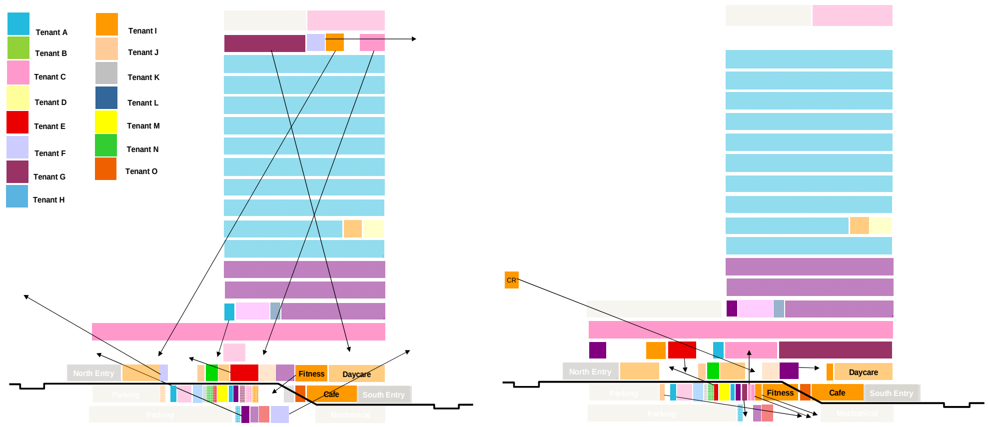


Figure 7. Renovation schedule for an office building renovation. The bold vertical lines correspond to the building configurations shown in Figure 8.



November 2011 **June 2013**

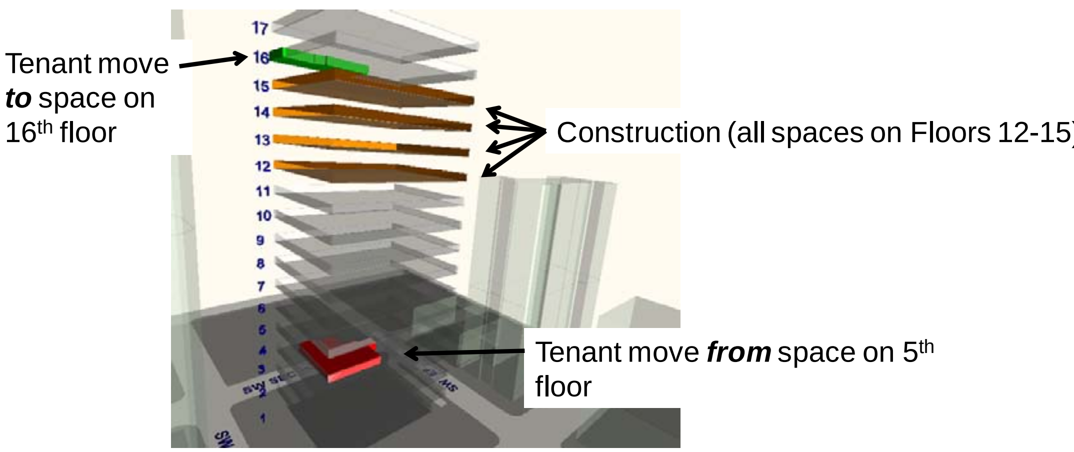
Figure 8. Building configurations corresponding to vertical lines in Figure 7 show where tenants are during the renovation. The arrows indicate tenant moves. While the names and locations of tenants are detailed, the timing of the moves is not indicated, making it necessary for project planners to synthesize both documents to fully understand the changes in building configurations.

All of the seven projects had multiple sources of the same information at varying levels of detail. Four of the projects had separate schedule and location documents similar to Figures 7 and 8, where the detail in the renovation schedule did not specify tenants or start and end locations, but there were other documents which had this information, but no dates. This results in a manual process to synthesize and analyze building configurations. Since this is inefficient, all seven projects analyzed fewer building configurations than actually occurred.

4.3. Use of 4D models to identify occupant interactions

4D models of the renovation schedule provided the necessary level of detail for tenant move activities to track where tenants were moving to/from at the space level. Figure 9 shows snapshots of 4D models created from Projects 2 and 5. These 4D models integrate spatial and temporal information to allow the project planner to see the changes in occupant locations at the space level. The models show changes in occupant locations, where different colors indicate different types of spaces (e.g., red spaces indicate start locations, green spaces indicate end locations, and orange spaces indicate construction crew locations). On four of the seven projects, planners also used the 4D models to step through each change in building configuration to validate the renovation schedule. This was useful to validate the sequence of activities and see the locations of tenant moves in relation to locations of construction activities at any given time, but the planners could not use the 4D models to identify interactions. Most of the effort to create the 4D models was spent communicating with the project planners to gather the information for the tenant move activities (e.g., which tenant, start spaces, and end spaces) because the traditional documents only provided detail to the floor level.

Project 2



Project 5

Figure 9. Snapshots of the 4D models for Projects 2 and 5 show that tenant moves can be visualized at the space level of detail.

Since the detail of the location information is at the space level, the 4D models were able to provide square footage information of the swing space for the two projects that required the analysis. Figure 10 shows a snapshot of the 4D model created for Project 6 which depicts the unused swing space in a separate color. This allowed the project planner to see the under-utilization of space in the building.

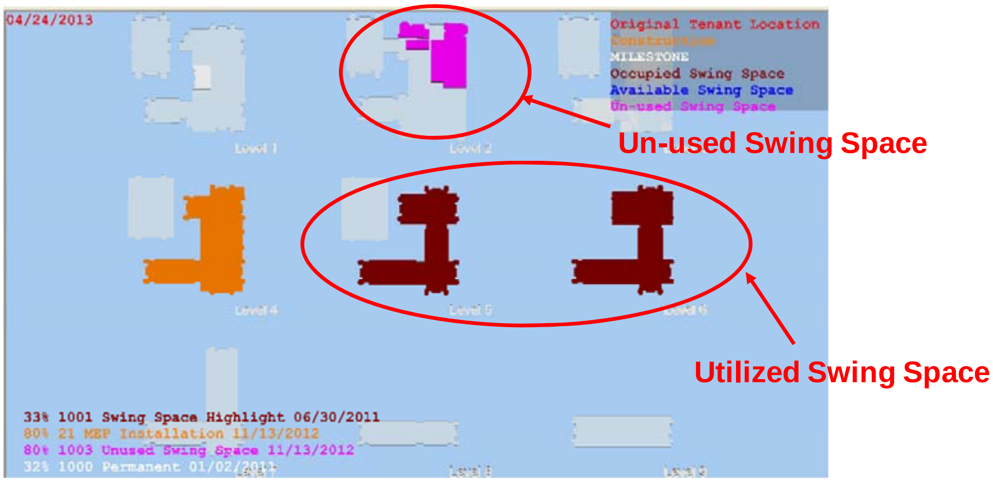


Figure 10. Use of 4D model on Project 6 to visualize vacant space over time

4.3.1. Limitations of 4D models to identify interactions

While 4D models addressed some of the limitations found with traditional methods, there were still several limitations of 4D models to identify occupant interactions:

- Since 4D models were originally developed to apply to new construction, they associate only one set of spaces with an activity. However, tenant move activities relate to two sets of spaces. Therefore, the 4D models needed to have dummy activities inserted to show the start locations and end locations of the tenant move in different colors. On average across the seven projects, there were 34 dummy activities needed. As the number of tenant moves increase, the number of dummy activities increases, making creation and use of 4D models for renovation scheduling increasingly difficult.

- The identification of occupant interactions is still manual. The models only show changes in occupant locations, but do not show the complete updated building configurations. For example, in Figure 9, the project planner was not able to see whether a tenant was already occupying a space since non-moving tenants are not represented in the model. While it is possible to visualize building configurations over time using commercially available 4D modeling software, the number of activities can grow exponentially and become unmanageable. For example, in Project

1, over 12,000 activities were required in order to visualize the locations of each occupant during the renovation. Furthermore, to identify occupant interactions, the project planner would need to analyze each space manually and subsequently determine whether another occupant moved into the space. This can be time-consuming and inefficient. On Project 3, there were 102 spaces and 92 unique building configurations, which means that the project planner would need to check 9,384 spaces over time. The average number of these checks that would need to be performed on Projects 1-6[4] for a thorough analysis was approximately 9,400. It is practically impossible to do this thoroughly with a manual method.

- None of the 4D models provided details regarding occupant work schedules or space sharing abilities, which prevented distinguishing minor and major tenant-crew interactions. For example, in Figure 11, there is no visible difference between the daytime and nighttime installation of the condensate piping activities in the project schedule or 4D model. The project planners concluded that the occupant interactions would be the same for both activities. Upon further analysis, the daytime installation of the piping created a major tenant-crew interaction in the support space above, whereas the nighttime installation led to a minor tenant-crew interaction.

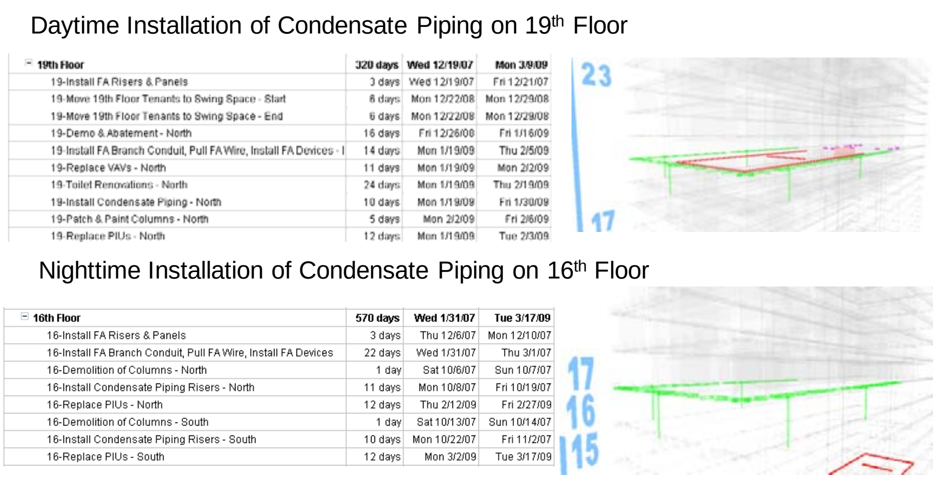


Figure 11. The 4D model of the condensate piping activity does not allow project managers to distinguish the impact of construction workshifts on tenants.

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[4] We excluded Project 7 from this average because of the high number of spaces in the 4D model due to the unusually high detail in the spatial model.

In summary, traditional planning and 4D modeling methods do not detail or integrate renovation planning information sufficiently, resulting in an inefficient and not thorough manual identification of occupant interactions.

5. Requirements for an automated method to identify occupant interactions

Given the large number of checks that project planners must perform to analyze a renovation schedule thoroughly, automating the identification process can improve the renovation scheduling process. While the requirements for accuracy, detail, thoroughness, and efficiency apply to any method to identify occupant interactions, there are particular representation and reasoning requirements that must be met to automate the identification process. The requirements for an automated method can be categorized into two areas: requirements in the representation of location, organization, and activity renovation planning information, and requirements for the reasoning methods to utilize this information.

The representation of location, organization, and activity renovation planning information must:

- Represent occupant locations at the space level.
- Represent organization information to allow project planners to describe project-specific occupant work schedules and space sharing abilities and how these space sharing abilities change over different workshifts. The representation must be generic enough to describe different types of tenants and crews.
- Represent tenant move activities to describe spatial, organizational, and temporal information to allow project planners to describe project-specific tenants and their start and end locations to enable updating of building configurations.
- Represent construction activities to describe spatial, organizational, and temporal information to allow project planners to describe project-specific crews, their work locations, and their workshift.
- Represent different types of occupant interactions to enable a computer-based method to distinguish disruptive from tolerable interactions.
- These representations must be integrated to eliminate inconsistencies and multiple sources of information and support a computer-based method.

The reasoning methods must be able to:

- Track occupant locations to updated building configurations.
- Update occupant space sharing abilities at the workshift level of detail.
- Identify different types of occupant interactions from project-specific data about occupant locations and their space sharing abilities.

6. Existing concepts and methods to support an automated identification process

Prior research in the areas of renovation planning, product modeling, occupant modeling, activity modeling, and space sharing analysis provide useful concepts to represent and reason about spatial, organizational, and temporal renovation planning information. While prior work in renovation planning methods anecdotally supports the need to identify occupant interactions, there has been no previous work that provides a formal method to identify occupant interactions or a specification of the renovation planning information necessary to identify interactions. Prior work in product modeling provides the necessary basis for representing locations at the space level. Prior work in organizational modeling provides a basis to represent occupant work schedules and a link between occupants and spaces, but no representation of occupant space sharing abilities exists. Prior work in 4D-based activity modeling provides a representation to relate an activity, occupant, and space, but this representation requires the use of dummy activities to represent tenant move activities and the modeling of additional activities and spaces to represent construction activities at the workshift level of detail. Prior work in space sharing analysis also builds on activity modeling, but these methods identify shared spaces using geometric mechanisms and represent space sharing abilities as an attribute of the space, not the occupant. These representations and geometric mechanisms are inefficient to identify occupant interactions at the workshift level of detail because they require additional spaces and activities to be modeled for every occupant and at every workshift. Table 4 summarizes the existing concepts and methods with respect to the requirements identified previously.

Table 4. The existing concepts and methods indicate that prior work in renovation planning literature, 4D model based methods, and occupant modeling provide a useful starting point, but only partially satisfy the requirements for an automated method to identify occupant interactions. There is no method that satisfies all of the requirements identified.

O - Does not meet the requirement **P** - Partially meets requirement **X** - Meets the requirement	**Representation of renovation activities**		**Representation of occupants**			**Reasoning methods to identify occupant interactions during renovation activities**		
	Tenant move	**Construction activity**	**Location at the space level**	**Work schedule**	**Changing space sharing abilities**	**Update building configurations**	**Update occupant space sharing abilities**	**Distinguish different types of occupant interactions**
	Link start and end spaces	**Crew space sharing abilities at workshift LOD**						
Renovation planning literature *(Section 6.1)*								
Case studies	P	P	P	P	P	O	O	P
Disturbance techniques	O	P	O	P	P	O	P	P
Type of interactions	N/A							P
Product modeling *(Section 6.2)*								
BIM and IFC models	N/A		X	N/A		N/A		
Occupant modeling *(Section 6.3)*								
Energy modeling	N/A		X	X	O	N/A		
Virtual design team			O	X	O			
Crew representation in activity ontologies			X	P	P			
4D model based methods *(Section 6.4)*								
Activity modeling	P	P	X	P	P	P	O	O
Space sharing identification methods *(Section 6.5)*	P	P	X	P	P	P	P	P

6.1. Renovation Planning Literature

Much of the guidance in managing tenants and the renovation schedule is anecdotal or only provides general guidelines. Sze et al (2004) showed that partnering agreements contribute to successful projects through increased quality of communication and interaction between project planners and tenants. Fawcett and Palmer (2004) stated "Make every effort to ensure that people who are affected by the refurbishment know what is happening…Occupants and neighbours are usually more tolerant if they understand why the work is needed." Greenberg (2000) suggested that nurses be involved early in the renovation of hospital projects. Although these guidelines are worthwhile, they do not provide project planners a method to identify interactions that can be used with project-specific data.

6.1.1. Disturbance Techniques

Two prior renovation planning methods utilized project-specific data to incorporate tenant schedules into the renovation schedule. Whiteman and Irwig (1988) developed a "Disturbance Scheduling Technique" which modifies the critical path method to incorporate tenant renovation requirements. However, this method still requires project planners to identify possible occupant interactions manually to adjust activity durations in the schedule. On the seven projects examined, since the project planners did not have activity or organizational information at the workshift level of detail, it was difficult to understand if and how activity durations could be adjusted. As a result, the planners focused mainly on the sequencing of activities to avoid disruptive interactions. Shami and Kanafani (1997) developed a "Disturbance Matrix" decision support system which pre-defines the correlation between airport operational activities and construction renovation activities. The matrix is a database that can be updated as additional historical information (e.g, the relationship between airport delays and duration of construction activities) becomes available to inform future project decisions. This system requires the project planner to pre-identify occupant interactions, which, as illustrated in the first part of this paper, is problematic using traditional methods. While these methods utilize project-specific data, project planners need a method that can identify interactions from a renovation schedule without pre-identifying possible interactions.

6.1.2. Types of occupant interactions

Prior research identified different types of occupant interactions, but did not formalize a representation of these interactions to make them computer-interpretable. Whiteman and Irwig (1988) provide a list of different types of situations which require different construction work shifts (e.g., "time periods that require reduced construction impact due to tenant concerns"). Other researchers identified the use of tenants working during the day and crews working at night as an acceptable interaction (Fawcett and Palmer 2004; Fiedler 1987). Akinci et al (2002c) formalized a computer-interpretable representation of different types of crew-crew interactions for new construction, but the formalization does not include tenants.

6.2. Product Modeling

Prior formalizations of product models allow building locations to be formalized at the space level of detail (International Alliance for Interoperability 2000). Building Information Modeling (BIM), a concept which attaches non-graphical data to 3D objects, provides both the necessary spatial level of detail as well as the ability to attach organizational data to each space to represent occupant locations (National Institute of Building Sciences 2007; Yang 2003).

6.3. Occupant Modeling

Prior research areas related to representing and reasoning about tenants have addressed areas such as energy modeling (Clevenger and Haymaker 2006; Hoes et al. 2009; Yamaguchi et al. 2003) and computational organizational modeling (Carley 1995; Jin and Levitt 1996). In energy modeling, occupancy schedules (e.g., number of occupants in a space at each hour of the day) describe the work schedule and location of a tenant, but not a tenant's space sharing abilities. In organizational modeling, organizations are also modeled by their work schedules, as well as other characteristics that are not relevant to identifying occupant interactions (e.g., required expertise level of a job function), but they do not relate the organization to a location or describe its space sharing abilities.

Akinci et al (2002a) also formalized construction crews as occupants of workspaces. In her representation, each workspace is occupied by one construction crew and has a single space type which determines the workspace's space sharing ability. The representation does not associate the space sharing ability with the crew; instead, it is associated with the workspace itself. The limitations of this representation are explained in detail in the following section.

6.4. Activity Modeling

Since the integration of product, organization, and process information is required, we investigated prior activity representations which integrate this information. Darwiche et al.'s (1989) <OAR> ontology provides a representation to integrate a single activity, space, and occupant, but it does not provide a way to relate both start and end spaces to a single activity. As observed in the projects, 4D models were beneficial in providing activities at the spatial level of detail and integrating this information with activity information, but the analysis was not at the workshift level of detail and would have required a great deal of extra work to create a 4D model that displays the changing building configurations.

Darwiche et al's ontology represents activities that have a resource <R> that acts <A> on a specific object <O>. This ontology is also the basis for many 4D model-based applications including the analysis of workspace conflicts, automated schedule planning, and geometric simulation of construction processes (Aalami 1998; Akbas 2004; Akinci et al. 2002c). Darwiche et al.'s activity ontology (Darwiche et al. 1989) and Akinci et al.'s workspace conflict analysis (Akinci et al. 2002c) provide fundamental starting points that need to be extended, though, to identify occupant interactions.

4D modeling has been established as an effective tool for construction schedule visualization and coordination in new construction (Aalami 1998; Heesom and Mahdjoubi 2004; Jongeling and Olofsson 2006; Koo and Fischer 2000) and renovation projects (Collier and Fischer 1996; Messner and Lynch 2002). 4D-model based analysis goes beyond visualization to enable project managers to analyze schedules to support a variety of design and construction challenges including: workspace requirements, construction specifications, and many other areas (Akinci et al. 2002b; Boukamp and Akinci 2007; Heesom and Mahdjoubi 2004; Jongeling et al. 2005). There are, however, several limitations in using prior 4D modeling methods to update and track occupants. These limitations are described in the next two sections in the context of modeling tenant activities and construction activities, respectively.

6.4.1. Tenant Move Modeling

Much of prior research on activity representation has focused on activities for new construction projects. There has been no prior formalization of tenant move activities, which are mainly found in renovation projects. Prior research in path planning of construction processes and equipment movement (Ali et al. 2005; Stouffs et al. 1994) formalize the concepts of start and end spaces. However, since the focus of this area of research is on the geometric mechanisms of the path between start and end locations, no organizational information related to these locations is represented. With respect to 4D model-based representations, there are two limitations of the <OAR> ontology to represent a tenant move activity. First, it cannot represent a tenant move activity as a single activity. Two separate activities are required to distinguish the start and end locations of a move, because the <OA> tuple associates only one object type with one action type. Separate “move from start spaces” <OA> and “move to end spaces” <OA> tuples are required to represent a tenant move. These activities, however, are not independent – moving out of one space is the same activity as moving into another space. If the move is represented as two separate activities, any changes in dates to one activity would not be updated in the other activity. To eliminate the use of two activities to represent a tenant move, the action <A> should be associated with two space object types <O>.

Second, the <OAR> ontology does not formally represent object property information (e.g., the amount of square footage the tenant will occupy or vacate) as part of the <O> representation. Darwiche et al.'s representation allows the project planner to know the locations of the tenants, but not how much square footage each tenant occupies in that location. In situations where a tenant only partially moves out of a space, the <OAR> ontology is not able to represent this change.

In addition to the insufficient representation of a tenant move, prior research does not formalize methods to update occupant locations and occupied square footages based on activity information. The methods found in prior 4D modeling research provide a basis for tracking construction crew locations (Akbas 2004; Akinci et al. 2002a), but lack the ability to track tenant locations.

Tracking construction crews only requires the tracking of active crews because the absence of a construction crew in a construction activity indicates the absence of the crew from the entire building at that time. No additions or deletions of crews in spaces need to be made. These methods are insufficient for updating building configurations because they do not track non-moving tenants. Project planners need representation of the tenant move activity, where all tenant locations are able to be tracked to provide a complete representation of the building configuration. The distinction lies in the necessity to track tenants that occupy the building, but may not have tenant move activities associated with them. In other words, even if a tenant does not move during the renovation, they must still be represented in the building configuration.

In summary, current 4D modeling methods cannot sufficiently track a building configuration for two reasons. First, a method is needed to initialize object properties (i.e., start configuration) as input into their reasoning methods. Akbas (2004) utilized start conditions to describe the geometric object properties of components (e.g., volume) to update work locations of crews through geometric manipulation mechanisms. These geometric mechanisms do not apply to tracking of occupant locations since the organizational information to be tracked is non-geometric. Second, there is insufficient representation of a tenant move activity to describe the relationship between start and end tenant locations.

6.4.2. Construction Activity Modeling

Prior representation of construction activities does not sufficiently represent a crew's space sharing abilities in a way that allows the space sharing ability to change over time. Darwiche et al.'s ontology allows project planners to understand in which space a construction crew is working, however, it does not represent the space sharing abilities of the crew. The project planner, therefore, does not know if a space can be shared by other tenants (e.g., if the crew is changing light bulbs) or if it should be completely off limits to tenants (e.g., if the crew is abating asbestos).

For each construction activity, Akinci et al. (2002b) can represent the space sharing ability of a labor crew by modeling a labor workspace. This workspace, however, is occupied by a single crew and has a single space type. Because Akinci et al.'s representation limits a space to have only one space sharing ability per activity, it is unable to represent the changing space sharing abilities of construction crews. The project planner would need to create separate activities and spaces for each workshift to distinguish different space sharing abilities between active and idle shifts (Figure 12). For example, a 10-day condensate piping activity found on Project 2 would require twenty different activities and two different spaces to represent the changing space sharing abilities of the condensate piping crew. Since the project has 60 similar activities, the project planner would have to manage 1,200 activities and 120 spaces just for the condensate piping activities. This is time consuming and infeasible. A method is needed to distinguish these space sharing abilities at the workshift level without requiring renovation planners to create additional activities or spaces.

Activity ID	Activity Description	Occupant ID	Work Shift
117	Install CP Piping	Condensate Piping Crew	Night

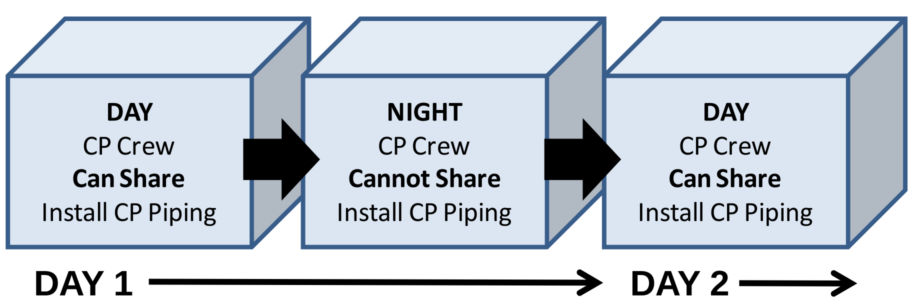

Figure 12. For a condensate piping (CP) activity, additional activities and spaces would need to be added to distinguish the space sharing abilities in active and idle workshifts.

6.5. Space Sharing Research

Prior methods to identify crew workspace conflicts from construction activities not only support the importance and value of identifying where and when different organizations share spaces, but also provide a computer-interpretable way to relate organizational (i.e., crews), spatial (i.e., workspaces), and temporal (i.e., construction activities) information. Prior approaches utilize geometric methods to create a separate space for each occupant and then determine if an interaction occurs if the spaces overlap (Akinci et al. 2002c; Zhang et al. 2005). To identify occupant interactions in renovation projects using prior approaches, spaces could be generated and deleted as tenants relocate and as construction crews renovate the building. For construction activities, the workspace size would be generated based on construction method models (Aalami 1998). Occupant interactions could then be identified if spaces overlapped geometrically. This method is inefficient because of the number of spaces that would have to be generated and deleted as occupants move in and out of spaces. In combination with the limitation of existing methods to represent an occupant's changing space sharing abilities, the use of geometric space identification mechanisms and the representation of space sharing ability as an attribute of the space results in the modeling of additional spaces for every occupant, every activity, and every workshift.

Finally, heuristic classification (Clancy 1985) has been shown to be beneficial in other construction analysis applications (Akinci et al. 2002c; Kim 2006) and can also be applied to identify tenant and crew interactions. Since there are only four ways in which occupants interact, a generic representation of these four occupant interaction types can be distinguished based on the type of occupant (i.e., tenant or crew) and how they share spaces (i.e., can share, cannot share). Project-specific information about the occupants and their space sharing abilities in each space can be abstracted and paired with this general "solution." This general solution can be refined to the specific project situation to identify the specific occupant interaction. The ability to abstract project-specific data could then enable a software program to analyze many different combinations of tenants, crews, and space sharing abilities in each space to determine automatically the space-specific occupant interactions for a renovation schedule.

7. Discussion

As building owners find ways to re-use existing buildings while maintaining business operations, the number of renovations of occupied buildings will increase. The development of better renovation scheduling methods will be crucial to ensure that business operations can continue and that there are no losses in productivity for both tenants and crews. This paper examined the use of traditional planning methods and 4D modeling on seven renovation projects to motivate the development of better methods to identify occupant interactions. It also developed the requirements for such a method, examined existing concepts and methods, and suggests extensions to meet these requirements.

Project planners must create a renovation schedule that enables both tenants and crews to work in the same building, in some instances in the same location, with no disruptive interactions. This is challenging because planners need to integrate and manage many locations in the building, occupant organizations, and renovation activities. There are many types of occupants and numerous activities, resulting in many changes to the building configuration and how occupants share space over the course of the renovation. Current methods to identify occupant interactions do not describe this location, organization, and activity information at the spatial and workshift level. 4D models provide advantages over traditional methods by enabling some integration of location and schedule information and visualization of changes in building configuration, but these models require additional activities to be created and still require manual identification of interactions. The combination of the requirement for thoroughness and detail to identify interactions accurately creates an abundance of location, organization, and activity information that makes it impossible for project planners to identify occupant interactions manually.

Based on these observations, this paper proposes that an automated method to identify occupant interactions could be more detailed and thorough, enabling a more accurate identification of interactions. To develop an automated method, an integrated representation and reasoning methods of location, organization, and schedule information are necessary. The review of the existing computer-interpretable approaches to integrate this information showed that existing concepts and methods in product, organization, and process modeling provide a strong foundation for such an automated method. Hence, the development of such a method appears feasible. There are, however, significant limitations to the efficiency of the analysis process due to existing formalizations that represent occupant space sharing abilities as an attribute of the space and existing geometry-based reasoning methods to identify shared spaces.

An automated method would provide planners with the necessary detailed data that would be infeasible to obtain with manual methods. This information could not only help project planners to identify occupant interactions more accurately, but also help identify potential space sharing opportunities. On the seven renovation projects, most planners did not analyze the information to the workshift level, forcing them to assume the most restrictive space sharing ability – that tenants and crews cannot share spaces at any time. If project planners were able to formalize occupant space sharing information at the workshift level, opportunities for sharing spaces over different workshifts could be identified, resulting in better space utilization and possibly reduced schedule duration. Ultimately, this could support the evaluation of different schedule alternatives, aid in negotiations with tenants and other stakeholders, and ultimately improve the satisfaction of both tenants and crews throughout the planning and renovation process.

8. References

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